PB213741

# EVALUATION AND FEASIBILITY STUDY

# OF ISOLATED ELECTRICAL DISTRIBUTION

# SYSTEMS IN UNDERGROUND COAL MINES

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APRIL 17, 1972

Bureau of Mines Open File Report 39-72

PREPARED FOR:

UNITED STATES DEPARTMENT OF INTERIOR
BUREAU OF MINES
WASHINGTON, D.C.
CONTRACT NO. HO111465

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## SECTION 1

## EXECUTIVE SUMMARY

### Introduction

This study consists of four descriptive sections covering respectively: a state-of-the-art literature survey on ungrounded and grounded power systems, a report on literature pertaining to human threshold limits of electric shock, an analysis of the performance requirements of isolated systems and a section on design and performance specifications for an isolated system. The final section includes copies, and translations where applicable, of the most important articles on foreign mining practice as well as some technical publications which could be difficult to obtain elsewhere.

### Section 2 - Literature Survey

In analyzing the available literature on ungrounded systems it became apparent that too strict an interpretation of Section 1.1 of the Contract would limit the survey in both period of time analyzed and in available literature which discussed several types of power systems. Therefore, the survey was expanded to cover approximately the past twenty-year period and to cover literature which addressed itself to both ungrounded and grounded power system operation. Section 2 gives a brief summary of this literature survey and lists the important papers and books which were examined.

Section 3 - Human Threshold Limits of Electric Shock

Section 3 examines the literature on the subject of human threshold limits of electric shock and includes an extensive separate bibliography of important papers and references on this subject. The contractor emphasizes that Section 3 is a report of information contained in existing literature and no attempt has been made to verify or justify the conclusions reached by the referenced authors. The contractor has used the information and conclusions of the various authors as a guide to understanding the various human threshold limits so that these limits can be considered in the analysis of the safety aspects of ungrounded power systems.

Section 4 - Performance Requirements of Isolated System

Section 4 is the real substance of this report in that it uses the information contained in the literature references of Sections 2 and 3 as the basis for an analysis of fundamental systems characteristics, systems performance and performance requirements, and a comparative examination of the advantages and disadvantages of ungrounded power systems with respect to existing systems used in underground coal mines and with respect to other system designs which might be used.

The most important human threshold limit mentioned in the study of Section 3 is the 9.0 mA "let-go current" limitation, since currents higher than the let-go current could cause the person subject to shock to "freeze" to the power system and cause death by paralysis, ventricular fibrillation, etc., as discussed in Section 3. Therefore, Section 4 examines power system design from the standpoint of "let-go current".

Section 4 establishes that there is really no such thing as an ideal ungrounded system due to the effect of inherent distributed capacitance to ground which is present in all components of the system. This capacitance establishes a path to ground for current to flow so that a shock hazard exists to a person touching a live conductor while standing on the ground or while in contact with a grounded metallic object. Analysis of system characteristics indicates that currents above the 9.0 mA let-go level can exist in a 480-volt ungrounded power system even with a limited amount of cable and equipment. The conclusion drawn is that a completely ungrounded system is no safer than any other system from a human shock standpoint. It is also shown that the ungrounded system has no advantage with respect to gas ignition hazard.

The conclusion reached in Section 4 is that the ungrounded system is not necessarily the best system for underground coal mines, but that consideration should be given to the high resistance grounded system which has important advantages over both the ungrounded system and low resistance or solidly grounded systems. It is stressed, however, that none of the described systems is intrinsically safe from a personnel standpoint.

Section 5 of this report covers design and performance specifications for an ungrounded system as required by the Contract. Where Section

4 was primarily concerned with fundamental system characteristics, Section 5 accepts these characteristics and defines an overall system and hardware specification designed to minimize the adverse safety characteristics of the ungrounded system. The design is based on the use of shielded transformers and cable to minimize stray capacitance problems and a sensitive relay system to detect high impedance fault conditions. (Unshielded symmetrical cable designs could also be used to minimize the stray capacitance problem, but shielded cable has safety advantages also.) The relay system is designed to detect single-line-to-ground fault currents as low as 9 mA, for the a-c system, and as low as 60 mA for the d-c system. The major limitation of the system is the need to shut down both 480 volt feeders for a fault on either feeder. The same limitation applies to the d-c system and to the 120/240 volt a-c system. This is because the relay system is a voltage sensing scheme and cannot distinguish between individual feeder faults and therefore is not selective. The current levels are too low for any known current sensing scheme, using sensors in the individual feeders, therefore there is no way to obtain a selective system.

The use of cable using shields around each individual conductor is a necessary part of this system. The shields should be tied to each machine frame and to the ground connection made at the ground fault sensor location. The shields balance the capacitive reactance to ground and also reduce the human shock hazard in case of cable insulation damage.

Each individual shield should be monitored to be sure they are all intact, so that maximum personnel safety is obtained and to minimize the risk of ground-to-ground arcing.

The system as specified in Section 5 has important advantages over present systems as discussed in Section 4. However, it still has the disadvantage of being subjected to excessive overvoltages if an arcing ground fault occurs. For this reason, it seems that the high resistance grounded system is a better choice.

Therefore, an electrical system essentially as described in Section 5, except using high resistance grounding, seems to be the best answer to personnel safety. In addition, the development of feeder ground fault sensors operating at a level of less than one ampere would permit selective tripping of faulted feeders and improve the availability of the substation.

Section 5 also includes a reliability analysis of the system described in the specification, using failure rate data based on general industrial experience. No specific data has been found for underground mining applications. Therefore, the analysis must be considered indicative only. The primary conclusion and recommendation is that a more reliable breaker should be used for the main 480-volt circuit breaker so that the reliability of the back-up protection would be improved.

## Power System for Lights

At the request of Mr. E. L. Litchfield, Bureau of Mines, the Contractor investigated single phase power systems for supplying lights used during the loading of explosives, although this is over and above the contract requirements. A 24-volt d-c system is suggested and it is described at the end of Section 4.

## Conclusion

We believe that the high resistance grounded power system has personnel safety advantages for underground mining application. We recommend additional investigation of this system including the type of grounding (e.g.: resistance vs. transformer coupled resistance), sensitive ground fault detectors, shielded cable design and ground continuity monitoring systems for shielded cable.

We recommend the establishment of technical interchange with the equivalent national bodies of other nations (e.g.: The National Coal Board of the United Kingdom). Much of the international literature we reveiwed is quite old, so the establishment of technical interchange agreements, and formal international technical sessions, would give an opportunity to assess past experience and current practice in this important area of human working environment.

## SECTION 2

## STATE-OF-THE-ART LITERATURE SURVEY

### Scope

Section 1.1 of the Contract requires the contractor to compile a state-of-the-art literature survey on the use of ungrounded electrical distribution systems in industrial applications. A strict interpretation of the wording "state-of-the-art" would limit the survey to current practice in the industry, but such a limitation does not permit a comprehensive survey to be made. For this reason, the search of the literature was extended back from the present time to about 1950. Anything earlier than this was not considered "state-of-the-art" unless the article discussed fundamentals rather than industry practice.

To confine the literature search strictly to "ungrounded electrical distribution systems" would place another limitation on the survey by eliminating a considerable amount of valuable literature that discusses more than one type of system. Such literature is much more valuable than literature dealing with only one system. It is inevitable, in any study such as this, that comparisons will be made between the ungrounded system and several other types of system. As a matter of fact, very few articles have been published on the use of ungrounded systems per se, at least not in recent years. This, no doubt, is due to the fact that there has been a gradual change in practice away from the ungrounded systems to the solidly grounded and high-resistance grounded systems.

The requirements of Section 1.1 are considered to have been met by the appended compilation of the state-of-the-art literature entitled, "Bibliography on Power Distribution Systems and Related Subjects". It is an expanded list of publications which include discussions of other types of systems than the ungrounded system and related subjects to permit a comprehensive study to be made of such systems. Reference may be made to some of the listings in this bibliography in other sections of this report, with the exception that a separate bibliography has been compiled for the report on human-threshold limits under Section 1 of the Contract. Certain listings to which specific reference is made in this report, and which are translations of foreign articles, or otherwise difficult to obtain, are marked with an asterisk* to indicate that copies are being supplied by the contractor and are included in Section 6.

Before proceeding with a detailed analysis of the ungrounded system (included in Section 4 of this report), it might be well to review the history of the use of this system in industry to gain a better understanding of the "state-of-the-art" today.

## A Brief History of the Ungrounded System in Industry

In the early days of the electrification of industrial plants, the ungrounded system was used almost universally for low-voltage in-plant distribution of power at 220 or 440 volts. Generators and transformers were almost always delta connected, hence there was no way to ground the neutral, even if the operators so desired, without additional equipment such as grounding transformers. The plant was usually supplied from the utility at 2400 or 6600 volts and these primary systems were also operated ungrounded. In the larger plants, such as steel mills, there were many motors operating directly on the 2400-volt or 6600-volt systems.

There are generally two reasons given for the popularity of the ungrounded system in the early days. One reason is that the initial cost was lower. There were no ground conductors and no ground connections to be made. In some of the older installations, only two instead of three breaker overcurrent trip devices were used, which was a cost saving. The other reason, of much greater importance, is that the first fault between any phase conductor and ground usually causes no interruption of power to any part of the system. Thus there is no loss of production or interruption of a continuous-type process. The system may continue in operation until a planned shutdown of the circuit or process permits the fault to be located and cleared.

Perhaps a third reason should be mentioned, this one explaining why ungrounded operation is continued long after a change is indicated by unsatisfactory operating experience. The reason is that the changeover from an ungrounded system to some form of grounded system may be expensive, especially if additional units, such as transformers, are to be added to the system. Then there is the personnel factor--a matter of training operators and maintenance men to understand, operate, and maintain a new system having different characteristics. This reason is given more often than appears justified.

In the late 1930's and early 1940's, a gradual change away from the ungrounded system to the solidly grounded system began to take place. This was brought on, no doubt, by the recognition of some of the serious deficiencies of the ungrounded system after long years of accumulated data and operating experience. These deficiencies will be analyzed in detail in the report under Section 4. During the next twenty years or so, the problem was given a great deal of thought, many tests and calculations were made, and most of the results were recorded in the literature. At first it appeared as though the change might be made completely to solidly grounded systems, but in more recent years, a third type of system -- high-resistance grounded (to be defined later) -- gained considerable favor for certain applications. Thus the power system engineer had a wide choice in the selection of a system best suited to his particular application. The good and bad features of the various types of systems will be studied under Section 4.

As is to be expected, there was, and still is, a difference of opinion among operators and engineers as to the best system. This is understandable because ungrounded and both high-resistance and solidly grounded systems have their advantages and disadvantages, and it was usually up to the individual engineer to choose the system he considers the best for his particular application. It is conceivable that personalities of individuals sometimes affected the choice made. Manufacturers of electrical equipment made contributions too, by devoting a considerable amount of their engineering talent and test facilities to a better understanding of the problems and their solutions.

No doubt another factor influencing the trend toward some form of grounded system was that industrial systems were becoming larger, with higher KVA and HP rated components. This may have emphasized some of the problems that operators began experiencing with their large ungrounded systems as contrasted to small ungrounded systems. For example, the system charging current may have become considerably higher due to more and longer feeder cables tied to the same source. Also, the use of system voltages higher than 220 volts not only produced new problems but seemed to amplify those experienced on the low-voltage systems. These, and the other undesirable characteristics of the ungrounded system, will be covered in the detailed analysis in the report under Section 4.

The literature records some of the experience, thinking, and practices of owners and power engineers, as well as the results of tests, calculations, and data accumulated by manufacturers of electrical equipment. In the following discussion, reference is made to the appended bibliography by item numbers.

As late as 1966, at least one large industrial plant, Kodak Park Works of Eastman Kodak Company, after fourteen years of experience with one hundred ungrounded systems, found the systems satisfactory. Geinger[1] concludes: "On systems of under 600 volts where continuity of service is of prime importance and where protected from lightning or contacts with other high voltage systems, and where a rigid practice of ground detecting, tracing with power on, and clearing the grounds is provided, benefits may be experienced which can justify operating such systems ungrounded."

In recent years, however, this same manufacturer has made it a practice to install only grounded systems of both the high-resistance and solidly grounded types in the same plant.

Also in 1966, a small industrial plant[2], Edmunds Manufacturing Company, decided the ungrounded system would be suitable for their operation, but for quite different reasons. It is interesting to note that the serving utility company's "highly dependable" experience with 240-volt ungrounded power distribution systems was a factor. Also, all maintenanance and repair work was done by an outside electrical contractor.

A perusal of the literature indicates the nature of the problems and the struggles of engineers and users to solve them. By 1951, one manufacturer[3] had accumulated ten "case histories" of failures due to over-voltage on ungrounded systems with explanations of what caused the failures. Thus, a better understanding of the characteristics of ungrounded systems began to emerge.

In 1954, the question of grounding the neutral of power systems was answered by several plant operators in various ways, but generally they leaned toward some form of grounding.[4]

In 1955, Thacker[5] made a prediction in the title of an article "Coming - More Grounded Systems", and in both this article and another one[6], discussed rather thoroughly the advantages and disadvantages of both types of systems. He also discussed another problem plaguing power system engineers at the time -- whether the secondary windings of the supply transformer should be delta or wye connected. Nearly all transformers in the early days were delta connected. There was no simple and inexpensive way to ground the neutral of these systems. In some cases, operators resorted to the practice of grounding one phase solidly ("corner-of-the-delta"), or even grounding the mid-point, if-any, of one transformer winding ("mid-phase grounding"). Both methods produced problems peculiar to such systems, which need not be considered here.

The use of wye connected and delta connected transformers presented problems of phasing and load sharing, as well as grounding, if the new transformers were to operate in parallel with the existing transformers. Yet some operators were reluctant to use wye connected transformers, even on independent systems, because of the somewhat higher cost at the time.

Brereton and Hickok[7] make a very good case for the high-resistance grounded system for petroleum plants, which by their nature are inherently continuous in operation. Forced and unexpected power failure can be both hazardous to personnel and costly in production losses. This paper discusses many important factors pertinent to the choice of power system. Dunbar[8] presents a very good discussion of the factors to be considered in choosing between the ungrounded and grounded system, including the interesting personnel factor. Austin[9], in designing an oil refinery system, used a solidly grounded 480 volt system but made the 2400 volt system delta connected ungrounded. The nature of the loads on the two systems seemed to be the determining factor in this particular case.

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For underground coal mines, Huffman[10] wrote in 1958 that the use of a neutral resistor in both primary and secondary circuits is the safest system devised so far, and placed great emphasis on proper design of the entire system. But in 1960, Stewart[11] defended the use of a delta connected ungrounded system for coal mines. In the same year, an article in Coal Age[12] describes mines with resistance grounded systems. Trasky[13], in 1965, recommended high-resistance grounding with suitable protective devices.

Although he is writing about public utility systems, Sutton[14] poses the question in the title "To Ground or Not to Ground is the Question", and then presents a very good analysis of the factors that should be considered in choosing between grounded and ungrounded systems. Eliasen[15] does somewhat the same thing in an article declaring "Grounding is a Local Problem."

Potter[16], in 1965, says, "In the design of large modern industrial plants, ungrounded delta electrical distribution systems are rarely considered today", but proceeds with a graphical analysis of ungrounded delta systems (for balancing loads). In 1966, Jackson[17], a consulting engineer, made a strong case for system neutral grounding after reviewing the characteristics of several systems.

As for foreign coal mine practice, Luxmore[18] indicates that it is now accepted practice in Great Britain to limit ground fault current, by means of a neutral grounding resistor, to not more than 15A, and in many cases to not more than 0.75A at 1100V and 0.25A at 550V, with ground fault protective tripping devices. Streich [19,20] indicates that the practice in West Germany is to operate the system ungrounded but with ground fault protective devices. Delauw[21] indicates that Belgium practice may be to operate ungrounded, but with proper protective devices.

The General Electric Company[22], in 1969, published GET-3548, entitled "System Grounding for Low-voltage Power Systems", which sums it up by comparing the characteristics, advantages, and disadvantages of eight methods of system grounding (including the ungrounded system).

There are probably many more solidly grounded systems than ungrounded systems in operation today in modern industrial plants. The use of high-resistance grounded systems has shown an increase in oil refineries, paper mills, and similar industries. The ungrounded system is still favored by many automated process companies, such as most large automobile manufacturers, in which a power shutdown is estimated to cost $2000 a minute or more in lost production. The corresponding cost for coal mines is probably in the order of $400 an hour per mine section. It should be noted that these large industrial plants generally have well trained maintenance personnel with adequate equipment, an advantage the smaller companies do not have, but this is not always true. A few automobile manufacturers have recently installed high-resistance grounded systems.

All of the above emphasizes the fact that there are many pros and cons on the subject of system grounding, and that the engineer should decide for himself which system will best serve his needs, provided, of course, that the system he chooses does not violate any laws, regulations, or codes that may apply to his industry.

## BIBLIOGRAPHY ON POWER DISTRIBUTION
## SYSTEMS AND RELATED SUBJECTS

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English from a foreign language, or that may be difficult to obtain.
Copies of the marked publications (but no others) are being supplied by the Contractor in Section 6.

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2) "240 Volt Distribution Powers Modern Plant" Electrical Construction and Maintenance v 65 n 3 March 1966 p 106-9.

3) "Cases of Failure Due to Overvoltage" General Electric Company publication Industrial Power Systems Data Book, 1951 - 1952, Section .2201 p 1-3.

4) "More Plant Problems -- Should we ground plant Neutrals?" Power Magazine June 1954, p 146, 222, 224, 226, 228, 234.

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7) "System Neutral Grounding for Petroleum Plant Power Systems" D. S. Brereton and H. N. Hickok Informal Conference presentation

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12) "Modernization with A.C. Equipment Doubles Productivity at Guyan Mines" Coal Age v 65 n 9 September 1960 p 80-3

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17) "System Neutral Grounding" D. W. Jackson, Power v 110 n 6 June 1966 p 84-7

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19) "Zur Grage der Sicherheit im elektrischen Betrieb unter Tage" Rudolf Streich Gluckauf April 25, 1962 p 482-9 ("Safety in Electrical Operations in Mines")

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21) "Etude de la securite dans les reseaux electriques 500 V utilises dans les travaux souterrains" G. Delauw, Annales des Mines de Belgique, n 9 September 1964 p 1114-35 (in French with English summary)

22) "System Grounding for Low-voltage Power Systems" General Electric * Company publication GET-3548 38 pages (includes discussion of ungrounded systems)

23) "Grounding of Industrial Power Systems" IEEE Publication No. 953 (the "Green Book" when issued)

24) "Electric Shock -- Its Causes and Prevention" Bureau of Ships publication NAVSHIPS 250-660-42 Also AIEE Paper 55-471 by R. L. Kline and J. B. Friauf 1955 (includes discussion of ungrounded system)

25) "Low Voltage Ignition of Hazardous Atmosphere" E. C. Magison, ISA Journal July 1962 p 29-32

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30) "The Impact of Arcing Ground Faults on Low-voltage Power System
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# SECTION 3

## REPORT ON STUDY OF HUMAN THRESHOLD LIMITS OF ELECTRIC SHOCK

### General

Section 1.2 of the Contract requires the Contractor to ascertain human threshold limits and appropriate safety factors for power distribution systems. It was necessary for the contractor, not skilled in the medical arts, to make a very comprehensive survey of the literature to understand the problems, limits, and tolerances of human shock hazards as they relate to coal mine types of power distribution systems. This understanding is essential prior to proceeding with the study and design of the coal mine power system itself.

The study of the power systems, reported under Section 4, will show why all types of systems present personnel shock hazards. A knowledge of the characteristics of systems and the effects of electric shocks on man are both important factors in the choice of the type of system and the application of suitable protective devices, not only for the man but for the system.

The purpose of this report is (1) to record the state-of-the-art literature on electric shock hazards and human threshold limits, (2) to summarize the data, observations, and conclusions of the authors of the literature, and (3) to emphasize what the authors consider to be important aspects of the problems and solutions in the matter of personnel safety. This report will not attempt to evaluate the work of the investigators, to draw conclusions not already in the literature, or to set forth guide lines or limits to insure personnel safety.

The reference numbers refer to the appended "Bibliography of Literature on Electric Shock Hazards and Human Threshold Limits".

In the evaluation of a power distribution system in which personnel safety is the prime consideration, it is important to understand the effects of an electric current on the human body. These effects range all the way from mild surprise to immediate death, with intermediate variations including fright, anxiety, violent involuntary reaction, paralysis, asphyxia, ventricular fibrillation, cardiac arrest, nerve and blood vessel damage, and severe burns.

A realistic approach to the problem, and a thorough study of the literature, will result in the conclusion that an extremely minute quantity of electrical energy can be injurious or even fatal. While a low value of current may cause only fright or surprise, serious injury or even death can result under certain circumstances if involuntary reaction to the shock causes the victim to fall from a high place, to jump so as to strike another object forcefully, or to tangle with machinery in operation. Whether or not a stated value of current through the human body is dangerous or lethal depends upon a set of variables such as body weight, health of the individual, whether male or female, the path of the current through the body and the duration of current flow. The actual value of current flowing depends upon another set of variables including the circuit voltage, the circuit frequency, and the total resistance of the body, contact points, and other circuit elements. While the circuit frequency has an effect on shock hazard, this report will consider only direct current and 60 Hz alternating current as applying to coal mine power distribution system practice.

The electrical resistance of the human body, mentioned in the foregoing paragraph, varies over a wide range, as reported by several authors.[1,2,3.] The actual value depends upon the circuit voltage[2], the nature of the contact[1], and the condition of the skin at the point of contact[1], among other things. Authors quote minimum resistance values as low as 400 to 600 ohms[3], although a more realistic value probably is 1000 to 1500 ohms. Much higher values have also been reported[2], applying when the skin is dry, shoes dry and in good condition, and whether the surfaces in contact are large or small.

It should be recognized that there is a distinction to be made between shock due to a flow of electric current and pathological shock defined as a collapse of circulatory function caused by disease, blood loss, or severe injury. In other words, a victim of a mild electric shock may be endangered by unrecognized pathological shock if he is badly frightened or severly injured by his involuntary reaction to free himself from the source of voltage.

The hazards of impulse currents should be included in any study of personnel safety. It is a well known fact that high voltage transients may appear on power distribution systems, and especially on ungrounded systems. These transients may be due to lightning, contact with another higher voltage source, switching surges, resonance between system capacitance and inductance, and certain types of faults. While most of the experimental work was done with steady-state currents, some work on the effects of impulse currents is also reported in the literature.[3]

Fortunately, a great deal of work has been done on electric shock hazards by many investigators, including engineers, scientists, and medical doctors, to observe effects and obtain data that can define the problems and lead to solutions. It should be understood that threshold limits of such dangerous effects as ventricular fibrillation, cardiac arrest, and severe burning, were arrived at by experimental data obtained on animals of various sizes and body weights. This data was then extrapolated to the human body by weight and other relationships. In other words, no directly-obtained data exists on the effects of dangerous values of current on the human body. However such relatively harmless effects as perception, pain sensation, and let-go current data were obtained directly on men and women under strictly controlled laboratory conditions. All of this work is well documented in literature dating back many decades and brought up to date by recent studies and reevaluations.

## Human Threshold Limits

Perhaps the best way to summarize the data, observations and conclusions of the authors of the literature is to consider increasing values of current in increments related to the changing effects of the current on the human body in approximately these steps: (1) perception, (2) painful sensation, (3) let-go current, (4) paralysis, (5) ventricular, fibrillation, (6) cardiac arrest, and (7) tissue destruction.

## 1 - Perception

The threshold of perception of an electric current flow through the human body is of much greater importance to public utilities and manufacturers of household appliances than it might be to the mining industry. However, it is a starting point and of interest if the possibility of injury as a result of surprise or fright is to be considered.

In a fairly large number of tests by Dalziel[4], under several different test conditions, it was determined that the average 60 Hz current just perceptible was 1.086 mA for men and 0.728 mA for women when holding a No. 7 or 8 copper wire in the hand. The minimum current was found to be 0.402 mA and the maximum 1.77 mA for men, and about two-thirds of these values for women. Comparable d-c current values for men were an average of 5.2 mA with a minimum of 2.2 mA and a maximum of 12.6 mA. In data such as these, pertaining to personnel safety, the minimum values are of greater significance than the average.

The above data, observations and conclusions seem to agree quite well with the work of other investigators reported in reference (5), in which perception threshold values from 0.90 mA to 1.05 mA were obtained in 50 Hz tests. It is to be noted that the paper by Dalziel[4] indicates quite clearly that with types of contact other than holding a wire, the threshold of perception by the most sensitive person is 0.2 mA for both men and women.

2 - Mild and Painful Sensation

Not much work seems to have been done specifically to determine current magnitudes required to produce just mild or painful sensation, probably because such values do not appear to be as important as others. However, currents between 1.0 mA and 9.0 mA have been reported in some of the literature [1,6] as producing a sensation varying from mild to very painful.

While shocks involving current magnitudes less than 9.0 mA may be more annoying and painful than harmful, they must be taken seriously as a warning and indication that a potentially dangerous condition exists on a system that should be found and corrected. For example if a mild shock is felt when touching the frame of a machine or equipment, it is certainly an indication that something is wrong.

3 - Let-go Current

To quote Dalziel and Massoglia[7], "For many practical purposes, the maximum current safe for man is just a little less than that causing him to 'freeze' to a circuit. This current is called his let-go current; this is the maximum current he can tolerate and still be able to release or let go his grasp of an energized conductor by using the muscles directly stimulated by that current."

The conclusions of Dalziel and others [7,8,9] are that the reasonably safe let-go 60 Hz currents for men and women are approximately 9.0 mA and 6.0 mA, respectively. Although only a few tests were made on d-c, Dalziel[9] reports that the reasonably safe let-go d-c currents for men and women are 62 mA and 41 mA, respectively. Their figures are based on the theoretical response of 99.5% of a large group of subjects (199 out of 200).

## 4 - Paralysis

The reason that the magnitude of current just a little less than the let-go current is considered to be the maximum safe current by Dalziel[7] is that breathing becomes difficult or impossible, due to paralysis of the breathing muscles, on higher values of current. In a United States Atomic Energy Commission publication[9], Dalziel says, "Prolonged exposure to currents only slightly in excess of a person's let-go limit may produce exhaustion, asphyxia, collapse, and unconsciousness followed by death."

It must be concluded then, from the work of Dalziel and others, that the design of a power system should be such that a man will not be subjected to more than 9.0 mA a-c or 60 mA d-c for a length of time that would result in death from asphyxiation. This is one of the most important considerations in the design of a power system with respect to personnel safety.

Because of the large number of variables in subjects, test procedures, and even psychological aspects, a clear understanding of the nature and danger of let-go currents cannot be had without a detail study of the literature, especially references 7,8, and 9.

## 5 - Ventricular Fibrillation

Ventricular fibrillation is a condition in which the heart beats wildly out of control. The rhythmic pumping action ceases and death follows rapidly if the condition continues. Worse yet, the condition is not self-correcting after the current flow is cut off. Special equipment and medical skill are usually required to save the victim. Whether or not fibrillation occurs depends upon the magnitude of current, duration of current flow, and body weight of the individual.[8,10,11] Because fibrillation is too dangerous a condition to experiment with, no tests on human beings have been made. However, elaborate and numerous tests on animals of different weights have permitted reasonably good extrapolations to be made to determine human limits.[2,6,8,10,11]

From the large amount of animal test data, Dalziel, Lee and others[2,8,10,11] determined that the relationship between current and time required to produce fibrillation in humans is an $I^2t$ relationship. In other words, $I^2t$ is equal to a constant K. In selecting the proper value for K, Dalziel used a probability factor of 1 in 200, or, in other words, selected a value of K that results in a current that will not cause fibrillation in 99.5 percent of humans subjected to that value of current. He further determined the value of K = 116 on the basis of a man weighing not less than 50 kg (110 pounds), and for a duration of current flow between 8.0 milliseconds and 5.0 seconds. This resulted in the formula:

$$I = \frac{116}{\sqrt{t}}$$

in which I is in mA and t is in seconds (for values of time between 0.008 and 5.0 seconds). For example, if t is five seconds, the current just below the value required to produce fibrillation in five seconds is about 52 mA.

The $I^2t$ characteristic suggests a basis for the design of protective devices to minimize shock hazards, a basis of protection that has been used in some foreign coal mines. However, as was pointed out under (3) above, the most important consideration should be the 9 mA let-go current limitation because currents above this value may cause death by paralysis and asphyxiation.

## 6 - Cardiac Arrest

There is evidence that current magnitudes considerably in excess of the values required to produce fibrillation may cause cardiac arrest.[5,6,9,10] Cardiac arrest means that the heart stops beating for the duration of current flow. When cardiac arrest occurs, there can be no fibrillation. The heart usually starts again when current stops flowing, provided of course that current has not been on too long. Since the heart usually starts again, cardiac arrest is thought to be less lethal than fibrillation, which is not self-correcting.[5,9]

## 7 - Tissue Destruction

The destruction of tissues, including nerves, blood vessels, and internal organs, results from shocks of high current magnitudes. Whether or not this is crippling or fatal depends, of course, on the tissues destroyed and the amount of irreversible damage. Destruction of tissues may occur due to either the flow of current through the body or to thermal effects of high temperatures close to the body.[6, 8] Delayed death may be due to serious burns or complications.[8]

Note on Tabulated Human Threshold Limits

Attempts have been made by several investigators and authors to tabulate the large amount of test data (references 1, 6, 9, 12). While these tabulations are useful for ready reference and comparison purposes, they should be used only with a full understanding of what the tabulated values actually mean. Use of the data without complete understanding of what it means, as explained in the literature, can be hazardous.

# BIBLIOGRAPHY OF LITERATURE ON ELECTRIC SHOCK HAZARDS AND HUMAN THRESHOLD LIMITS

Most literature published earlier than about 1936 is not included in the following listing because it is assumed that much of the early data probably has been superseded and re-evaluated in later publications. However, if there is any interest in the earlier work, a bibliography of literature published between 1747 and 1936 may be found in reference (5) below.

Special reference is made to "Bibliography on Electrical Safety... 1930 - 1953," AIEE Bulletin S-69, December 1954, which lists nearly 1,000 publications on electrical hazards and related subjects (reference 41 below).


1) "Electrical Safety in Industrial Plants" Ralph H. Lee IEEE Spectrum June 1971 pp 51-55, also IEEE Transactions Industry and General Application, IGA-7 January/February 1971 pp 10-16.

2) "Death from Electric Shock" W. R. Lee, Proc. IEE (London) Volume 113, January 1966, pp 144-148.

3) "A Study of the Hazards of Impulse Currents" C. F. Dalziel, AIEE Transactions, Volume 72, 1953, Part III Power Apparatus and Systems, pp 1032-1043, AIEE Paper 53-313.

4) "The Threshold of Perception Currents" C. F. Dalziel, AIEE Transactions Part III, 1954, pp 990-996. Also, AIEE Paper 54-209. Also, Electrical Engineering, July 1954, Volume 73, pp 990-996.

5) "Effect of Electric Shock on the Heart" L. P. Ferris, B. G. King, P. W. Spence, and H. B. Williams AIEE Transactions, Volume 55, May 1936, pp 498-515.

6) "Deleterious Effects of Electric Shock" C. F. Dalziel, in "Handbook of Laboratory Safety", second edition, published by the Chemical Rubber Company, Cleveland, Ohio, 1970, pp 521-527.

7) "Let-go Currents and Voltages" C. F. Dalziel and F. P. Massoglia, AIEE Transactions, Volume 75, Part II, 1956, pp 49-56. Also, AIEE Paper 56-111.

8) "Reevaluation of Lethal Electric Currents" C. F. Dalziel and W. R. Lee, IEEE Transactions, Industry and General Applications Volume IGA-4, September/October 1968, pp 467-476. Also, discussions November/December pp 676-677 Technical Paper SL-68-1.

9) "Effects of Electric Shock on Man" C. F. Dalziel, IRE Transactions on Medical Electronics, Volume PGME-5, May 1956, pp 44-62. Also, reprinted as United States Atomic Energy Commission Safety and Fire Protection Technical Bulletin No. 7. Also, AIEE Paper 60-40.

10) "Lethal Electric Currents" C. F. Dalziel and W. R. Lee, IEEE Spectrum, February, 1969 pp 44-50.

11) "Threshold 60-cycle Fibrillating Currents" C. F. Dalziel, AIEE Transactions, Power Apparatus and Systems, Volume 79, October 1960 pp 667-673.

12) "Physiological Aspects of Electrical Accidents in the Coal Mining Industry" S. J. Davenport and G. G. Morgis, Bureau of Mines Information Circular 7620, September 1951.

13) "Electricity in Hospitals -- Elimination of Lethal Hazards" Gordon D. Friedlander, Senior Staff Writer, published by IEEE Spectrum, September 1971 p 40-51.

14) "Standards - The Evidence of Concern" W. H. Middendorf, IEEE Spectrum, Volume 8, 1971, pp 70-73 (includes discussion of standards for electric shock hazards.)

15) "Transistorized Ground-Fault Interrupter Reduces Shock Hazard" C. F. Dalziel, IEEE Spectrum, Volume 7, January 1970, pp 55-62.

16) "Factors Determining Vulnerability to Ventricular Fibrillation Induced by 60-cps Alternating Current" T. Sugimato, S. F. Schaal, and A. G. Wallace, Circulation Res. Volume 21, 1967, pp 601-608.

17) "Increased Susceptibility of the Heart to Ventricular Fibrillation During Metabolic Acidosis" P. H. Gerst, W. H. Fleming, and R. J. Malone. Circulation Res. Volume 19, July 1966, pp 63 - 70.

18) "The Magic of $I^2t$" R. H. Kaufmann, IEEE Transactions Industry and General Applications IGA-2 - 1966 September/October, pp 384-392.

19) "Electric Shock Hazards of Fresh Water Swimming Pools" C. F. Dalziel, IEEE Transactions on Industry and General Applications, Volume IGA-2, No. 4 July/August 1966, pp. 263-273 (included because it includes descriptions of circuit protective devices designed to reduce electric shock hazards, and references to other articles on such protective devices.)

20) "Deaths from Electric Shock in 1962 and 1963" W. R. Lee, British Medical Journal, Volume ii, September 1965, pp. 616-619.

21) "Aspects of Isolated Power Systems for Hospital Operating Rooms" W. C. Huening, Jr. IEEE Transactions Industry and General Application, July/August 1965, pp. 285-294.

22) "Transistorized, Residual - Current Trip Device for Low Voltage Circuit Breakers" Transactions AIEE, Volume 81, 1962, pp. 978.

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26) "Electric Defibrillation" W. B. Kouwenhoven, AIEE Technical Paper 56-6, 1956.

27) "Electric Shock...Its Cause and Its Prevention" R. L. Kline and J. B. Friauf, AIEE Paper 55-471, 1955. Also Bureau of Ships publication NAVSHIPS 250-660-42

28) "Electric Shock...Its Causes and Prevention" Bureau of Ships publication NAVSHIPS 250-660-42, 1954.

29) "Electricity and the Human Body" National Safety News, Volume 63, February 1951, pp. 30-31 and 101-106.

30) "Effect of Frequency on Perception Currents" C. F. Dalziel and T. H. Mansfield, AIEE Transactions, Volume 69, 1950, pp. 1162-1168.

31) "Effects of Electricity on the Human Body" B. Kouwenhoven, Electrical Engineering, March 1949, Volume 68, pp. 199-203.

32) "Dangerous Electric Currents" C. F. Dalziel, AIEE Paper 46-112, AIEE Transactions Volume 65, 1946, pp. 579-585 and 1123-1124.

33) "Effect of Frequency on Let-go Currents" F. Dalziel, Eric Ogdon, and C. E. Abbott, AIEE Transactions, Volume 62, December 1943, pp. 745-750 and 998-1000.

34) "Effect of Wave Form on Let-go Currents" C. F. Dalziel, AIEE Transactions, Volume 62, December 1943, pp. 739-744.

35) "Effects of Electric Current on Man" C. F. Dalziel, and J. B. Lagen, Man. Elec. Eng. Volume 60, February 1941, pp. 63-66.

36) "Big Coal Mining Hazards...Electricity". Coal Age, Volume 46, December 1941, pp. 80.

37) "Electrical Shock" C. F. Dalziel, J. B. Lagen, and J. L. Thurston, AIEE Paper 41-7. AIEE Transactions Volume 60, 1941, pp. 1073-1079.

38) "Production of Ventricular Fibrillation by Alternating Currents" R. Wegria and C. J. Wiggers, Amer. J. Physiol, 1940, 131, pp. 119.

39) "Current Flowing Through the Heart Under Conditions of Electric Shock" D. R. Hooker, W. B. Kouwenhoven, D. R. Langworthy, The American Journal of Physiology, Washington, D. C., Volume 103, 1933 pp. 444.

40) "Hazards of Low Voltage Shocks" H. B. Williams Journal American Medical Association, Volume 97, 1931, pp. 156-157.

41) "Bibliography of Electric Safety, 1930-1953" AIEE Bulletin S-69, December 1954. Has five parts: (a) Electrical Accidents and Their Causes, (b) Accident Prevention Methods, (c) Effectives of Electric Shock, (d) Resuscitation, (e) Safety Codes and Standards.

42) "Electric Shock Hazard", C. F. Dalziel, IEEE Spectrum, February 1972, pp. 41-50.

## SECTION 4

## PERFORMANCE REQUIREMENTS OF THE ISOLATION SYSTEM

Section 1.3 of the Contract requires the Contractor to determine the performance requirements of the isolation system, the fault detectors, and disconnect devices for AC supplies from 110 to 4160 volts and for DC supplies of 300 and 600 volts.

In the following discussions, reference will be made by item numbers to the bibliography compiled in Section 2 of this study, entitled "Bibliography on Power Distribution System and Related Subjects" .

### DEFINITIONS

It is important that the terms "isolated" and "ungrounded" (used in the Contract) be clearly defined before proceeding with the study of the electrical distribution system. There does not appear to be a standardized definition of either term in the literature. Authors of technical articles on industrial power systems use the term "ungrounded" almost exclusively, and generally define it in similar but essentially the same wording. Authors of technical articles on high isolation techniques in the medical field use the term "isolated" to designate more elaborate procedures and techniques in system design than just ungrounding the system. According to the wording of Section 1.1 of the Contract, such procedures and techniques are to be minimized in this study. The term "ungrounded" will therefore be used exclusively in this report as being synonymous with the term "isolated" used in the contract.

The definition of an ungrounded system that will appear in the revised IEEE publication[23] No. 953 ("The Green Book"), when issued, is expected to read: "Ungrounded system means a system without an intentional connection to ground except through potential indicating or measuring devices or through surge protective devices. Though called 'ungrounded' this type of system is in reality coupled to ground through the distributed capacitance of its phase windings and conductors. The neutral of an ungrounded system under reasonably balanced load conditions will usually be close to ground potential, being held there by the balanced electrostatic capacitance between each phase conductor and ground." Note that the last sentence of the definition is true only under normal system operating conditions, as will be shown later.

An ungrounded system in accordance with the definition is illustrated in Fig. 4-1, in which the capacitors C represent the "electrostatic capacitance between each phase conductor and ground" in the definition. Although this capacitance is actually distributed more or less uniformly in all of the system components, it may be considered to be "lumped" for all the usual purposes in one capacitor connected between each phase conductor and ground as in Fig. 4-1. In some respects, especially for some mathematical calculations, the electrical behavior of any one phase conductor of Fig. 4-1 can be determined by a simplified equivalent circuit shown in Fig. 4-2, in which the phase-to-ground capacitances of Fig. 4-1 are shown further "lumped" in a single capacitor having a value equal to 3 x C connected between neutral and ground.

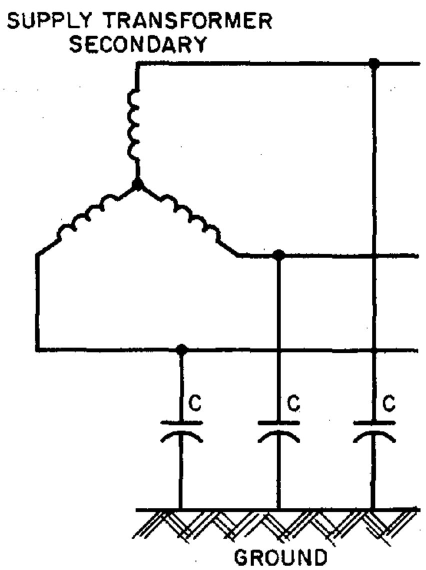



Figure 4-1. Ungrounded system, capacitively coupled to ground

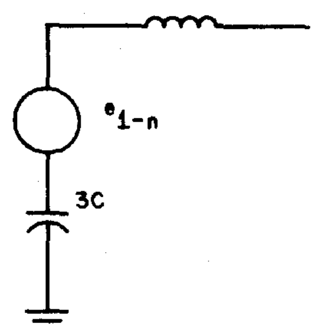



Figure 4-2. Equivalent circuit of ungrounded system

The IEEE publication [23] is also expected to define a <u>grounded</u> system as: "A grounded system is one in which at least one conductor or point (usually the neutral point of transformer or generator windings) is intentionally grounded, either solidly or through a current-limiting device". Note that the "transformer" is the supply transformer -- not a load transformer.

GET-3548[22] defines the ungrounded system in essentially the same wording as the IEEE publication. In addition, GET-3548 defines several different types of grounded systems in terms of the method of grounding and the magnitude of ground fault current limitation, if any. For example, the solidly grounded system is defined as a system in which the neutral point is connected directly to ground with no intentional impedance in the ground connection and hence no intentional limitation of ground fault current magnitude. Corner-of-the-delta grounding and mid-phase grounding are variations of the solidly grounded neutral system that, for the purposes of this report, need not be considered separately, as none of these systems is used in coal mine practice. Fig. 4-3 shows a solidly grounded system.

GET-3548 defines the low-resistance grounded system as a system in which a low value of resistor has been inserted in the neutral ground connection to limit the ground fault current to a value low enough to reduce damage significantly but high enough to operate ground fault protective devices. Although not defined too well quantitatively, the low-resistance grounded system, according to GET-3548, is one in which the ground fault current is limited to a value equal to 20 percent of the available three-phase short-circuit current downward to 1000 amperes. An exception is made for mine power systems, in which the current may be limited to a value as low as 25 amperes, Fig. 4-4 shows a resistance grounded system.

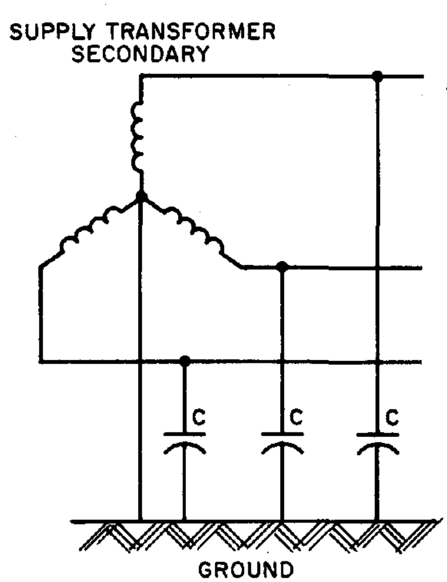



Figure 4-3. Solidly grounded system

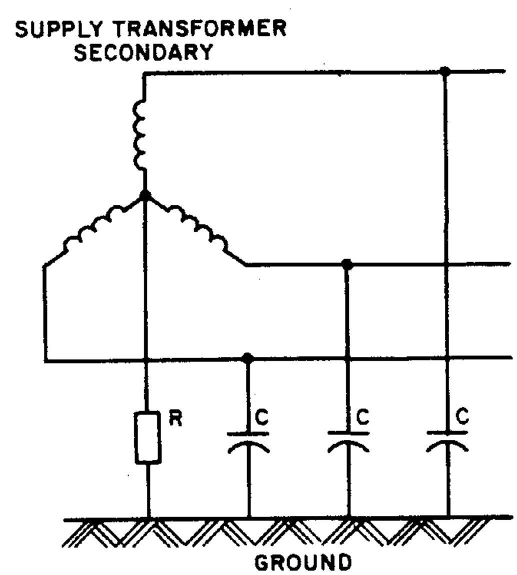



Figure 4-4. Resistance grounded system

GET-3548 defines the high-resistance grounded system: "The high-resistance grounded neutral system is one in which a high value resistor has been inserted in the neutral connection to ground to limit the resistor current under ground fault conditions to a value not less than the system charging current, resulting in a total ground fault current of approximately $\sqrt{2}$ times the charging current."

The "charging current" referred to in the definition is the current that flows from each phase conductor to ground thru the distributed phase-to-ground capacitance, represented by C in Fig. 4-1, due to the phase-to-neutral voltage of the system impressed across the capacitance. The total charging current then would be three times the current per phase, since there are three phases. When a phase-to-ground fault occurs on a high-resistance grounded system, the fault current flowing thru the resistor adds vectorially to the capacitor current. If the value of resistance is such that the ground fault current itself is equal to the system charging current, then the total current will be $\sqrt{2}$ times the charging current, thus meeting the requirements of the definition.

Note that the definition permits the use of ground fault current values higher than $\sqrt{2}$ times the charging current, which is frequently the case. Although the definition defines the minimum current of a high-resistance grounded system, it does not define the maximum. In the design of a high-resistance grounded system, the current is usually limited to the lowest value that will operate the protective devices chosen for the particular application to minimize the damaging effects of ground faults (as will be discussed later).

For the purposes of this study of power distribution systems for underground coal mines, the distinction between the high-resistance and low-resistance grounded systems will be made in terms of ground fault current magnitude. A high-resistance grounded system is one in which the neutral resistor limits the current to 15 amperes or less. A low-resistance grounded system is one in which the neutral resistor limits the current to values between 15 amperes and 20 percent of the maximum available three-phase short-circuit current. The other two systems discussed will be the ungrounded and the solidly grounded systems.

## ANALYSIS OF SYSTEM CHARACTERISTICS

A complete and detailed analysis of the ungrounded system will be made to gain an understanding of its unique characteristics before determining performance requirements of the system, fault detectors, and disconnect devices. This leads to the determination of advantages and disadvantages and inevitably to comparisons with other types of systems; namely:

the-high-resistance grounded system,

the low-resistance grounded system, and

the solidly grounded system.

This study is based on a three phase system energized at rated voltage. All comments apply to rated voltages up to and including 4160 volts unless otherwise noted. It is also assumed that there are no line-to-neutral or line-to-ground connected loads on the system (unless otherwise noted). There may be single phase line-to-line connected loads, but it is assumed they are relatively small.

It is emphasized here that for the purposes of this analysis, it is assumed that there are no ground fault detectors or other protective devices on the system, with the exception of the usual phase overcurrent trip devices or relays, and circuit interrupters, for short-circuit protection. Obviously, the inclusion of protective devices would modify the characteristics and thus defeat the purpose of the study. In other words, this is an analysis of the fundamental characteristics of the power distribution system itself. After the characteristics have been determined, then protective devices may be applied to modify the system as required.

The analysis will be made in three steps:

(A) List each characteristic of the ungrounded system and analyze it in detail.

(B) Determine which characteristics are advantages, disadvantages, or unimportant in underground coal mine practice.

(C) Determine if the disadvantages can be overcome by the use of another type of system without loss of any of the advantages.

(A) Characteristics of Ungrounded System Listed and Analyzed

Characteristic 1 - Presence of Line-to-Ground Voltage Normally

Under normal conditions, there is always a voltage present on an ungrounded system between the three line conductors and ground (the earth), or any grounded metallic objects such as frames, pipes, track rails, roof bolts, and conductors of other systems. If it were possible for an ideal ungrounded system to exist, as shown in Fig. 4-5, there would be no voltage whatever between any line conductor and ground. Actually, however, it is physically impossible for such a system to exist because of the inherent distributed capacitance to ground always present in all components of the system, including supply transformer, cable, and connected loads.

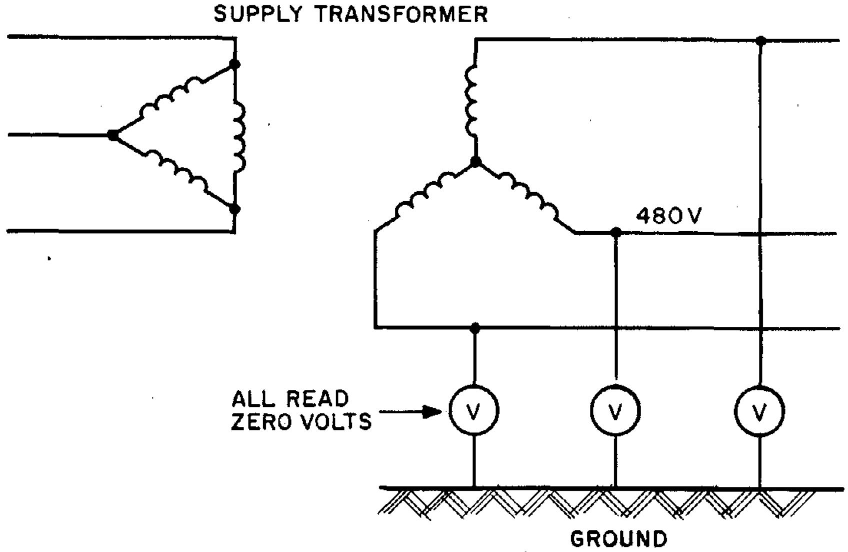



Figure 4-5. Idealized ungrounded system (no distributed capacitance)

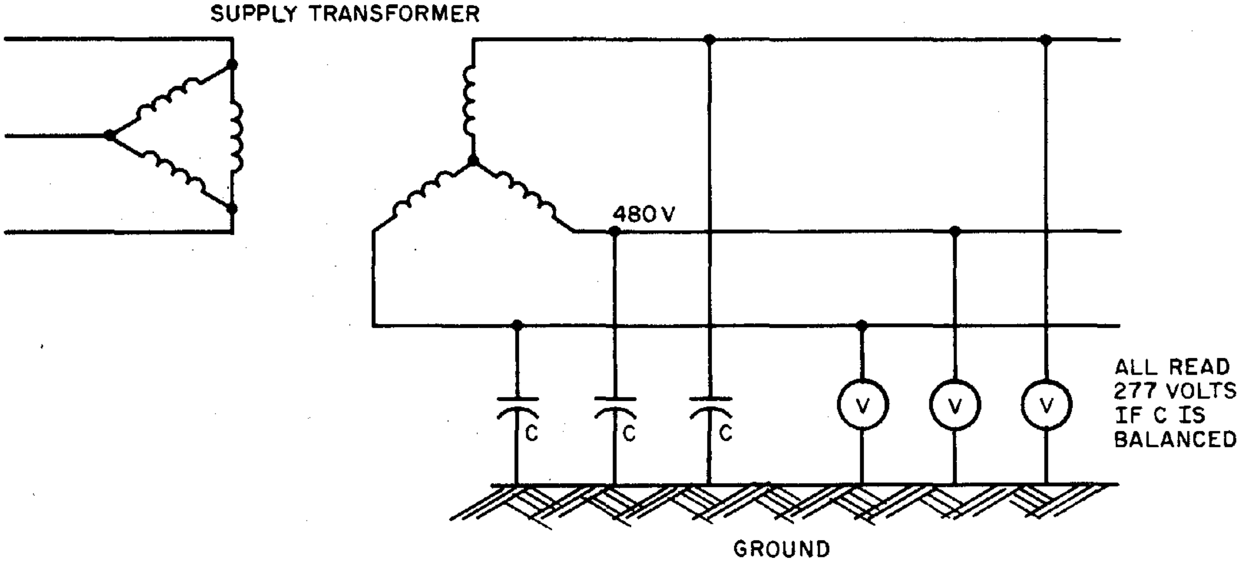



Figure 4-6. Actual ungrounded system (with distributed capacitance)

All insulated electrical circuits have distributed capacitance between the phase conductors and ground, as shown in Fig. 4-6. The magnitude of the capacitance depends upon many physical factors, such as the size of the conductor, nature of the insulation, and spacing of the conductors relative to ground. In addition to the capacitance of the cables of a system, there is also distributed capacitance between transformer windings and ground, and between the connected load and ground.

The existence of the distributed capacitance is well known, and, in fact, mentioned in most of the literature as an important characteristic of the ungrounded system (examples, references 22 and 24). A strictly ungrounded system simply cannot exist in actual practice.

Under most conditions, and in most systems, the distributed capacitance of the three phases are approximately equal, and such equal distribution is assumed to be the case in this analysis. However, if the conductors of a cable, for example, are not symmetrically arranged with respect to each other in the cable, the capacitances between phase conductors will not all be the same magnitude. This may or may not unbalance the capacitances to ground. If it does unbalance the three capacitances to ground, it will in effect displace the "neutral" of the ungrounded system so that it is no longer in the center of the voltage triangle. Under such conditions, the three voltmeters shown in Fig. 4-6 will not all read the same voltage. However, the vector sum of the three voltages will be the same as for a balanced system.

The electrical effect of the distributed capacitances shown in Fig. 4-6 can be evaluated by using the simplified circuit shown in Fig. 4-2. In other words, because of the distributed phase-to-ground capacitances, the neutral of an "ungrounded" system may be considered to be grounded thru a capacitor connected between neutral and ground having a value equal to three times the phase-to-ground capacitance.

Some feeling for the magnitudes of distributed capacitances may be had from the following examples:

The capacitance between the low voltage winding and ground of a standard type mining transformer is in the order of 0.0042 μF.

The capacitance of a typical mine cable is in the order of 0.02 μF per 1000 ft.

Simple tests were made by the Contractor on a simulated 480 volt, three phase, ungrounded system. The object of these tests was to show that because of the capacitance between each phase of even a short length of cable and ground, there exists a definite and measurable shock hazard to a person touching a live conductor while standing on the ground, or in contact with a grounded metallic object.

Fig. 4-7 shows a simple ungrounded system consisting of a power transformer and a length of cable. The capacitors $C_t$ represent the total capacitance between the secondary winding and ground. The capacitors $C_c$ represent the total capacitance of the cable conductors to ground. A man is shown standing on the ground and touching one of the line conductors. The actual tests were made in the laboratory, using the equivalent circuit shown in Fig. 4-8. The capacitors C, representing the total capacitance of the system to ground, were varied in steps from 0.005 μF. The resistor, representing a human body, was varied in steps from zero to 100,000 ohms for each of the capacitance steps. The ammeter reading was recorded in each step.

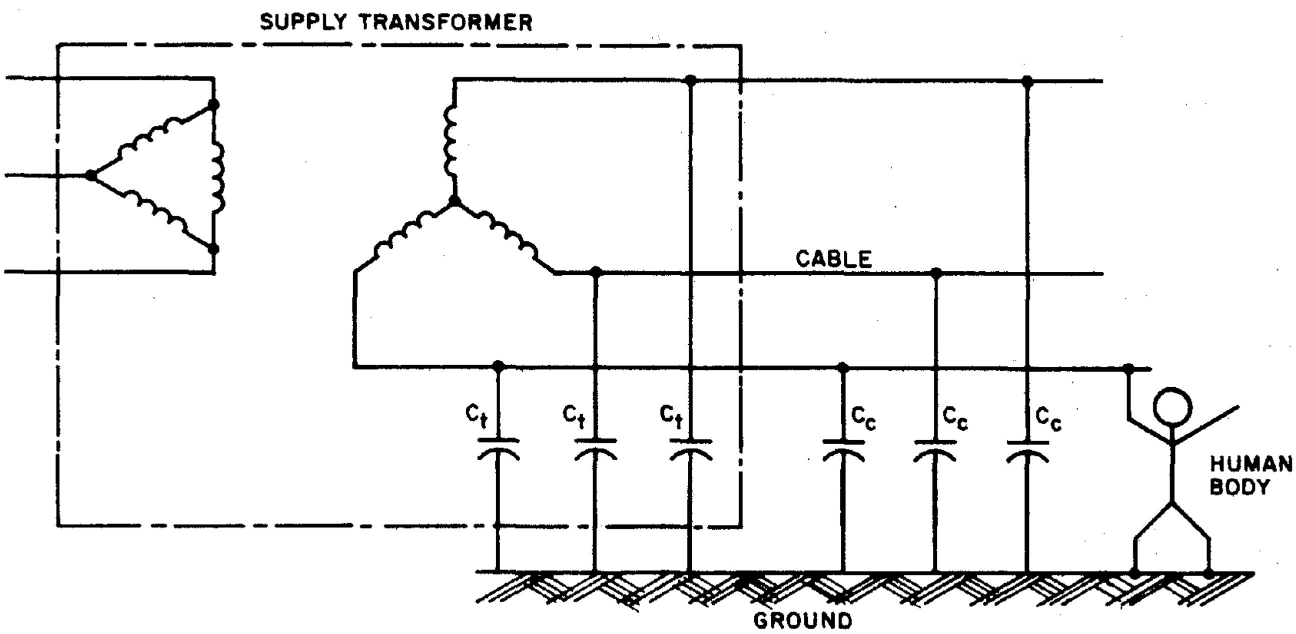



Figure 4-7. Ungrounded system with human body between line and ground

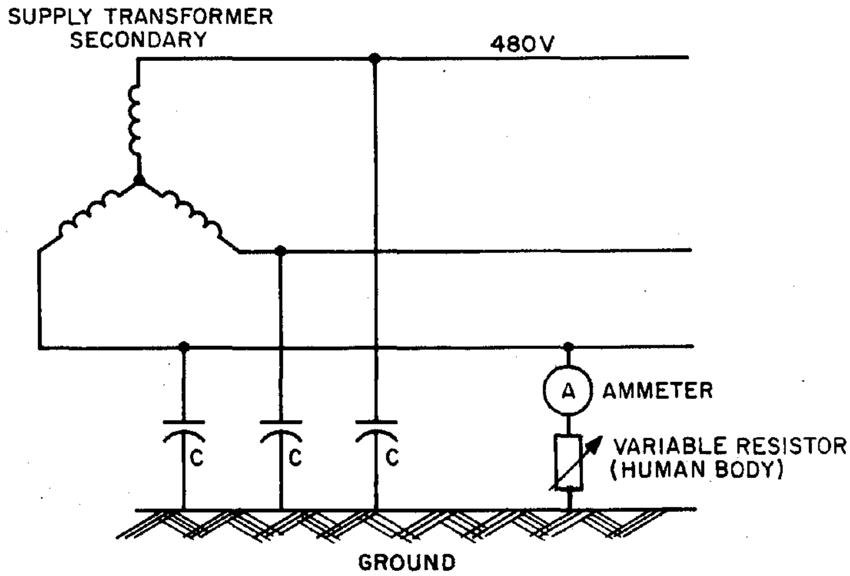



Figure 4-8. Test connections simulating person in contact with ungrounded system.

The data from the tests were plotted on log-log paper, Fig. 4-9, in which "ground path resistance" represents the resistance of the human body and "ground current" represents the current thru the body. Instead of using the curves of Fig. 4-9, the following equation may be used to calculate the current that would flow thru the body for any values of system capacitance, body resistance, and system voltage:

$$I = \frac{E \sqrt{3} \times 10^3}{\sqrt{9R^2 + \left(\frac{10^6}{WC}\right)^2}}$$

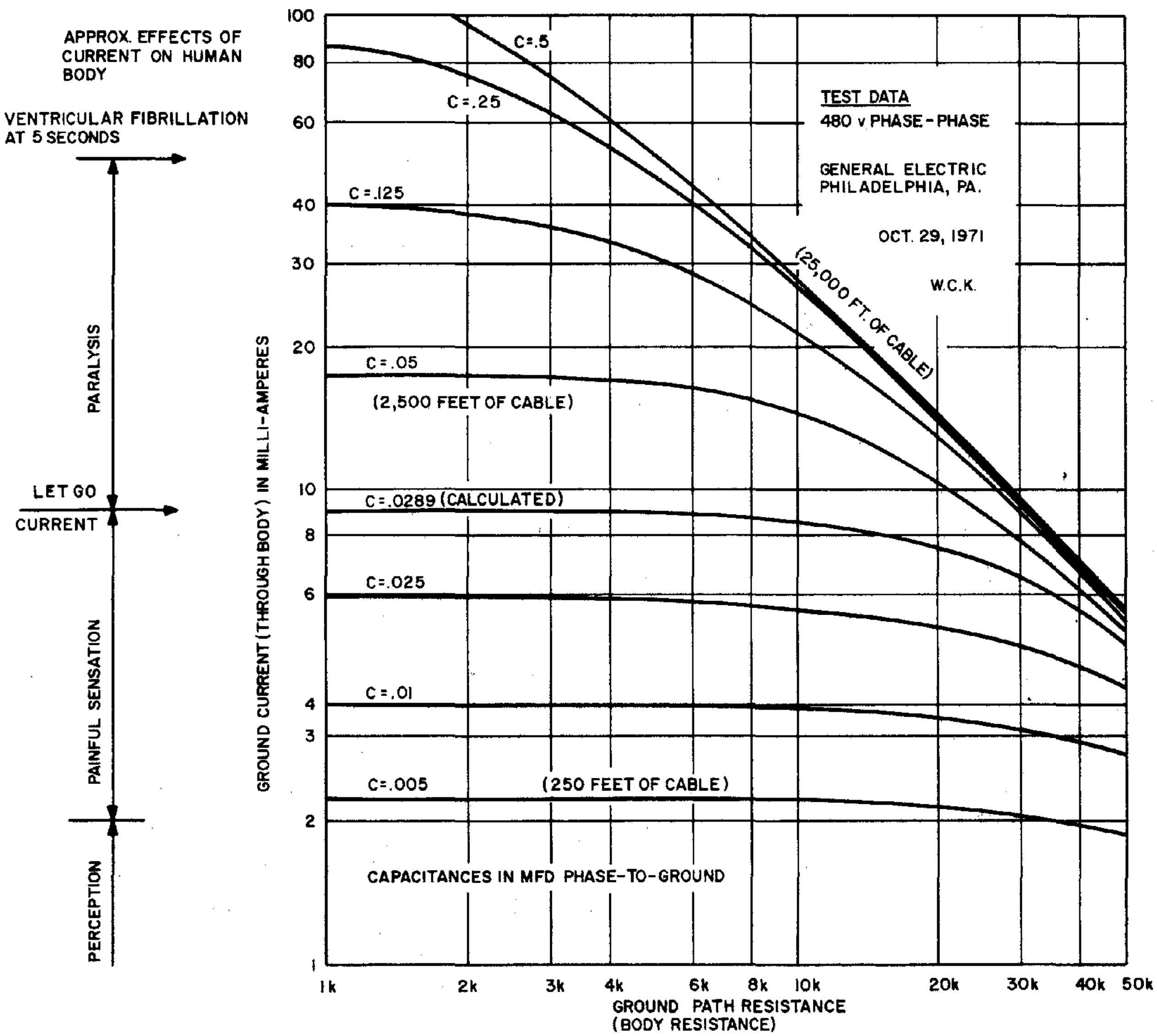



Figure 4-9. Relationship between ungrounded system capacitance, body current and body resistance

in which $I$ = current thru body in milliamperes

$E$ = system voltage (line-to-line)

$R$ = resistance of body in ohms

$W$ = 377 for a 60 Hz system

$C$ = total system capacitance, one phase to ground, in microfarads

It is interesting to note that for a 480 volt system, and a body resistance of 1000 ohms (which is the value usually assumed), the maximum current obtainable thru the body is 277 mA, regardless of the magnitude of total system capacitance. This is the current due only to the capacitance to ground and not some other condition such as insulation leakage or a fault on the system.

The resistance of the human body referred to in the foregoing actually consists of the body and whatever clothing the victim may be wearing, especially shoes and gloves. The body resistance itself varies with the path of the current thru the body, the parts of the body in contact, and the condition of the skin -- wet, dry, tender, injured, or calloused. In addition, there is considerable variation due to the condition of the clothing, especially shoes and gloves -- wet, dry, new, old, worn, or damaged. The total resistance can vary from a very low value to an extremely high value. Some investigators use a minimum of 500 ohms while others use 1000 ohms. The 500 ohm value represents a man standing on wet ground with worn-out shoes, firmly grasping a relatively large conductor with a sweaty hand. The 1000 ohm value seems more realistic.

Referring to the "Report on the Study of Human Threshold Limits of Electric Shock," included under Section 3, the threshold of perception of an electric current by man is about one milliampere, the maximum safe value of let-go current is 9.0 mA, and the minimum current that can cause heart fibrillation is about 50 mA (for 5.0 seconds of current flow duration).

From Fig. 4-9, it is evident that a system having a total capacitance to ground of about 0.004 μF, if touched by a man standing on the ground, would produce an unpleasant and probably painful shock sensation, as the current thru his body would be between 1.0 mA and 2.0 mA for all values of body resistance. Since the capacitance of a typical mine cable is 0.02 μF per 1000 feet, a value obtained from cable manufacturers and substantiated by Mr. Litchfield (Bureau of Mines), a cable as short as 200 feet has sufficient capacitance to produce this shock sensation even on an ungrounded 480 volt system alone.

From Fig. 4-9, it is also evident that a system having a total capacitance to ground of 0.05 μF may "freeze" a man at 9.0 mA if his body resistance is 25,000 ohms or less. This means that a current of 9.0 mA can make it impossible for a man to free himself from contact with the electrical circuit, and, if this paralysis of the muscles extends to the breathing muscles, the man will be unable to breathe. If the current is not cut off, or the victim not otherwise rescued, he is quite likely to die of asphyxia (suffocation). Thus the 9.0 mA value is an important one to consider from the standpoint of personnel safety. Assuming a body resistance of 1000 ohms, a system capacitance of only 0.035 uF would result in 9.0 mA thru the body. At 0.02 μF per 1000 feet, this represents a maximum cable length of 1750 feet.

Also it is evident from Fig. 4-9 that a system capacitance of 0.25 uF may cause ventricular fibrillation at 50 mA if the body resistance is 4500 ohms or less. Fibrillation is the condition in which the heart beats wildly out of control, resulting in death in a matter of seconds. This condition usually will continue even after the current flow is stopped, as it is not self-correcting. Special equipment and medical skill are required to save the victim, neither of which is usually available at the scene of an accident. Assuming a body resistance of 1000 ohms, a system capacitance of only 0.15 μF would result in fibrillation. At 0.02 μF per 1000 feet, this represents a maximum cable length of 7500 feet.

The results of the tests shown in Fig. 4-9 agree very well with similar data published in Germany by Streich[19], taking into account the differences in system voltage (500 volts in Fig. 8a and 1000 volts in Fig. 8b of Streich's paper). Streich also discusses relations between the current thru the body of a person in contact with an ungrounded system and the speed of the circuit interrupter required to protect the person against death due to fibrillation. Although Streich states that values of current between 8.0 and 10.0 mA are dangerous, he evidently uses the current and time duration values required to produce fibrillation as the criteria for determining the characteristics of switching and protective devices. He does not explain how the person is protected from death by asphyxia due to prolonged currents between let-go and fibrillation values.

Writing about coal mine power systems in Czechslovakia, Hudecek[34] shows the effect of distributed system capacitance and leakage resistance of ungrounded systems on the current thru the body of a person in contact with a line conductor and ground. The effects are shown by rather complex calculations and diagrams. The overall objective seems to be to determine the characteristics of the switching and protective devices to prevent fibrillation. Hudecek does not explain how the person is protected from death by asphyxia due to currents between the let-go and fibrillation values.

As to the gas ignition hazard, it is understood from Mr. Litchfield (Bureau of Mines) that the minimum amount of energy that may be dissipated in an electric arc without danger of gas ignition is considered to be 0.25 millijoules. Magison[25] shows test results indicating that the amount of energy required to ignite various gases can be roughly 15 times as high, at voltages in the 100-1000 volt range; hence the 0.25 millijoules includes a margin of safety when the supply is not more than 480 volts.

The amount of capacitance in a 480 volt system required to store 0.25 millijoules may be calculated from the equation: energy in watt-seconds (joules) = $1/2\ CE^2$. Although the capacitance may be charged at the peak voltage at the moment the arc occurs, the line-to-neutral voltage, 277 volts, will be used as the value for E in the equation. Hence

$$C = \frac{2 \times 0.25 \times 1000}{277 \times 277}$$

$$= 0.0065\ \mu F$$

Since typical mine cable may have a capacitance of 0.02 μF per 1000 ft., it is seen that only 325 feet of cable will store 0.25 millijoules at the assumed value of 277 volts.

In discussing limits for electric ignition of explodable gas, Streich[19] says that the system capacitance (of an ungrounded system) must not exceed approximately 0.02 μF if a line-to-ground fault is not to cause gas ignition.

The Contractor is fully aware of the fact that gas ignition by capacitor discharge is not nearly as simple a matter as indicated in the foregoing, depending as it does upon many other factors. However, the calculations do show that the gas ignition hazard is a characteristic of the ungrounded system that should be considered.

In the foregoing discussion of system capacitance to ground, it has been assumed that there are no purposely-added capacitors on the system -- only the natural intrinsic line-to-ground capacitance of the system components. In some systems, power factor correction capacitors, radio interference filters, or surge capacitors may be in use. Surge capacitors are not recommended for use on ungrounded systems, but occasionally are so applied. All these devices increase the system capacitance to ground.

Note that the data in Figure 4-9 applies to a 480 volt system. If the system voltage is higher, all current values in Figure 4-9 will be higher in direct proportion to the voltage for the same values of capacitance. The energy stored in the capacitance of the system would be higher in proportion to the square of the voltage. For example, on a 4160 volt system the currents in Figure 9 would be roughly 8.6 times the values shown. The stored energy in the capacitance of a 4160 volt system would be roughly 75 times the energy calculated above for a 480 volt system, for the same value of capacitance.

Several important conclusions may be drawn from the tests, calculations, and literature. One conclusion is that a completely ungrounded system is no safer than any other system from a personnel shock hazard. In fact, it may even be less safe, because some personnel, not fully understanding the system, simply assume it is safer since it is not intentionally connected to ground. This is also the conclusion of Kline and Friauf[24], Sutton[14], Thacker[5, 6], and others.

Another conclusion is that a completely ungrounded system is no safer than any other system from a gas explosion hazard. This is also the conclusion of Streich.[19]

## Characteristic 2 - Subject to Excessive Overvoltage

The voltage between line and ground (the earth) of an ungrounded system may rise to values several times the voltage rating of the system under certain abnormal but not necessarily unusual conditions, and in some cases, remain high for indefinite lengths of time. Perhaps it would help to visualize this phenomenon by thinking of the ungrounded system as "free-floating" with respect to ground, since no point on the system is connected to ground. If the system distributed capacitance is taken into account, then the system may still be thought of as floating, but very loosely tied to ground by a very stretchable rubber band.

There are eight abnormal conditions mentioned in the literature[26, 27] that can cause overvoltages in power distribution systems, but for ungrounded systems in coal mines, perhaps only these need be considered:

1. Physical contact with a higher voltage system.
2. Resonance effects in series inductive-capacitive circuits.

3. Intermittent ground faults.

4. Autotransformer connections.

5. Switching surges.

These and the other phenomena have been well documented in the literature. Perhaps the most thorough coverage is in the Industrial Power Systems Handbook[26] and in the General Electric Company's Industrial Power Systems Data Book.[27] Simpler but less thorough explanations can be found in references 7, 28, 29 and 30. Belyakov,[31] writing about arcing ground faults in 6 to 10 kV ungrounded systems, for example, indicates overvoltages can reach from four to five times rated voltage and perhaps more.

Since this characteristic of the ungrounded system is so thoroughly covered in the literature, there is no point in attempting to offer any further explanation here. Accordingly, the pertinent portions are reproduced herewith directly from the literature.[27] Note that the Bibliography references on pages 4-41 and 4-42 concern material in pages 4-23 to 4-41.

1. Physical Contact with a Higher Voltage System

If the conductors of a high-voltage electrical circuit come in contact with those of a lower voltage circuit, then the same potential will exist on both circuits at the point of contact. If the low-voltage circuit does not have its neutral grounded its potential will be increased to that of the high-voltage system or flashover will occur. If the low-voltage system is anchored close to ground potential as by the use of a solidly grounded neutral, high values of current may flow from the high-voltage system but at the same time much lower voltages will appear than with an isolated neutral system.

Accidental contacts between primary and secondary voltages on industrial systems are guarded against by the use of metal enclosures and metal barriers which separate conductor systems of difficult operating potentials. In some cases overhead circuits have both primary and secondary on the same pole, but substantial clearances reduce the danger of accidental contact to a minimum. Occasional crossups have occurred between primary and secondary on overhead circuits, and a few cases are known where failure has occurred between primary and secondary inside a transformer.

Fig. 4-10 illustrates this type of fault connection. It can be responsible for dangerous overvoltages on ungrounded low voltage systems. The most effective protection against that type of overvoltage is grounding of the low voltage system with the grounding impedance

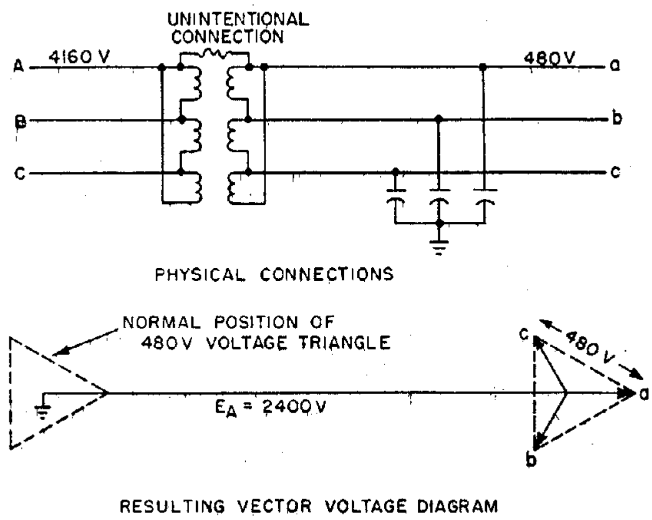


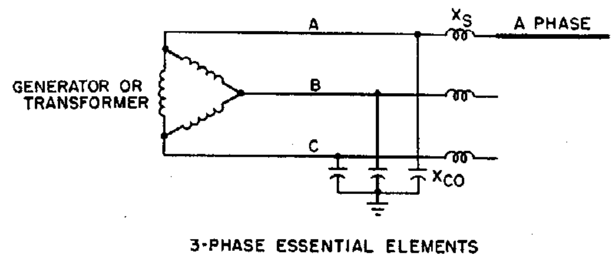

Figure 4-10. Ungrounded systems--overvoltages resulting from contact with higher voltage system

made low enough to accept the maximum line-to-ground fault current of the high voltage system without biasing the neutral of the low voltage system by a dangerous amount.

2. Resonant Effects in Series Inductive-capacitive Circuits (Limited to a-c Systems)

Ungrounded neutral a-c systems are most commonly subject to overvoltages originating from this cause. It is important to recognize that ungrounded neutral systems are actually capacitively coupled to ground rather than truly divorced from ground. It is ungrounded in the sense that no interconnection with ground has purposely been made, but every element of the electric system incorporates some capacitance to ground which constitutes an inherent capacitive impedance interconnection between the electric system conductors and ground.

Every ungrounded electric system contains the essential elements presented in the upper diagram of Fig. 4-11. The electric behavior of any one phase conductor relative to ground can be determined by a much simpler equivalent circuit as indicated in the lower sketch of Fig. 4-11. In terms of this simpler equivalent circuit it will be



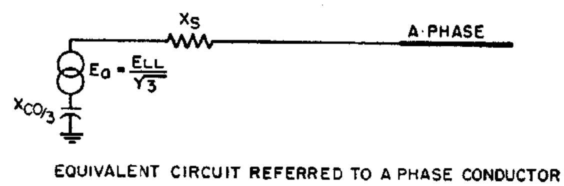




Figure 4-11. Ungrounded three-phase system

possible to understand readily the effect of connecting different types of impedance between line and ground as portrayed in Fig. 4-12. It becomes evident that the connection of any value of either resistance or capacitance between one line and ground produces no dangerous overvoltages. The potential on the phase to which the impedance is connected progressively diminishes from normal value to zero. The potential to ground on the remaining two phase conductors will be increased to full line-to-line value at the time the first phase conductor has been reduced to zero potential. This represents an overvoltage of only

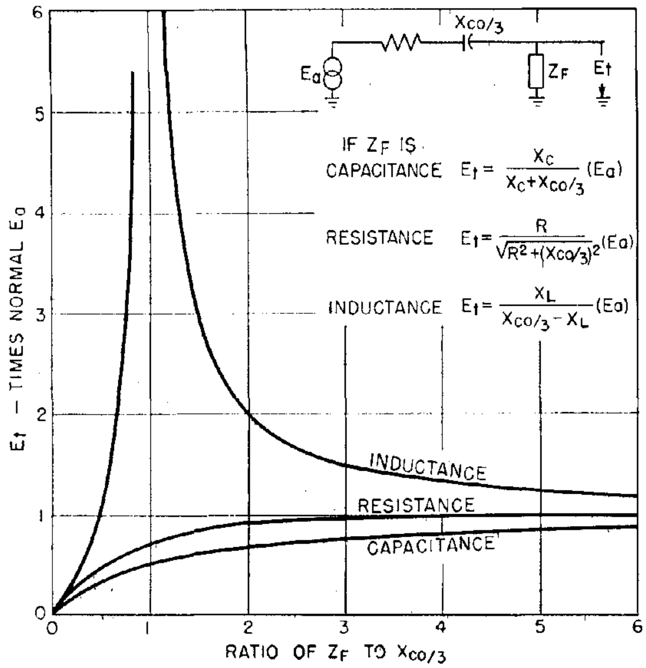



Figure 4-12. Ungrounded systems--overvoltages due to ground fault through inductance

73 per cent which is not dangerously high and will normally produce no ill effect unless continued for a long time.

The connection of an inductive reactance between line and ground, on the other hand, can be responsible for the production of serious overvoltages to ground. It is the ratio of the inductive reactance of the line-to-ground circuit to the total capacitive reactance of the system to ground which controls the degree of overvoltage. The highest overvoltage will occur when these two reactances are equal and at this point may be as much as 10 to 20 times normal. It is significant to note however that over a two to one range of reactance, overvoltages of three times normal or more would be produced.

The unintentional connection of an inductive reactance between a phase conductor and ground can occur in a number of ways, some of which are illustrated in Fig. 4-13. The operating magentic coil of a motor-starter contactor may be inadvertently connected between phase and ground by a ground fault in the control wire to the push-button station or the slip of a maintenance man's screw driver. Any time that the inductive reactance value, which becomes connected from phase to ground, falls in the danger region indicated on Fig. 4-12 dangerous overvoltages to ground will be produced which are communicated over the entire metallic conductor system of that operating voltage.

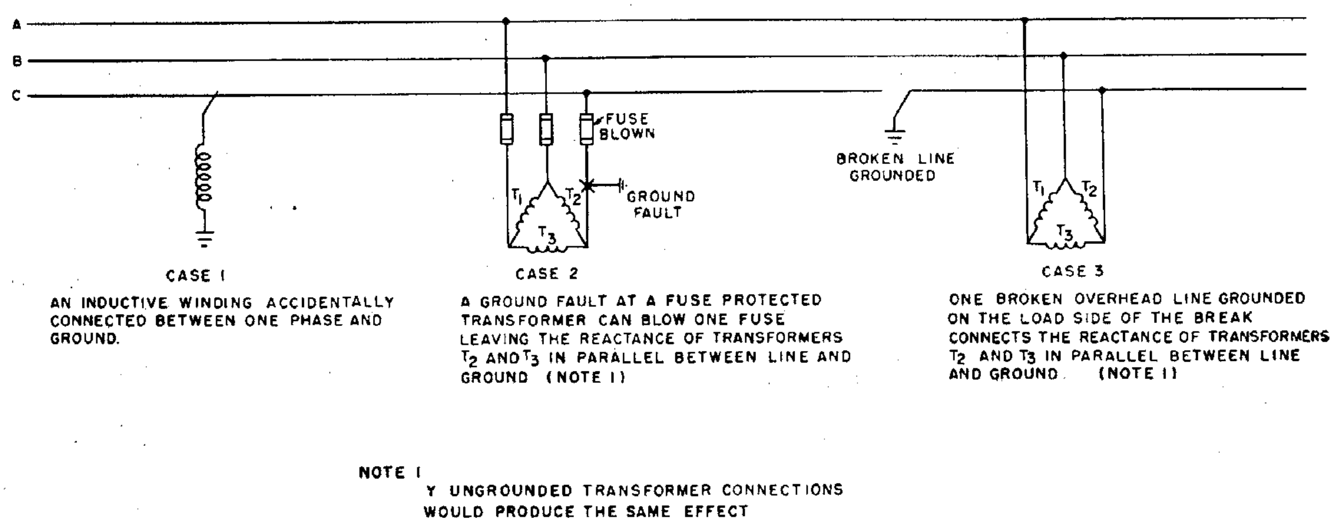



Figure 4-13. Examples of unintentional high reactance connections between line and ground

Overvoltages originating from this cause can be completely suppressed by a relatively light resistance ground on the electric system neutral. A grounding resistor of about the same ohmic value as the total charging capacitive reactance to ground is sufficient to almost completely eliminate overvoltages. It will be evident that there is good reason to adopt electric system neutral grounding with a much lower value of grounding resistance for other considerations.

Fig. 4-12 has been computed on the basis that the inductive reactance is linear. If this reactance incorporates an iron core which during the mode of operation being considered should encounter saturation of the iron core, the performance will be somewhat different. Under such conditions the effective reactance of the inductive circuit can become much lower than the unsaturated reactance and the voltage will tend to automatically oscillate between voltage limits which cause the effective inductive reactance to match the capacitive reactance value. This character of operation has been named ferro-resonance.

The maximum voltage so developed may not be as high as would be produced by a linear reactor but may still be in excess of two or three times normal. Substantial overvoltages may result by ferro-resonance when the unsaturated reactance is many times the capacitive reactance to ground.

The application of grounded wye potential transformers on ungrounded systems with a wye or broken delta secondary connection can be responsible for damaging overvoltages as a result of resonant or ferro-resonant action since the magnetizing reactance of the potential transformers becomes connected from phase conductors to ground.

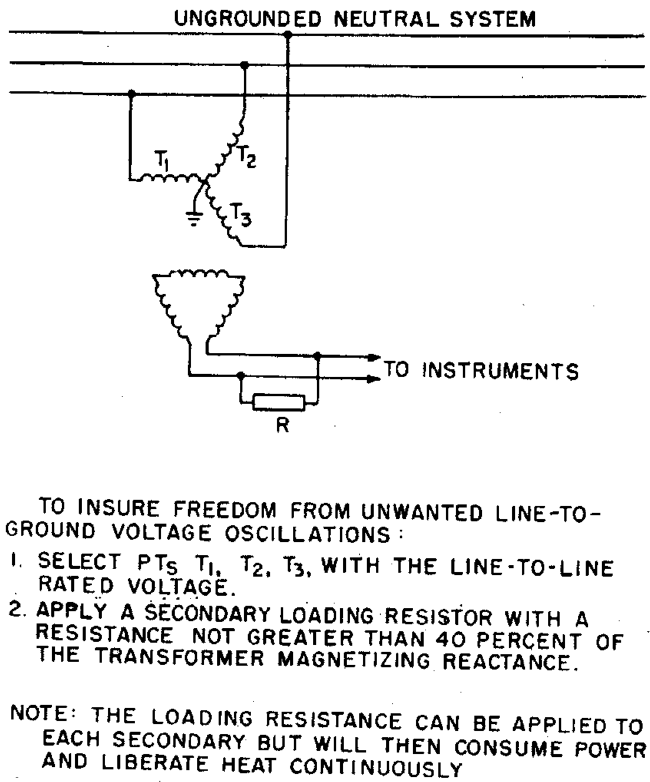



Figure 4-14. Grounded wye-broken delta potential transformers for ground indicator or zero sequence voltage

A complete description of this phenomena need not be taken up here as it has been adequately treated in an AIEE technical paper[3]. These system voltage oscillations will not occur if the electric system neutral is grounded. Freedom from this particular type of voltage oscillation can be obtained even with ungrounded neutral operation by using potential transformers with a line-to-line voltage rating and the application of shunting resistors on the secondary windings as is outlined in Fig. 4-14.

Series capacitor welders are occasionally applied, particularly in the case of large size machines because of their ability to reduce the kva demand and improve the operating power factor to substantially unity.

However, the series capacitor welder presents a definite voltage hazard to an ungrounded neutral a-c supply system. During welder operation the voltage across both the series capacitor and the welding transformer primary will be several times the rated line-to-line voltage. The physical electric connections and the associated vector voltage relationships are indicated in Fig. 4-15.

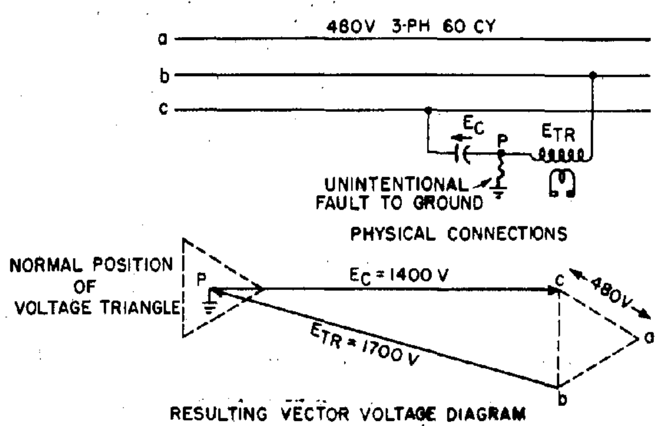



Figure 4-15. Ungrounded systems--overvoltages resulting from ground fault on series capacitor welder circuit

Should a fault to ground occur at the junction between the series capacitor and the welding transformer (Point P), the location of ground potential will tend to become that of this junction point instead of the center of the a-c system voltage triangle. The total system capacitive impedance to ground would generally be expected to be high, relative to that of the welder series capacitor, and thus offers practically no opposition to this shift in the location of ground potential. In the case illustrated in Fig. 4-15, it will be evident that the potential of the "A" phase conductor may be elevated to about 2000 volts to ground which is about seven times normal. As in the other cases, this overvoltage is communicated to all equipment metallically interconnected at this common operating voltage.

All of the these resonant inductive-capacitive overvoltage hazards can be eliminated by electric system neutral grounding.

3. Intermittent Ground Faults

Substantial overvoltages can be developed in ungrounded a-c industrial systems by sputtering or intermittent ground faulting connections. The intermittent character of the fault path may be the result of vibration which causes an electrical conductor to make contact intermittently with ground; the result of scattering particles of molten conductor metal which intermittently establishes a conducting path to ground; or as a result of successive breakdown and seal-off of the separating space between conductor and ground. In the last case involving a fixed separation between conductor and ground, a progressively increasing breakdown voltage across this gap is an essential element in the build-up of severe overvoltages.

Intermittent ground fault conditions on low voltage ungrounded neutral systems have been observed to create overvoltages of five or six times normal quite commonly. An unusual case involved a 480 volt ungrounded system. Line-to-ground potentials in excess of 1200 volts were measured on a test voltmeter. The source of trouble was finally traced to an intermittent ground fault in a motor starting auto-transformer. About two hours elapsed while the source was being located during which time between 40 and 50 motors broke down.

Electric systems which are grounded through reactance of too high an ohmic value ($X_0$ more than 10 times $X_1$) are also subject to overvoltage by this same mechanism acting in a little different form.

An understanding of the manner in which a discontinuous electric connection can be responsible for the generation of overvoltages can be most easily acquired by examining the case of a sputtering or intermittent line-to-ground fault on an ungrounded neutral system.

In Fig. 4-16 at "A" is shown the vector voltage pattern of a three-phase a-c system as it would normally operate under balanced unfaulted conditions. The voltage vectors $E_a$, $E_b$ and $E_c$ rotate about the neutral at synchronous speed. The electric neutral is a point of central symmetry and remains constant at ground potential if the individual phase voltages are pure fundamental frequency sine waves.

Should the "A" phase conductor become grounded, the system voltage triangle would become displaced as illustrated in "B". At the phase position illustrated in "B", the "A" phase voltage is at its maximum

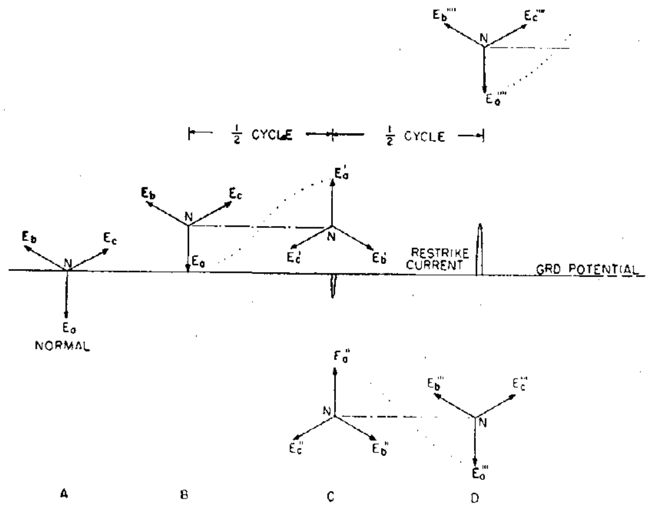



Figure 4-16. Overvoltages developed by repetitive restrike on ungrounded systems

value at which instant the charging current to ground is passing through zero. In case the fault circuit contains a small gap or an arc, the arc current would become extinguished at this point. Note that the trapped charge on the line-to-ground capacitance will tend to maintain the voltage triangle in the same displaced position. In other words, the potential of the neutral would tend to remain at d-c potential equal to the crest value of the a-c voltage wave relative to ground. All of this merely says that there will be little tendency for any voltage to reappear across the gap in the ground fault circuit immediately following the current zero which occurs at "B."

During the next half cycle, however, the a-c generated voltages will reverse their polarities (vectors rotate 180 degrees) which would cause the three-phase voltage vector pattern to assume the position shown in the upper part of "C." Note that during this one-half cycle time interval, the potential of the "A" phase has progressively increased from zero value to about twice the normal line-to-neutral crest voltage relative to ground potential. This value of line-to-ground potential of the "A" phase may be sufficient to break down the gap in the ground fault circuit and re-establish the connection between the "A" phase and ground. If so, the "A" phase potential will tend to be suddenly yanked to ground potential. There will inevitably be some system reactance in the "A" phase conductor to the ground fault point which would result in an oscillation of the "A" phase conductor potential between plus and minus two at a frequency probably 20 to 100 times normal. If the fault circuit consisted of a solid metallic connection, this oscillation would decay to zero leaving the "A" phase conductor at ground potential. Note that associated with this high frequency transitory oscillation there will be associated a corresponding transitory charging current to ground. This transitory charging current to ground, or restrike current, will again reach zero value when the system voltage triangle is at the maximum excursion in the negative direction as shown in the lower part of "C." Thus, an opportunity is afforded for the gap in the ground fault circuit to reclear. If reclearing does occur, a charge is again trapped on the system capacitance to ground which would tend to maintain a constant d-c potential to ground on the system neutral.

In the course of the next following half cycle, the voltage vector system will again rotate 180 degrees causing the potential of the "A" phase conductor to ground to be elevated from minus two to minus four as indicated by the transition from the lower part of "C" to the lower part of "D." This increased voltage across the fault gap may again result in restrike by the same mechanism as before in which case the voltage triangle would tend to be thrown in the positive direction in the form of a high frequency oscillation between potential limits of minus and plus four, which in the presence of a solid metallic connection would gradually decay to zero.

In this explanation of the mechanism, it will be noted that all conditions have been most favorable to the creation of the highest possible restrike voltages in the shortest possible time. The restrike has been assumed to occur at the time the maximum recovery voltage was reached but not before. Likewise it has been assumed that a reclear occurs at the first current zero after restrike. Under these conditions a line-to-ground potential of five times normal has been developed in less than two cycles. In practical cases, the restrike may occur before the maximum recovery voltage has been reached and several cycles of the transitory oscillation may take place before the fault circuit reclears. While in theory it might be possible to progressively increase the line-to-ground voltage by successive restrike without limit if the dielectric strength progressively increases, voltage measurements on actual systems indicate that voltage levels of five to six times normal are rarely exceeded.

There is reason to believe that damaging overvoltages of repetitive restrike origin are far more common on ungrounded neutral systems than would at first be suspected. The case which was mentioned in an earlier paragraph is very unusual in that the obnoxious restriking conditions persisted for a long interval of time while the source was being located. A far more common occurrence is one in which several pieces of electric equipment on the system suffer electrical breakdown apparently simultaneously and one or more of the fault conditions was known or believed to involve ground. These multiple failures are commonly associated with ungrounded neutral system operation. It is also known that a solid metallic ground connection on one phase may exist for substantial intervals of time without producing multiple breakdowns in equipment although it does produce 73 per cent overvoltage on two of the phase conductors. It therefore seems reasonable to assume that the multiple failures result from the appearance of overvoltages considerably in excess of 173 per cent normal.

Distribution system overvoltages of repetitive restrike or intermittent ground origin can be entirely eliminated by effective system neutral grounding. Resistance grounding with a resistance ground fault of any value upwards of the line-to-ground charging current will be effective. For various other reasons it will be evident that higher values of available ground fault current will be desirable.

If reactance grounding is contemplated (it rarely finds application in industrial systems) it is important to keep the reactance of the grounding circuit sufficiently low so that the ratio of $X_0$ is no more than 10 times $X_1$. If this grounding reactance value is exceeded, opportunity is given for another type of repetitive restrike action which again can result in system overvoltages to ground.

4. Autotransformer Connections

Autotransformers for interconnecting two electric systems of different insulation level should be avoided in industrial systems which are not solidly neutral grounded. The common metallic interconnection between the two systems which is formed by the autotransformer windings tends to subject the lower voltage system to nearly the same transitory voltages as would be expected on the higher system voltage level. There are some exceptions, and a specific example will serve to illustrate the nature. Should a system be planned which is to initially operate at 2400 volts and later be converted to 4160 volts with all equipment therein containing insulation levels commensurate with 4160 volt operating potential it would be satisfactory to employ a suitable autotransformer for interconnecting this 2400 volt system with another 4160 volt system.

An unusual variation of autotransformer action which has been responsible for system overvoltages in a number of instances is represented by a transformer with extended windings operating on an ungrounded neutral system such as illustrated in Fig. 4-17. Applications of this sort are most often found in test areas or developmental areas which contain multi-purpose transformers with a multiplicity of taps to permit a wide variety of output voltages to be obtained. If operated with system line voltage impressed across a fraction of the total winding, the vector voltage at the end of the winding extension will be as illustrated in Fig. 4-17 because the volts per turn developed in the winding extension will be exactly the same as the volts per turn in the excited winding. Should the end of the winding extension be inadvertently connected to ground or develop a fault to ground, the point of ground potential would tend to move away from the center of the voltage triangle to the potential of the extreme end of the winding extension resisted only by the high system to ground capacitance coupling. It will be evident that as a result of this action, the presence of any extended winding would cause the potential of one phase conductor to be elevated to more than 173 per cent of normal operating potential. The degree of overvoltage may be much more severe if greater amounts of winding extension are present. It is again important to realize that these overvoltages on phase conductors would be conveyed to all apparatus connected to the same metallic system. Thus, a ground fault on a winding extension of a transformer in a small test area at one corner of a building might impose overvoltages on all equipment fed from the same load center substation which might encompass half of the productive machinery in that building.

As has been true so many times before, grounding of the electric supply system neutral will cure this type of potential overvoltage also. A system grounding equipment which makes available a ground fault current which is equal to or greater than the short circuit current resulting from short circuit of the extended winding portion of the offending transformer will keep the system line-to-ground potentials well within safe bounds. It is quite generally true that transformers of this character to be found in test areas are of relatively small physical size and do not impose restrictive requirements on the necessary system grounding equipment. As a matter of fact, on all low voltage system equipment (600 volts and less) it is the standard practice to ground the neutral solidly.

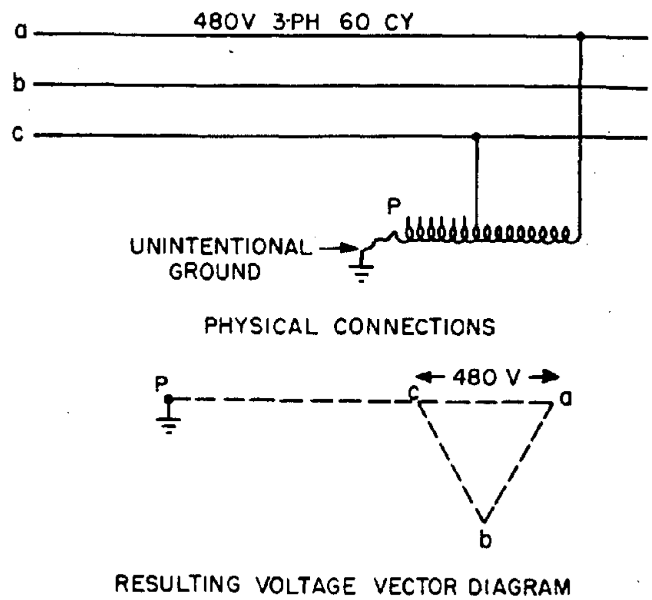



Figure 4-17. Ungrounded systems-overvoltages resulting from ground fault on transformer winding extensions

The application of three-phase transformers or three-phase banks of single-phase transformers, which do not incorporate a closed delta winding in their make-up, should in general be avoided or quite carefully examined to insure that the resulting operation will be free of damaging overvoltages. This would be equally true of wye connected autotransformers.[4] Because of the nonlinear shape of transformer magnetizing curves, the required transformer magnetizing current to produce a fundamental frequency sine wave of voltage will contain rather prominent amounts of harmonic currents. In a wye connected transformer system energized from a three-phase supply in the absence of a delta connected winding the transformers are unable to obtain a source of third harmonic current or multiples thereof because these are of zero sequence. As the result of the inability to obtain a third harmonic exciting current, there will appear a third harmonic voltage which may be as much as 50 per cent of the normal operating potential. Should the neutral of such a transformer system become grounded intentionally or accidentally and the supply system be ungrounded or high resistance grounded, this third harmonic voltage will be imparted to and appear on the system phase conductors and represent a sustained source of overvoltage. Even though the transformer system neutral be ungrounded, some fraction of the third harmonic voltage will appear on the phase conduction depending on the ratio of capacitance to ground within the transformer structure to the distributed capacity to ground of the rest of the system.

Core type three-phase transformers present a fairly low zero sequence magnetizing reactance which would hold the zero sequence voltage to much lower levels than shell type three-phase transformers or banks of three single-phase transformers and are thus much less susceptible to overvoltage difficulties. If operated with grounded neutral on an ungrounded neutral system, a careful check should be made to insure freedom from neutral instability as treated in reference.[3]

While grounding the electric system neutral may not solve all of the troubles of the wye-wye transformer connections, it will eliminate appearance of overvoltage on the phase conductors of a system to which such a bank of transformers might be connected.


1. Voltage Recovery Rates Associated with Transmission Line Faults; W. F. Skeats, C. H. Titus, W. R. Wilson; AIEE Trans. Power Apparatus and Systems; Feb. 1958, pp 1256-1266
2. Switching Surges Due to Deenergizing Capacitor Circuits; AIEE Committee Report, 57-171; AIEE Trans. Power Apparatus and Systems; Aug. 1957, pp 562-4
3. Some Fundamentals of Capacitor Switching; I. B. Johnson, A. J. Schultz, N. R. Schultz, R. B. Shores; AIEE Transactions, Vol. 74, Part III, 1955, pp 727-736
4. Abnormal Voltage Conditions by Open Conductors on Three-phase Circuits Using Shunt Capacitors, P. E. Hendrickson,

I. B. Johnson, N. R. Schultz; AIEE Trans. Power Apparatus and Systems; Dec. 1953, pp 1183-93

5. Overvoltages in Saturable Series Devices; A. Boyajian and G. Camilli, AIEE Trans. Vol. 70, Part II, 1951, pp 1845-51

6. Criteria for Neutral Stability of Y-grounded Primary Broken-delta Secondary Transformer Circuits; H. S. Shott, H. A. Peterson; AIEE Transactions Vol. 60; Nov. 1941, pp 997-1002

5. Switching Surges

There are several ways in which switching operations (the closing and opening of circuit breakers) can cause transient overvoltages in nearly all types of systems, but the ungrounded system is particularly vulnerable to transients due to unequal closing times of the poles of the breaker in the primary of the transformer supplying the ungrounded system.[32] The difference between the closing times of individual poles may be a matter of milliseconds.

Figure 4-18 shows a power transformer rated 7200 V primary supplying an ungrounded 480V system. Typical values of capacitances are shown between each primary winding and ground ($C_1 = 0.0009\ \mu F$), between each primary and secondary phase winding ($C_2 = 0.0026\ \mu F$), and between each secondary winding and ground ($C_3 = 0.0014\ \mu F$). In normal operation, the neutral of the primary system is near ground potential, either because the system neutral is grounded or because of the distributed capacitances to ground. The neutral of the 480V system is also near ground potential because of the distributed capacitances to ground. Hence there is no voltage difference between the two neutrals.

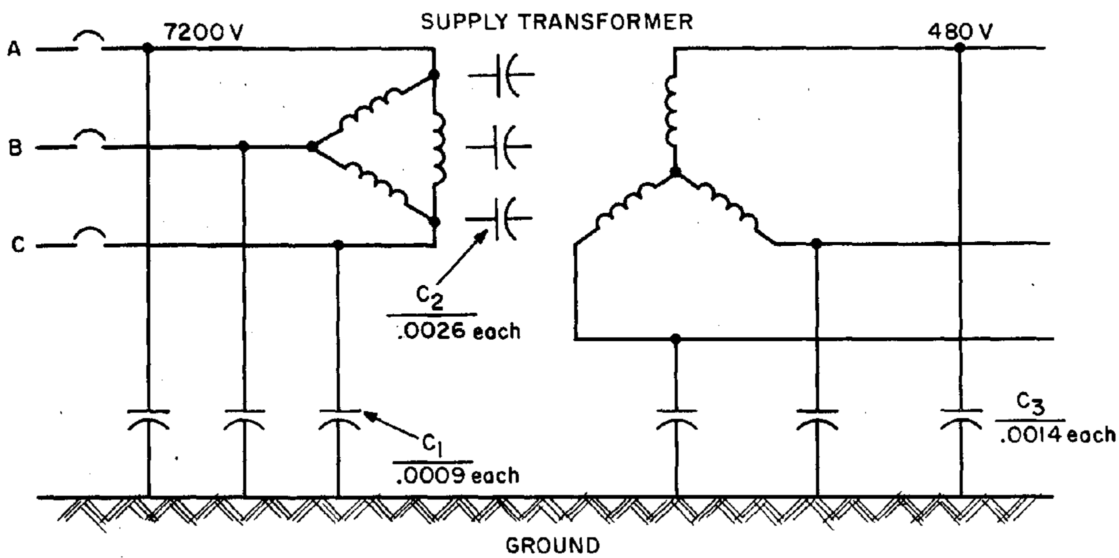



Figure 4-18. Illustration of conditions producing switching transients due to unequal pole closing of transformer primary breaker

Now consider what happens when the primary breaker is being closed and pole A, for example, closes first ahead of the other two. During the brief but finite length of time (milliseconds) that only pole A is closed, approximately 4160 V is applied to the entire primary winding relative to ground. Note that this voltage might instantaneously be almost any value between zero and 4160 $\sqrt{2}$ depending upon the moment in the cycle that pole A closes.

The equivalent circuit of the three capacitances under this condition is shown in Figure 4-19, in which it is seen that $C_2$ and $C_3$ are now in series across 4160V. Since the voltage across two capacitances in series divides inversely proportional to the capacitances, the voltage to ground on the 480 V secondary winding, and whatever might be connected to it, is 2700 V until poles B and C of the breaker close. While this voltage usually exists for only a very brief period of time (milliseconds), it can during that time stress insulation or cause a flashover. Such repeated overvoltage transients weaken insulation to cause premature breakdown.

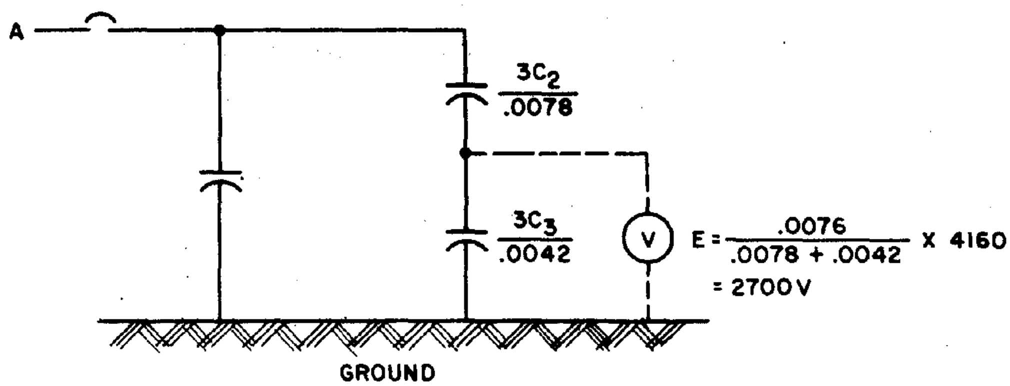



Figure 4-19. Equivalent circuit diagram of unequal pole closing of primary breaker

Another way in which the transient overvoltage may occur is by prestrike between contacts of one pole of the primary breaker during the closing operation. The effect is about the same as one pole closing before the others.

In order to minimize the transfer of transient overvoltages from the primary circuits to the secondary low voltage system, the transformer should be provided with a Faraday shield between the primary and secondary windings. The shield is a turn of metal sheet placed between windings, insulated from all windings, and connected solidly to ground. Such a shield not only minimizes the transfer of disturbances from the primary to secondary windings, but prevents a short circuit between the two sets of windings. In other words, it prevents the low voltage windings from coming into contact with the high voltage windings due to an internal fault in the transformer. The shield does not increase transformer cost significantly if specified before manufacture.

It can be concluded, from the foregoing analysis of each of the five abnormal conditions, that only the first-mentioned condition (physical contact with a higher voltage system) can occur on the solidly grounded and resistance grounded systems, whereas all five conditions can occur on the ungrounded system. It is very difficult to predict just what will happen when the high voltage and low voltage systems come in contact. If the low voltage system is ungrounded, or resistance grounded, all the insulation will be stressed until a breakdown occurs, causing a line-to-ground fault on the high voltage system, which should cause protective devices to operate. If the low voltage system is solidly grounded, it is quite likely that there will be sufficient fault current to cause immediate tripping of the protective devices on either or both systems.

As for the remaining four conditions named, they all depend upon the presence of distributed capacitance to ground of the ungrounded system. In the case of the resistance grounded and solidly grounded systems, the distributed capacitance is completely bypassed by the neutral-to-ground connection and therefore cannot cause the phenomena described.

## Characteristic 3 - First-ground Fault Current Magnitude

On an ungrounded system, the first solid connection, either intentional or accidental, between any one line conductor and ground (the earth), or any grounded metallic object such as frames, track rails, roof bolts, or grounded conductors, causes very little fault current to flow. From Fig. 4-20, it can be seen that a ground fault on phase 2, for example, provides no path for any current to flow except thru the distributed capacitances to ground of the other two phases. Hence, the only current thru the fault is the charging current of the system capacitance.

In the case of a high-resistance grounded system, Fig. 4-21, the ground fault current is purposely limited to the desired low value by the choice of a neutral resistor of proper ohmic value, taking into account also the charging current of the system capacitance.

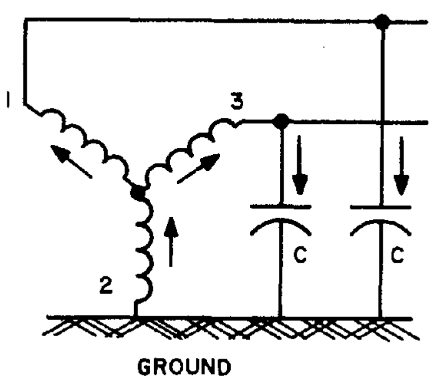



Figure 4-20. Ungrounded system with ground fault on one line.

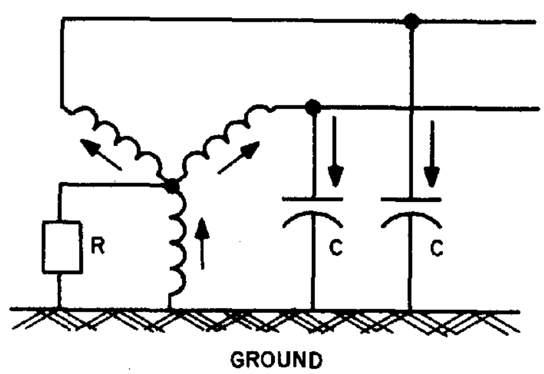



Figure 4-21. Resistance grounded system with ground fault on one line.

In the case of the solidly grounded system, the resistance in the neutral connection to ground is nearly zero, hence a very high fault current flows, approaching in magnitude that due to a three phase short circuit. The overcurrent protective devices operate to de-energize the circuit.

Characteristic 4 - Rise in Voltage on First Ground Fault

The first solid line-to-ground connection, described under Characteristic 3 above, will cause the voltage between the line conductor and ground at the point of fault to fall to zero. The voltage between each of the other two phases and ground will rise to full line-to-line voltage.

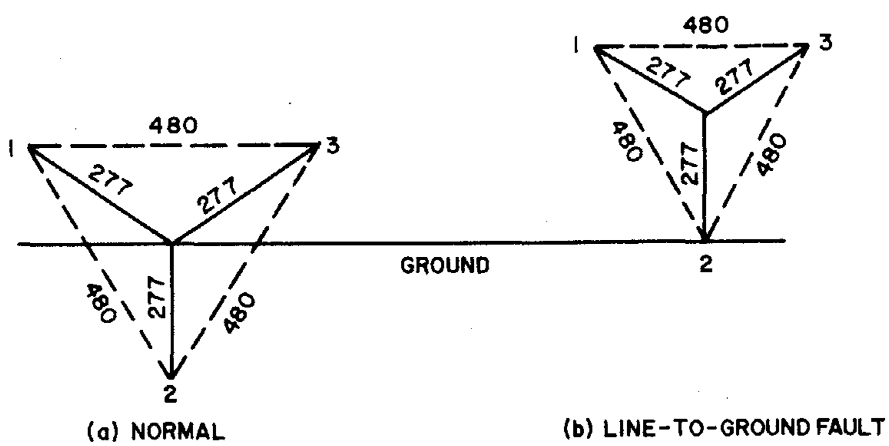



Figure 4-22. Ungrounded system voltage vectors under normal and line-to-ground fault conditions.

The vector diagram in Fig. 4-22 (a) shows the voltage between each phase conductor and ground, under normal conditions, to be the line-to-neutral voltage of the system, 277 V in this example. The ground fault on phase 2 connects phase 2 to ground, and, as shown in Fig. 4-22 (b), the voltage between phase 1 and ground, and between phase 3 and ground, each rise to 480 V. This means that all insulation on phases 1 and 3 of the system are stressed at $\sqrt{3}$ times the voltage stress under normal operating conditions. This must be taken into account in selecting the voltage rating of all system components; for example, the cable must have a voltage rating at least 1.75 times the line-to-neutral voltage at which it will normally be operated.

On the high-resistance grounded system, the first solid ground fault will have the same result; that is, the voltage between the other two phases and ground will rise to full line-to-line voltage, the only difference being that the fault current will be somewhat higher, the amount depending on the ohmic value of the neutral resistor. On the solidly grounded system, a very high fault current flows, approaching the three-phase short circuit capability of the system. The voltage of the other two phases will not rise above normal value; in fact, the voltage will drop due to the high current flowing thru the system impedance. Over-current trip devices should operate to de-energize the circuit.

## Characteristic 5 - First Ground Fault Does Not Affect System Operation

The first line-to-gound fault, described under Characteristic 3 above, will not affect the operation of the system as long as it is a solid connection to ground and no other phase of the system has a ground fault on it (it is assumed there are no low-level protective devices on the system that respond to ground fault conditions). The reason that system operation is not affected is that the fault current is not more than the charging current of the system capacitance, as described under Characteristic 3 above. The same is true of the high-resistance grounded system except that the ground fault current may be somewhat higher, being limited by the neutral grounding resistor.

In the case of the solidly grounded system, the fault current is so high that overcurrent protective devices operate to de-energize the circuit.

## Characteristic 6 - Second Ground Fault Causes System Short-Circuit

The second solid line-to-ground fault on the same system, occurring on one of the other two phases before the first line-to-ground fault is cleared, will cause a double line-to-ground fault (line-to-ground to-line). The amount of short-circuit current depends on the total impedance in the ground path between the two faults. Since this impedance generally is low, the fault current is usually very high, high enough to cause the overcurrent protective devices to shut down the affected portions of the system. If the protective devices are circuit breakers, one or more load circuits are de-energized. Fused type protective devices create additional problems, such as single-phasing, but these problems can usually be overcome by proper choice of equipment.

Figure 4-23 illustrates an ungrounded system with two line-to-ground faults and shows the path of the fault current thru the impedance Z of the ground circuit. It should be noted that due to the flow of current thru impedance Z, there is a difference in voltage between points A and B. This could be a shock hazard to personnel if it should so happen that points A and B are physically close enough together so that a person can make contact simultaneously with both points, or any metallic objects electrically in contact with these points, such as frames, track rails, equipment enclosures, ground conductors, or the earth itself.

In the case of the high-resistance grounded system, everything is the same as for the ungrounded system. As can be seen from Fig. 4-23, connecting a high resistance (not shown) between the neutral and ground will not affect the flow or path of the major portion of the fault current.

In the case of the solidly grounded system, two line-to-ground faults are possible, provided the second fault occurs almost immediately that is, before the first fault ground is cleared by the operation of protective devices. Fig. 4-24 shows the several paths the fault currents can take, depending on the path impedances $Z_1$, $Z_2$, and $Z_3$. Here again, there may be a voltage difference between points A and B.

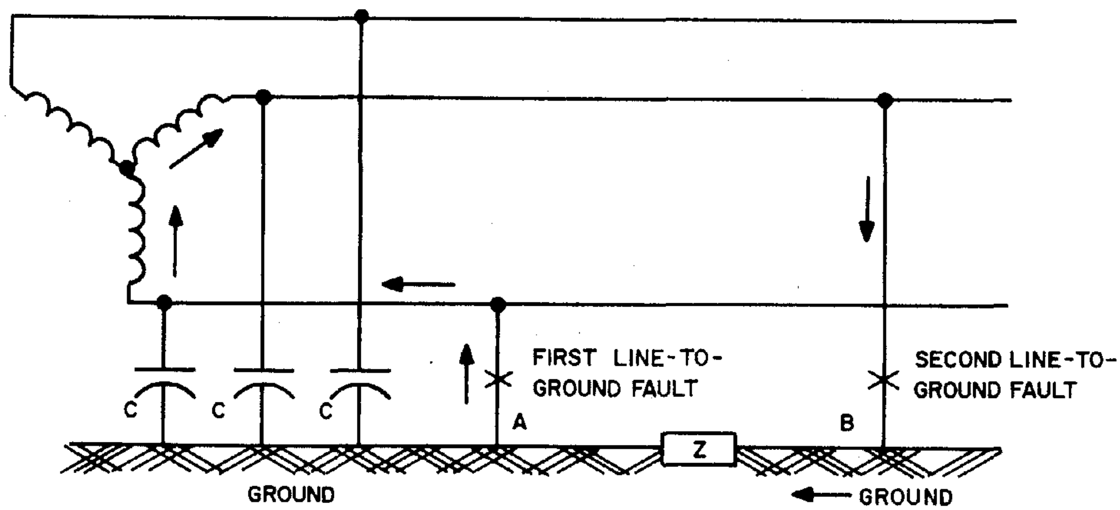



Figure 4-23. Double line-to-ground fault on ungrounded system

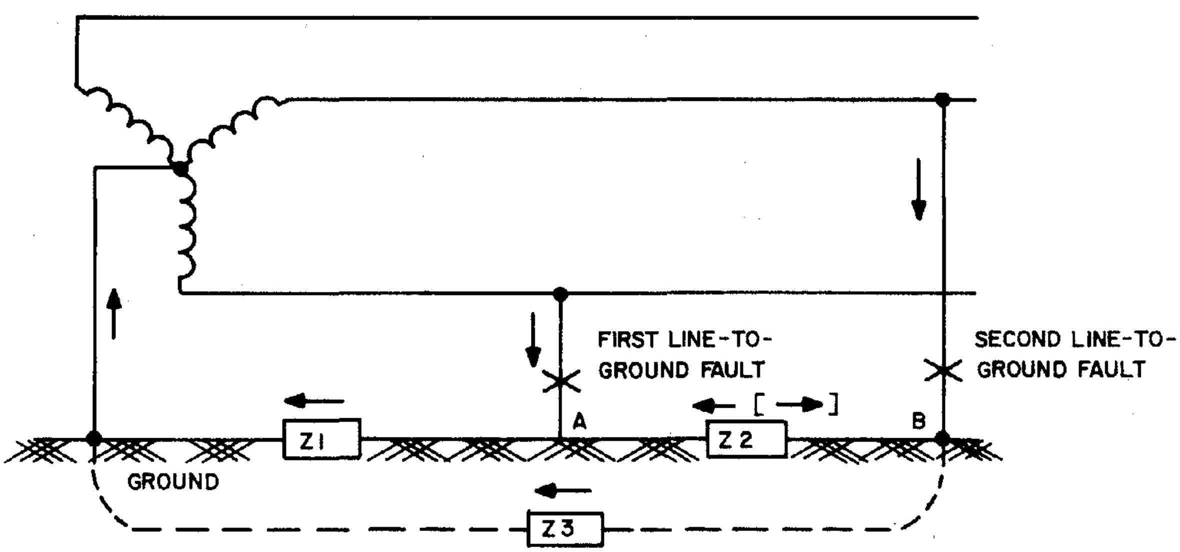



Figure 4-24. Double line-to-ground fault on solidly grounded system

Characteristic 7 - Second Ground Fault May Occur Immediately

One of the characteristics (5 above) of an ungrounded system is that the first line-to-ground fault does not affect operation of the system. Under certain circumstances, however, the first fault does set up the conditions for a second line-to-ground fault to occur almost immediately or very soon afterward. This is especially true if the first fault is a sputtering, intermittently arcing type fault. This phenomenon, which cannot occur on resistance grounded or solidly grounded systems, is fully explained above under Characteristic 2.

Even a solid line-to-ground fault can set up a condition for a second line-to-ground fault by raising the voltage on the two unfaulted phases to full line-to-line voltage as explained above under Characteristic 4. Any weakness in the system insulation at any point, due to age, abrasion, repeated overvoltage stresses, or accumulation of moisture or dirt, may show up under the stress of the higher than normal voltage and cause the second line-to-ground fault. This can happen also on the high-resistance grounded system, but not on the solidly grounded system because the first fault causes overcurrent protective device operation.

Characteristic 8 - Probability of Arc Escalation

The fact that the current due to a line-to-ground fault on an ungrounded system is very low (see Characteristic 3 above) means that the amount of arcing on an arcing type fault is also very low. Thus the amount of heat, flash, and damage is very small. The probability that such an arc will sustain itself very long, or escalate to involve the other two phases, is also very low.

Although the fault current in the case of the high-resistance grounded system is somewhat higher than in the ungrounded system, it is not enough higher to increase the probability of sustaining the arc, or escalating the arc, significantly.

In the case of the low-resistance and solidly grounded systems, the amount of arcing ground fault current may be so high that the probability that the arc will be sustained, or escalated to involve the other phases, is very high. Thus an arcing line-to-ground fault may very quickly escalate to a three phase short circuit.

### Characteristic 9 - Initial Cost

It is generally agreed in the literature[5,8,14,22] that the initial cost of an ungrounded system is lower than the cost of any other type of system. All authors agree, however, that the difference in cost is not very much, and therefore is not an important factor in system design. The higher cost of the resistance grounded and solidly grounded systems is mainly in the material and installation of a suitable ground, ground conductors, and resistor, if used. In addition, there may be costs involved in alarm, indicating, and protective devices, depending on system design and operating requirements.

In most coal mine applications, there will be at least one additional conductor for the purpose of connecting all the frames together. This means that the cost of the cable may be the same on an ungrounded system as on any other system. The conclusion then is that the ungrounded system does not really have much cost advantage over other systems, if any.

### Characteristic 10 - Maintenance, Repair and Downtime Cost

The cost of trouble shooting, repair and maintenance, and the cost of loss of production during downtime, could be high for the ungrounded system for several reasons.

Since the magnitude of fault current for the first line-to-ground fault on an ungrounded system is very low (see Characteristic 3), there may be no visible evidence to pinpoint the location of the fault. The trouble-shooting time required to find the fault may be costly in terms of labor and loss of production. Usually each power circuit must be isolated and tested for grounds, and even after identification of the faulty circuit, the problem of pinpointing the fault remains.

If the system remains in operation after the first fault occurs, a second fault may occur due to the increase in voltage on the other two phases as mentioned under Characteristic 4 above. The damage may be more severe. This increase in cost for repairs may not have been incurred if the first fault had been removed promptly.

In the case of the high-resistance grounded system, the first line-to-ground fault will not be pinpointed by any visible evidence either, but it is much easier to apply ground fault detectors on each circuit of a high-resistance grounded system, thus reducing the trouble-shooting time by identifying the faulty circuit.

In the case of the solidly grounded system, the first line-to-ground fault usually results in sufficient current flow to cause overcurrent trip devices to operate. The higher fault current may cause considerable damage due to the more intensive arcing, resulting in possible higher repair cost or even equipment replacement. Fast fault clearing effectively reduces potential burning damage.

If the first line-to-ground fault on an ungrounded system is of the intermittent, sputtering, or arcing type, the resulting system overvoltage (see Characteristic 2 above) may cause multiple breakdowns in other parts of the system. This, of course, would increase the downtime and cost of repairs.

(B) Advantages and Disadvantages of Ungrounded Systems

In the determination of advantages and disadvantages of an ungrounded system for use in underground coal mines, comparisons must be made with other types of systems; i.e., with a high-resistance grounded system, a low-resistance grounded system, and a solidly grounded system. Each of the ten characteristics of the ungrounded system enumerated and analyzed in (A) above will be considered in turn. A summary of this analysis appears in Table I.

1. It has been shown that on an ungrounded system there is always a voltage between line and ground under normal operating conditions. The ungrounded system is no different in this respect from the resistance grounded or solidly grounded systems. However, it is recognized that many operators, and especially maintenance personnel, erroneously consider the ungrounded system safer. Thacker[6] says, "If maintenance personnel treat all circuits with equal care and respect, the hazard of shock on an ungrounded circuit is slightly less. However, a subconscious tendency to be less careful in working on a normally ungrounded, energized circuit often exists, even though the impression that one phase of the ungrounded circuit can be safely contacted is often false". The same reasoning can be applied to mine personnel who may come in contact with live conductors by handling damaged cable. Similar thoughts are expressed by Sutton.[14] Streich[19] leaves no doubt about the personnel and gas ignition hazards of an ungrounded system even under normal conditions.

Since the ungrounded system is just about as hazardous as any other system with respect to this characteristic, it has no advantage relative to any other type of system.

2. It has been shown that high values of overvoltage can occur due to a sputtering type of ground fault, or due to several other possible conditions enumerated under Characteristic 2. This is the most serious disadvantage of the ungrounded system relative to any other system because of the personnel shock hazard, gas ignition hazard, and stresses on the insulation of all system components. These phenomena cannot occur on high-resistance, low-resistance and solidly grounded systems.

3. The fact that the first ground fault on an ungrounded system results in a very low value of fault current is an advantage of the ungrounded system relative to the low-resistance grounded and the solidly grounded systems. In the latter system, the ground fault current can be very high, approaching the value obtained when all three phases are short-circuited. These high values of fault current may cause considerable damage to cable, motor windings, and other equipment. They can also be a serious flash and burn hazard to personnel close by the fault, as well as an explosion hazard if gas is present.

The ungrounded system does not have too much advantage over the high-resistance grounded system because of this characteristic. The personnel and gas ignition hazards are about the same. Since the fault current may be a little higher in the high-resistance grounded systems, depending upon the ohmic value of resistance used, somewhat more damage might result for certain types of faults; for example, a ground fault in a motor winding or in control devices.

The conclusions then are that this characteristic is neither a great advantage nor a disadvantage relative to the high-resistance grounded system. It is, however, a distinct advantage relative to the solidly grounded and low-resistance grounded systems with respect to the magnitude of ground fault current and therefore with respect to personnel flash and burn hazard, and equipment damage. There is also the possibility that heavy ground fault currents may cause ground-loop voltage problems relative to personnel and gas explosion hazards.

4. The fact that the first ground fault on an ungrounded system raises the voltage to ground in the other two phases to rated circuit voltage is neither an advantage nor disadvantage compared with a high-resistance grounded system because the change in voltage and its effects are approximately the same for both systems. This is also true for a low-resistance grounded system in which the current is limited to a relatively low value.

In solidly grounded systems, the first ground fault causes immediate tripping of circuit interrupters due to the relatively high magnitude of fault current. The voltage on the other two phases does not rise because of the fault and there is no greater stress than normal on the insulation. This characteristic, then, may be considered a disadvantage of the ungrounded system relative to the solidly grounded system.

5. The fact that the first line-to-ground fault does not require a shut down of the system is a distinct advantage, in industrial plants, of the ungrounded system relative to the low-resistance and solidly grounded systems which require immediate shut down because of the high values of fault current. Historically, it is because of this advantage that the ungrounded system has been used in continuous process industries and in many applications where even a short shut down cannot be tolerated.

The ungrounded system, however, has no advantage relative to the high-resistance grounded system with respect to continued operation of the system after the first ground fault, because it is not necessary to de-energize the high resistance grounded system either.

This characteristic of ungrounded and high-resistance grounded systems may not be too important in coal mine systems because continuity of service is probably not of prime importance in most mine operations.

6. The fact that the second ground fault on another phase short-circuits the system is true of both the ungrounded and high-resistance grounded systems. In the case of the low-resistance and solidly grounded systems, the first ground fault causes the protective devices to operate, assuming proper devices are in use. Hence, there are no advantages or disadvantages either way.

7. The fact that the second, or even more ground faults may occur immediately after the first ground fault, for the reasons enumerated under Characteristic 2, is a disadvantage of the ungrounded system relative to the high-resistance and low-resistance grounded systems because there may not be time to locate and clear the first fault before the others occur. This is not likely to be the case with either the high-resistance or low-resistance grounded systems. In the case of the solidly grounded system, the first ground fault usually causes overcurrent trip devices to function, hence there is neither an advantage nor disadvantage.

8. The probability that a line-to-ground arc will not sustain itself or escalate into a line-to-line arc, because of the very low value of ground fault current, is a distinct advantage of the ungrounded system over the low-resistance and solidly grounded systems. The high-resistance grounded system has the same characteristics as the ungrounded system, although the arcing ground fault current may be a little higher.

9. The lower initial cost of the ungrounded system over all the other types is an advantage, but of dubious value. The cost saving is usually small relative to the total cost of the installation. It should not really be a determining factor.

10. The higher cost of trouble shooting, repair, and maintenance, and the cost of loss of production during down time, is a disadvantage of the ungrounded system relative to all other systems with the possible exception of the solidly grounded system. In the latter, an arcing type ground fault can do extensive and costly damage to equipment, even requiring complete replacement. In this respect, the ungrounded system has an advantage over the solidly grounded system.

The above advantages and disadvantages of the ungrounded system relative to other systems are summarized in Table I.

TABLE I ADVANTAGES AND DISADVANTAGES OF UNGROUNDED SYSTEM

| Characteristic of Ungrounded System | Advantages or Disadvantages of Ungrounded System<br>Relative to:<br>High Res. Grounded System | Low Res. Grounded System | Solidly Grounded System |
|---|---|---|---|
| * 1-Presence of line-to-ground voltage normally | N | N | N |
| * 2-Subject to excessive overvoltage | D | D | D |
| * 3-First-ground fault current magnitude | N | A | A |
| * 4-Rise in voltage on first ground fault | N | N | D |
| 5-First ground fault does not affect system operation | N | A | A |
| 6-Second ground fault causes system short-circuit | N | N | N |
| 7-Second ground fault may occur immediately | D | D | N |
| * 8-Probability of arc escalation | N | A | A |
| 9-Initial cost | A | A | A |
| 10-Maintenance, repair, and downtime cost | D | D | ** |

A = Advantage D = Disadvantage N = Neither

* Considered important as to personnel shock hazard, gas explosion hazard, and/or equipment damage.

** Depends on nature and severity of fault.

(C) Overcoming Disadvantages of Ungrounded Systems

A study of summation Table I shows that the ungrounded system has several disadvantages relative to one or more of the other types of systems due to certain of its characteristics; namely 2, 4, 7 and 10. A review of the discussions under (B) suggests that one way to overcome these disadvantages is to ground the system thru a properly selected relatively high resistance connected between the system neutral and ground (the earth). The results of this approach, summarized in Table II, would be as follows (considering each of the characteristics of the ungrounded system in turn):

1. There is no doubt that voltage is always present between line conductors and ground under normal conditions in the high-resistance, low-resistance, and solidly grounded systems, because the neutral is connected to ground thru a resistance or thru a solid connection. It has been shown in the study under (A) that the same is true of the ungrounded system because of the ever-present line-to-ground capacitance. Therefore, it is neither an advantage nor a disadvantage with respect to this characteristic, and relative to the other types of systems, to ground the system thru a high resistance.

2., 7., and 10 - It was shown in (A) that a serious disadvantage of the ungrounded system is that a sputtering type ground fault, and other abnormal conditions, can cause the voltage to soar to values many times rated voltage.

These excessive overvoltages can cause a second line-to-ground fault to occur immediately (characteristic 7), resulting in possible higher maintenance, repair, and downtime costs (characteristic 10). Since such overvoltages cannot occur on a high-resistance grounded system, the high-resistance grounded system has an advantage over the ungrounded system with respect to these three characteristics. It has neither an advantage nor disadvantage over the low-resistance and solidly grounded systems as to overvoltage and multiple faults, but it has an advantage over these two types with respect to repair and downtime costs in most cases.

3. It has been shown in (A) that the fault current in the case of the first solid ground on an ungrounded system is a very low value because the return path is thru the relatively high impedance of the system distributed capacitance. In the case of the high-resistance grounded system, the ground fault current is somewhat higher because the return path includes, in effect, the system distributed capacitance in parallel with the grounding resistor. However, the fault current even so is very low in comparison with the fault current obtained in low-resistance and solidly grounded systems. Therefore, it is neither an advantage nor a disadvantage, with respect to this characteristic, relative to an ungrounded system, to ground the system thru a high resistance. But it is advantageous relative to the low-resistance and solidly grounded systems because of the lower magnitude fault current.

4. It has been shown in (A) that the first solid line-to-ground fault raises the voltage to ground on the other two phases in both the ungrounded and high-resistance grounded systems. This may or may not be true of the low-resistance grounded system, depending on magnitude of ground fault current limitation and action of protective devices, if any. However it is not true of the solidly grounded system. Therefore, it is neither an advantage nor a disadvantage, with respect to this characteristic, to ground the system thru a high resistance. This characteristic of all three types of systems, however, may be considered to be a disadvantage relative to the solidly grounded system.

5. Since the first solid ground fault in either the ungrounded or high-resistance grounded system does not result in enough ground fault current to require shutting down the system, it is neither an advantage nor a disadvantage, with respect to this characteristic, to ground the system thru a high resistance. However, this characteristic is an advantage relative to the low-resistance and solidly grounded system.

6. Since the second ground fault on both the ungrounded and high-resistance grounded system results in complete shutdown by protective devices, the same as the first ground fault does on both the low-resistance and solidly grounded systems, there are no advantages or disadvantages either way.

8. Since the probability of arc escalation was shown to be low for both the ungrounded and high-resistance grounded systems, there are no advantages or disadvantages either way. However, relative to the low-resistance and solidly grounded systems, there are definite advantages.

9. Since the initial cost of the high-resistance grounded system is somewhat higher than the initial cost of an ungrounded system, this is a disadvantage. With respect to the low-resistance and solidly grounded systems, there may be no significant advantages or disadvantages.

The advantages and disadvantages of the high-resistance grounded system relative to the other types is summarized in Table II.

TABLE II ADVANTAGES AND DISADVANTAGES OF HIGH RESISTANCE GROUNDED SYSTEM

| | Characteristic of Ungrounded System | Advantages and Disadvantages of High-Resistance Grounded System Relative to: | | |
|---|---|---|---|---|
| | | Ungrounded System | Low Res. Grounded System | Solidly Grounded System |
| * | 1-Presence of line-to-ground voltage normally | N | N | N |
| * | 2-Subject to excessive overvoltage | A | N | N |
| * | 3-First-ground fault current magnitude | N | A | A |
| * | 4-Rise in voltage on first ground fault | N | N | D |
| | 5-First ground fault does not affect system operation | N | A | A |
| | 6-Second ground fault causes system short-circuit | N | N | N |
| | 7-Second ground fault may occur immediately | A | N | N |
| * | 8-Probability of arc escalation | N | A | A |
| | 9-Initial cost | D | N | N |
| | 10-Maintenance, repair, and downtime cost | A | A | A |

A = Advantage D = Disadvantage N = Neither

* Considered important as to personnel shock hazard, gas explosion hazard, and/or equipment damage.

Conclusions

The conclusions that may be drawn from a comparison of Table II with Table I are that the high-resistance grounded system:

(1) has several important advantages over the ungrounded system (2, 7, 10),

(2) has one relatively unimportant disadvantage relative to the ungrounded system (9),

(3) has the same advantages as the ungrounded system relative to the low-resistance and solidly grounded systems (3, 5, 8), plus an additional advantage (10), and

(4) has the same single disadvantage over the solidly grounded system as the ungrounded system has (4).

## POWER SYSTEM FOR LIGHTS

At the suggestion of Mr. E. L. Litchfield, Bureau of Mines, on November 5, 1971, the Contractor investigated single phase power systems for supplying lights used during the loading of explosives and other hazardous operations, although this is over and above the requirements of Contract H0111465.

One way to minimize the hazards would be to use a "dedicated" circuit, i.e., a circuit especially designed and installed for a specific light or group of lights. This circuit should be supplied from a separate especially designed transformer with a solidly grounded protective shield between the primary and secondary windings to prevent electrical breakdown between the windings.

The voltage rating of the lights should be as low as feasible for the lamp wattage required; for example, 24 volts. This minimizes insulation failure, arcing, and personnel shock hazard. The conductors should be over-insulated; for example, 600 volt wire for the 24 volt circuit.

Because of the low voltage, the current will be relatively high for a given lamp wattage. This means that the resistance of the conductors and the inductance of the circuit will cause relatively poor regulation (high voltage drop under load). The resistance drop can be minimized by using sufficiently large conductor size. The inductance of the circuit can be eliminated entirely by means of a full-wave bridge rectifier near the supply transformer. The secondary voltage of the transformer must then be the proper value to produce rated d-c voltage at the lamps.

Figure 4-25 shows a circuit embodying all the features mentioned in the foregoing.

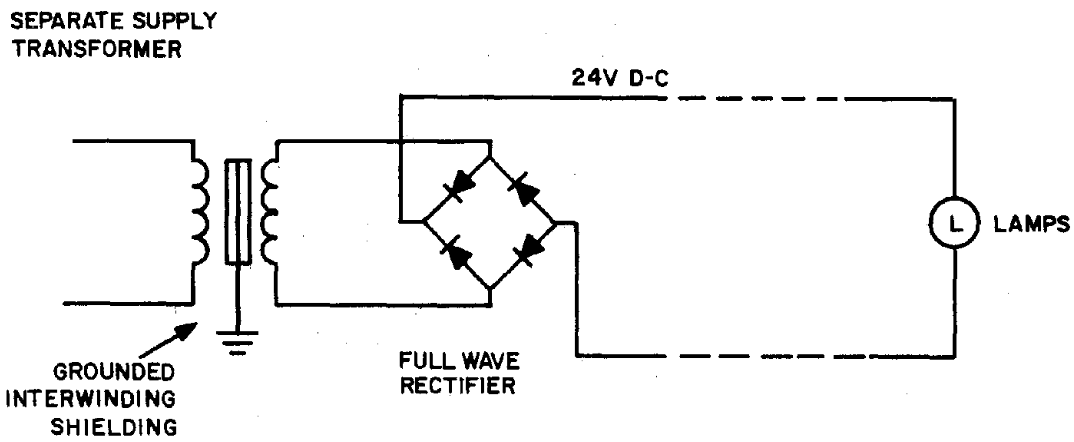



Figure 4-25. Low-voltage power supply for lighting

## SECTION 5

## SPECIFICATION OF AN UNGROUNDED DISTRIBUTION CENTER FOR WORKING SECTION

These specifications are not intended to be complete from an overall installation point of view, but merely to identify the equipment necessary to provide ground fault detection and breaker tripping.

### Description of System

The system one-line diagram shown in Fig. 1 represents a 500 kva skid-mounted underground mine load-center with a delta connected 4160 volt primary winding and two plus and minus 2-1/2% no-load taps. The secondary winding is wye connected for 480 volt operation. The neutral will be left floating for ungrounded system operation. To minimize capacitive coupling and dielectric breakdown between the primary and secondary winding, the transformer should be designed to provide proper shielding. The shield should be tied solidly to the high voltage ground system.

The 480 volt main and feeder breakers are usually molded case breakers, equipped with under-voltage (UV) trip devices. To maintain a circuit breaker in the closed position it is necessary to keep the UV device energized through normally closed contacts of the GDR device. Upon de-energization, the UV trip will cause the circuit breaker to trip. Shunt trip devices may also be used but a reliable source of control power must be provided.

The ground detection scheme utilizes static relays (Fig. 2) to sense a ground fault as low as 9 mA on the ac power system and 60 mA on the dc power system. In the proposed detection scheme, a ground fault anywhere on the ungrounded 480 volt system will cause both relays GDR-1 and GDR-M to pick up. Relay GDR-1 operates after an extremely short time delay (10 cycle) to minimize false operation due to transient displacement of the system neutral. When it operates, GDR-1 will trip both ac power feeder breakers no. 1 and no. 2. Relay GDR-M will time out after about 2 seconds if the ground fault condition is not removed by opening of the two ac power feeder breakers. In this event, relay GDR-M will trip the transformer main secondary breaker.

It should be noted that operation of relay GDR-M could be initiated by any one of the following conditions:

1. failure of GDR-1 to operate

II. failure of breakers 1 or 2 to trip

III. ground fault on 480 volt system did not occur on feeder circuits no. 1 or no. 2.

Thus relay GDR-M functions as back-up protection for condition I and II, but it provides primary protection for condition III.

A ground fault current on the dc power supply system of 60 mA or greater will be sensed by relay GDR-3 which is wired to trip breaker no. 4. It should be noted that the ground fault detector relays on the 480 volt system do not sense a ground fault on the dc power system, because the rectifier transformer isolates the dc system from the 480 volt system.

Similarly a ground fault on the 120/240 volt lighting system will not be sensed by GDR-1 or GDR-M, because of the transformer isolation. To remove a ground fault anywhere on this lighting system, relay GDR-2 is wired to trip breaker no. 3 and will disconnect only the lighting system.

The extremely low ground fault sensitivity of 9 mA, as determined by the human let-go limitation, makes it essential that the system capacitive reactance to ground be balanced. In cable circuits, this objective can be approached when the three individual power conductors are equilaterally spaced in a three conductor cable and/or by metallically shielding each power conductor. In addition the shielded cable construction not only minimizes phase-to-phase faults but also reduces the human shock hazard in case of cable insulation damage due to mechanical abuse.

SECTION LOAD CENTERS FOR UNGROUNDED WORKING SECTION

500 KVA skid mounted, underground mine load center, 4160 volt delta primary two 2½% taps above and below, 480 volt secondary with the following devices mounted and wired for 4160 volt underground mining service:

a) 1 - Incoming coupler with cover.

b) 1 - Loop feed coupler with shorting cover.

c) 1 - Set coupler wrenches with mounting provisions.

d) 1 - Air interrupter switch, 4.8 kV, 3 pole, load break with auxiliary switch and viewing window.

e) 3 - Lightning arresters, 4.5 kV.

f) Dry type transformer, 500 kVA, 4160 volt delta primary with taps, 480 volt secondary, ungrounded with grounded shield between high and low voltage windings. Shield to be tied directly to 4160 volt system ground.

g) 1 - 480 volt main circuit consisting of:

1) 1 - Air circuit breaker, 600V, 3 pole, 800 amp with three time delay and instantaneous direct acting trips and 120 volt ac undervoltage device.

2) 1 - Time delay ground relay.

3) 3 - 277 volt ground detection circuits, 9 mA maximum.

h) 2 - 480 volt, 200 ampere feeder circuits with:

1) 1 - Air circuit breaker, 600 volt, 3 pole, 225 ampere frame, three 200 ampere time delay and instantaneous direct acting trips and 120V ac undervoltage device.

2) 1 - Receptacle with cover.

3) 1 - Mating plug with cover.

i) 1 - Control power transformer, kVA to suit, 480 volt primary with fuses, 120 volt secondary.

j) 1 - 480 volt, 3 pole lighting primary breaker, 60 ampere with 120 volt ac undervoltage trip.

k) 3 - 10 kVA, 480 volt to 240/120 volt lighting transformers connected delta-delta, provided with shield between primary and secondary windings, shield to be connected solidly to the ground point of the 480 volt ground sensing system.

l) 6 - 240 volt, 3 pole, 30 ampere lighting breakers, air circuit breaker type, with three time delay and instantaneous direct acting trips.

m) 6 - Receptacles, 3 pole, 240 volt with cover.

n) 6 - Mating plugs.

o) 3 - 138 volt ground detectors, 9 mA max.

p) 3 - 69 volt ground detectors, 9 mA max.

q) 1 - 600 volt, 3 pole air circuit breaker, 600 ampere, with three time delay and instantaneous direct acting trips and 120 volt ac undervoltage trip.

r) 1 - Rectifier transformer, 480 volt primary with straddle taps, kVA and secondary voltage for 300 KW, 600 volt dc rectifier. Transformer to be provided with shield between primary and secondary windings, shield to be connected solidly to the ground point of the 480 volt ground sensing system.

s) 1 - 300 KW, 600 volt dc silicon diode rectifier with normal protective devices for mining service, ungrounded.

t) 2 - 300 volt dc ground detectors, 60 mA max.

u) 4 - 600 volt, 300 ampere, 2 pole dc contactors.

v) 4 - 600 volt, 300 ampere, 2 pole dc receptacles with cover.

w) 4 - Mating plugs.

x) X - Necessary cover and door interlocks including E-Stop push-button wired in series with incoming pilot circuit.

## RELIABILITY ANALYSIS OF UNGROUNDED DISTRIBUTION CENTER

### General

A reliability analysis is made of the "Underground Distribution Center for Working Section" shown in Fig. 1. This is an ungrounded system. The "GDR" ground detection relay circuits operate the circuit breakers when ground faults are encountered.

Operation of 480 Volt System

The GDR #1 relay will trip Circuit Breakers #1 and #2 if a ground fault current greater than 9 mA occurs on any of the three phases of the 480 volt power system and persists for longer than 10 cycles (.167 second). The GDR main relay has a two second time delay and will trip the Main Circuit Breaker if a ground fault current greater than 9 mA occurs for more than 2 seconds on any of the three phases of the 480 volt system.

Thus the GDR Main relay plus the Main Circuit Breaker acts as a backup to GDR #1 relay plus Circuit Breakers #1 and #2. This backup is for clearing ground faults on either of the two 200 ampere circuits of the 480 volt three phase power system if they are not cleared by the Circuit Breakers #1 and #2. The main GDR relay and circuit breaker also provide ground fault protection for the portions of the 480 volt system not protected by Circuit Breakers #1 and #2.

Lighting Power

The power for the lighting circuits is isolated from the 480 volt power by three single phase ungrounded transformers. A ground fault on the 120/240 volt circuits of the Lighting System greater than 9 mA will cause GDR #2 relay to trip Circuit Breaker #3. Failure to operate of GDR #2 relay or Circuit Breaker #3 will not result in a ground fault on the 480 volt power system because of the transformer isolation, and the fault could go undetected. The use of redundant ground sensing relays with time delay tripping of the Main Circuit Breaker is recommended.

A ground fault greater than 9 mA on the 480 volt power system between Circuit Breaker #3 and the primaries of the 10 kVA transformers will be cleared by the GDR Main relay tripping the Main Circuit Breaker after a two second time delay. Circuit Breakers #1 and #2 will also have been tripped, since the sensing system is not selective.

Power for DC Machines

The power for the D.C. machines is isolated from the 480 volt AC power by a 300 kW transformer. A ground fault greater than 60 mA on the D.C. system will cause GDR #3 relay to trip Circuit Breaker #4. Failure to operate of GDR #3 relay or Circuit Breaker #4 will not result in a ground fault on the 480 volt power system because of the transformer isolation and the fault could go undetected. The use of redundant ground sensing relays with time delay tripping of the Main Circuit Breaker is recommended.

A ground fault greater than 9 mA on the 480 volt AC power system between Circuit Breaker #4 and the primary of the 300 kW transformer will be cleared by the GDR Main relay tripping the Main Circuit Breaker after a two second time delay. Circuit Breakers #1 and #2 will also have been tripped, since the sensing system is not selective.

Reliability Analysis of the Two 200 Amp 480 Volt Circuits

The ungrounded 480 volt system shown in Fig. 1 has two 200 ampere 3 phase circuits that supply power to mining machines. For safety reasons, it is desirable to trip Circuit Breakers #1 and #2 after the first ground fault greater than 9 mA current has occured. A reliability analysis attempts to look at various equipment failure modes and effects and make a reliability prediction of the likelihood of it happening. Documented sources of field failure data are used wherever possible. However, in many cases the data is for electrical equipment that has been used in general industrial applications rather than in the probably more hostile environment encountered in mining applications. Since the environment is somewhat different than for mining applications, the failure rates are not necessarily the same as could be expected in underground mining applications. Data for molded case breakers has been used since they are in wide use currently in underground power systems.

Fig. 2 shows a more detailed diagram of the GDR ground detection relay circuit that is used with both the Main Circuit Breaker and with the Circuit Breakers #1 and #2. The control circuits for tripping these breakers are also shown in Fig. 2.

Fig. 3 shows a reliability analysis for a circuit breaker not operating to clear a ground fault when it should.

Fig. 4 gives a list of equipment failure modes that would result in a false trip of a 480 volt circuit.

## Conclusions from Reliability Analysis

The failure rate of a molded case breaker and its associated auxiliary devices is high enough such that the Main Circuit Breaker will be operated quite often for back-up protection to clear a ground fault. The auxiliary devices, such as a UVR or a shunt trip, degrade the basic reliability of a molded case breaker. A shunt trip is believed to be more reliable than a UVR; however, a separate reliable power source is required for use with a shunt trip, and the combination could be less reliable than the UVR.

## Recommendations

It is recommended that very reliable breaker and auxiliaries be used for the Main 480 volt Circuit Breaker. This is desirable to assure that the back-up protection for clearing a ground fault is highly reliable.

Source of Failure Rate Data Used in Fig. 3

1. Sensing Circuit (GDR) - a failure rate of .012 per year was calculated by using MIL217A for a similar circuit used in a High Voltage DC transmission terminal containing light emitting diodes and light detection circuits and amplifiers.

2. Undervoltage Relay (UVR) - this failure rate is assumed to be 1.5 times the failure rate of the molded case breaker.

3. Molded Case Circuit Breakers - the Nov.-Dec. 1965 issue of "Electrical Tester" published by Multi-Amp Corporation stated that 7 out of 402 molded case breakers tested at an industrial plant would not trip at all at any current. This gives a probability of failure of .017 per breaker operation. If it is assumed that each breaker is required to clear six ground faults per year, then this gives a failure rate of .102 per year. A failure is defined to be "failed to clear a ground fault when called upon".

## Reliability Analysis of Lighting Circuit

If the lighting circuit has a ground fault current greater than 9 mA, Circuit Breaker #3 will be opened to clear the ground fault.

See Figure 5 for a calculation of Circuit Breaker #3 failure rate of .000034 failures per year. In addition the GDR #2 relay sensing may fail or its UVR may fail, so to this figure must be added the UVR failure rate (.000051) and the sensing circuit failure rate (.012) for a circuit failure rate of .012085 failures per year.

## Reliability Analysis of 600 Volt DC Circuits for the DC Machines

If a ground fault current greater than 60 mA occurs on the 600 volt D.C. circuits, the AC Circuit Breaker #4 will be opened to clear the ground fault.

See Figure 6 for a calculation of Circuit Breaker #4 failure rate of 0.102 failures per year. In addition the GDR #4 relay sensing may fail or its UVR may fail, so to this figure must be added the UVR failure rate (.153) and the sensing circuit failure rate (.012) for a circuit failure rate of .267 failures per year.

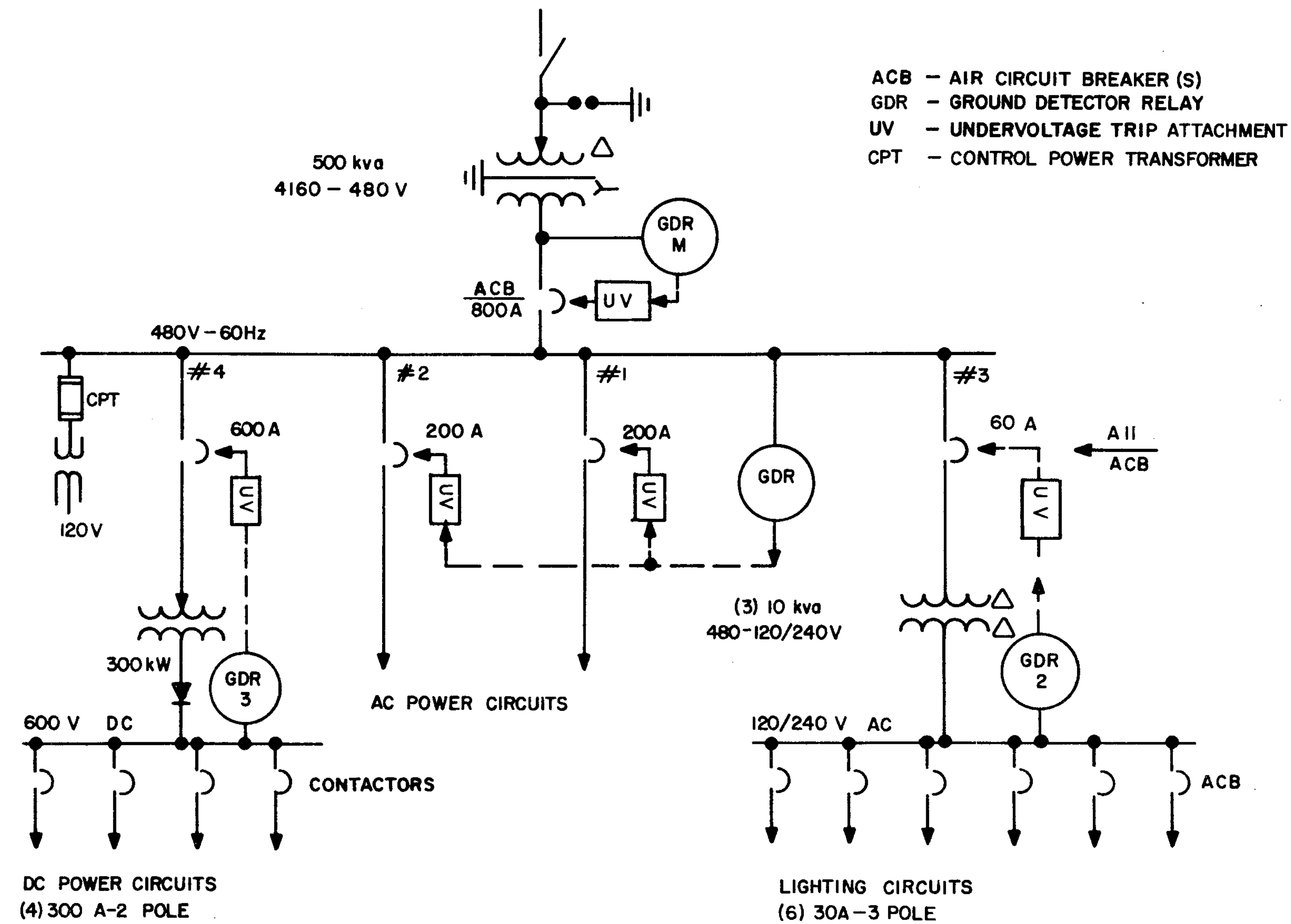



Fig. 1 Ungrounded Distribution Center for Working Section

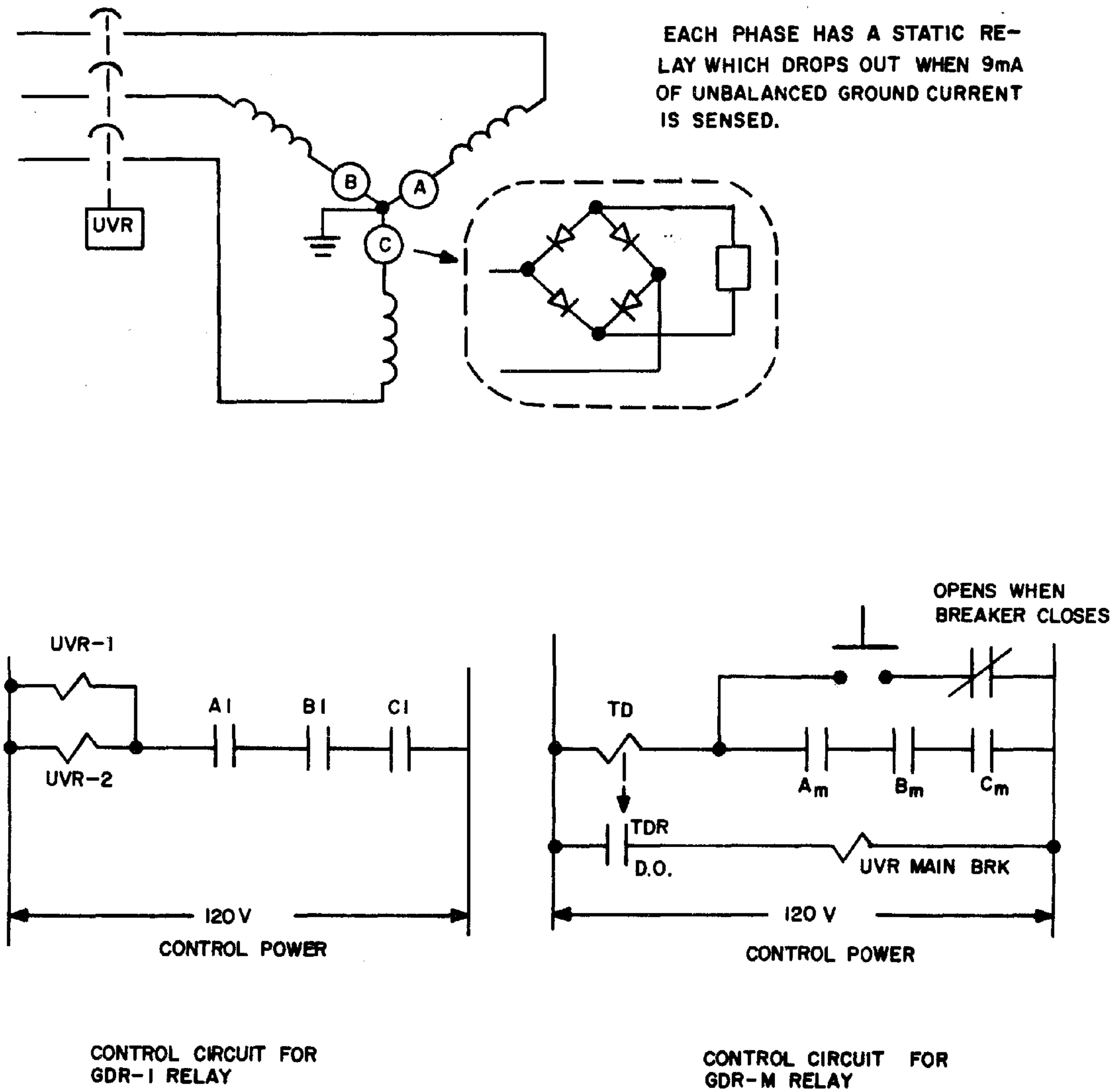
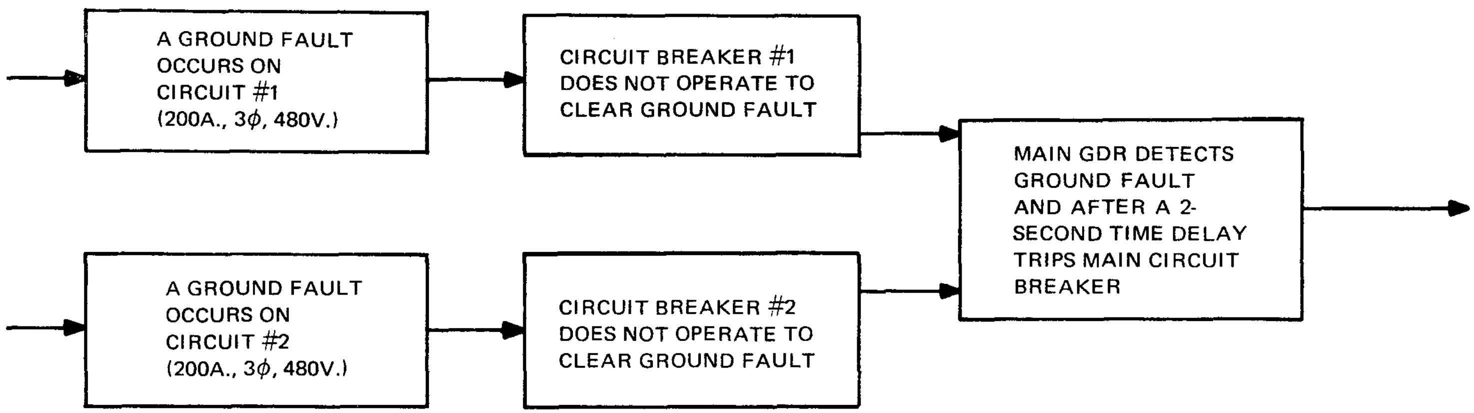



Fig. 2 GDR Ground Detection Circuit

RELIABILITY DIAGRAM




FUNCTIONAL FAILURE MODE

BACKUP PROTECTION

| • CIRCUIT BREAKER #1 DOES NOT OPERATE TO CLEAR GROUND FAULT | FAILURES PER YEAR |
|---|---|
| 1. SENSING CIRCUIT (GDR #1) FAILS TO OPERATE WHEN CALLED UPON | .012 |
| 2. UVR #1 FAILS TO OPERATE WHEN CALLED UPON | .153 |
| 3. CIRCUIT BREAKER #1 FAILS TO OPERATE AND CLEAR GROUND FAULT WHEN CALLED UPON | .102 |
| TOTAL FAILURE RATE FOR CIRCUIT #1 | .267 |
| TOTAL FAILURE RATE FOR CIRCUIT #2 | .267 |
| TOTAL FAILURE RATE FOR BOTH CIRCUITS | .534 |

Fig. 3 Predicted Failure Rate-Failure of 480 Volt Circuit Breaker and Detection Circuit to Clear a Ground Fault

- FALSE TRIP OF # 1 AND # 2 AND MAIN CIRCUIT BREAKERS
  1. LOSS OF 120 VOLT CONTROL POWER

- FALSE TRIP OF EITHER OR BOTH # 1 OR # 2 CIRCUIT BREAKERS
  1. UVR # 1 OR # 2 DROPS OUT WHEN IT SHOULDN'T
  2. SHUNT TRIP # 1 OR # 2 OPERATES WHEN IT SHOULDN'T
  3. CIRCUIT BREAKER # 1 OR # 2 OPERATES WHEN IT SHOULDN'T
  4. SENSING CIRCUIT (GDR # 1) OPERATES WHEN IT SHOULDN'T

- FALSE TRIP OF MAIN CIRCUIT BREAKER
  1. UVR MAIN DROPS OUT WHEN IT SHOULDN'T
  2. SHUNT TRIP MAIN OPERATES WHEN IT SHOULDN'T
  3. CIRCUIT BREAKER MAIN OPERATES WHEN IT SHOULDN'T
  4. SENSING CIRCUIT (GDR MAIN) OPERATES WHEN IT SHOULDN'T

Fig. 4 Equipment Failure Modes that will Cause False Trip of 480 Volt Circuit Breakers

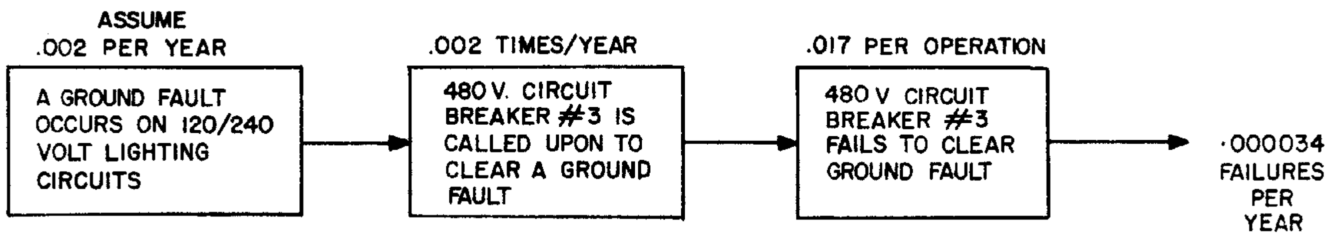



Fig. 5 Calculation of Failure Rate of Circuit Breaker No. 3 for Lighting Circuits

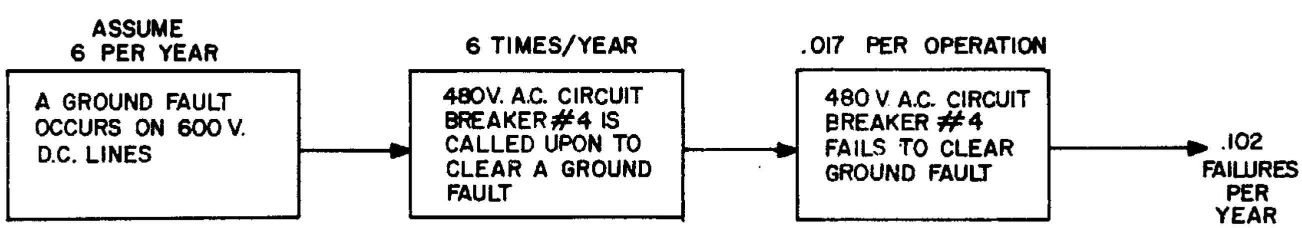



Fig. 6 Calculation of Failure Rate of Circuit Breaker No. 4 for 600 Volt D.C. Circuits

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ENERGY SYSTEMS

## APPLICATION ENGINEERING INFORMATION

# System Grounding for Low-voltage Power Systems

published by

INDUSTRY SALES & ENGINEERING OPERATION
INDUSTRIAL SALES DIVISION
SCHENECTADY, N. Y.

GENERAL ELECTRIC

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# Report on Power Systems Grounding

## CONTENTS

# Report on Power Systems Grounding

## by the Task Force on

## Low-voltage Power System Grounding

## THE NEED FOR THIS STUDY

For many years the recommendation of the General Electric Company for the grounding of low-voltage industrial and commercial power systems has been **solid grounding** of the power system neutral. For special operating or safety requirements, alternative methods of grounding — such as high-resistance grounding or low-reactance grounding—have been advised. On the basis of such recommendations a long-term trend toward the installation of power systems with a solidly grounded neutral developed, with the result that such systems are currently the most widely used in industrial and commercial power system design. These systems have, in general, performed adequately and provided the safety, reliability and continuity of service which had been anticipated from them.

Recently, however, it has been suggested that the high-resistance grounded neutral system is better suited for certain systems—particularly insofar as personnel safety and process continuity are concerned. Proposals to this effect have arisen because of serious injuries or fatalities which have occurred to operating or service personnel during line-to-ground arcing faults in solidly grounded neutral systems.

In response to such proposals General Electric's Energy Systems Operation put together a task force which has restudied the question of power system grounding. As part of its activities, this task force has worked to bring into focus the characteristic features of competing alternative grounding methods.

## RESULTS OF TASK FORCE STUDY

The typical features of alternative grounding methods are presented herein, covering individually the characteristics, benefits, drawbacks and typical application areas for each of the available methods of low-voltage system grounding which were studied. Specific recommendations of one method of grounding in preference to another have been avoided, however, in recognition that no single method of system grounding will prove unrivaled and completely satisfactory in all the application situations which may be encountered. In illustration of this, the solidly grounded neutral system is very extensively used in industrial and commercial building applications, yet the so-called "ungrounded" system, when complemented with ground-fault detection and first-quality electrical system maintenance, has provided desirable performance characteristics and adequate service in certain process industries.

Additionally, specific recommendations are not given because it is felt that the comparative merits of the various methods of system grounding, for any given set of customer conditions and objectives, will be self-evident from the listing of the characteristics and features of the individual system grounding methods; and that the power system designer, application engineer, or power distribution equipment sales engineer is best qualified to consult with the customer and advise him on the choice of grounding method for his specific conditions and objectives.

## TYPES OF SYSTEM GROUNDING REVIEWED

All the methods of low voltage power system grounding which have been applied or used in significant numbers were covered by the task force review. Grounding methods of very infrequent use, such as the dual-resistance grounding and ground-fault neutralizer methods, were not included in this review. The specific methods of power system grounding which are covered in this report are

1. the ungrounded system.
2. solid neutral grounding.
3. low-resistance grounding.
4. high-resistance grounding.
5. high-resistance grounding with traceable signal to the fault.
6. corner-of-the-delta grounding.
7. mid-phase grounding.
8. low-reactance grounding.

For each of these methods of system grounding the characteristic features, advantages, disadvantages, and typical areas of application, as well as general remarks on the particular system of grounding, are given in the following pages.

It is appropriate to point out that selection of a specific method of system grounding should not be based on the number of advantages or disadvantages it possesses, since these attributes are not necessarily absolute, and generally have firm meaning and significance only when related to such factors as equipment cost and quality, electrical system maintenance, safety of personnel, damage to equipment arising from ground fault conditions, system protective devices and their settings, power continuity requirements of the process or service being powered, and so forth. In addition, certain attributes are common to most, if not all, of the methods of system grounding; in these instances the attributes may be listed as "characteristic features" in the tabulation, rather than as advantages or disadvantages.

# THE UNGROUNDED SYSTEM

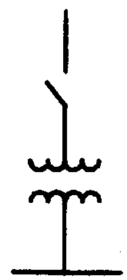
**Characteristic Features**

Definition

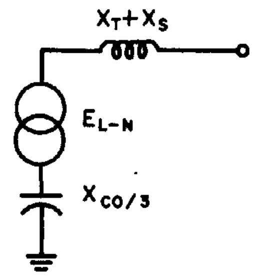
The ungrounded system is one which has no intentional connection to ground except through potential indicating or measuring devices, or through surge overvoltage protective devices. Although called "ungrounded" this type of system is in reality capacitively coupled to ground through the distributed phase-to-ground capacitance of the windings and phase conductors of the system.

---

Circuit Schematic and Thevenin line-to-ground equivalent circuit diagram①.



Circuit




Thevenin Equivalent

---

Suitable for serving load circuits of the type indicated

Two-wire, single-phase
Three-wire, three-phase

---

Grounding equipment required for this method of system grounding.

None required, but potential transformers, a voltage relay and/or ground indicating lights and possibly stabilizing resistors are advisable for ground fault detection.

---

First cost, relative to a solidly grounded neutral system with phase relaying only.

Same cost, if no ground fault detection. Ground fault detection adds to cost.

---

Current for bolted line-to-ground fault, in percent of bolted three-phase rms fault current, for terminal fault at supply point.

System charging current, $(3\ E_{L\text{-}N})/X_{co}$. Less than one percent; usually less than 1 ampere. System charging current rarely exceeds 5 amperes, except on systems having surge capacitors.

---

Probable level② of sustained single-phase line-to-line arcing fault current, in percent of three-phase bolted fault current.

Value is function of system voltage as well as of arc and restrike voltage values. For particular conditions, calculated values are:

| System Volts | Fault Current, Percent③ | Arc Volts | Restrike Volts |
|---|---|---|---|
| 208 | 2 | 275 | 275 |
| 480 | 74 | 275 | 375 |
| 600 | 85 | 275 | 375 |

For footnotes see Page 33.

| | |
|---|---|
| Probability of sustained arcing for line-to-line fault on single-phase circuit extension (no escalation to three-phase fault). | 208-volt systems small probability, but sustained arcing can occur.<br>480-, 600-volt systems—high probability; in the order of 1.0. |
| Shock hazard, phase-to-ground, for<br>(a) No ground fault.<br>(b) Ground fault on phase conductor. | (a) Phase-to-neutral voltage exists from each phase to ground.<br>(b) Line-to-line voltage appears on two phases, for solid fault and no series resonant L-C circuit. With repetitive restrike to ground, or series resonant L-C circuit, voltages to ground well in excess of line-to-line voltage may appear. |

**Advantages in Relation to:**

| | |
|---|---|
| Probability of sustained arcing for line-to-ground fault on single-phase circuit extension (no escalation). | Extremely low probability, near zero. A sputtering fault with repeated restrikes may continue indefinitely. |
| Rms current value for sustained single-phase line-to-ground arcing fault. | Very low value, if fault could be sustained. Single-phase line-to-ground arcing fault in ungrounded system would very likely be self-extinguishing, unless of the sputtering type. |
| Probability of escalation of single-phase line-to-ground arcing fault into line-to-line or 3-phase arcing fault, in bare bus system. | Very small probability. Probability of escalation would be prominently influenced by closeness of phase conductors. |
| Automatic tripping by phase (or ground) over-current devices for first line-to-ground fault. | No automatic tripping for the first ground fault occurs, provided a second line-to-ground fault on another phase does not occur before the first one is removed. The faulty circuit continues in operation; in certain process industries and conditions of service this is regarded as an advantage. |
| Ease of discrimination between an arcing line-to-line fault and normal system load current. | For the usual levels of line-to-line arcing fault currents, discrimination is not difficult. But low-level line-to-line or double line-to-ground arcing faults are possible which will operate phase overcurrent devices only with considerable delay, or not at all. Then burndown may occur. |
| Flash hazard to personnel arising from accidental line-to-ground fault (no escalation). | Basically no flash hazard exists, unless the system has an unremoved ground fault on another phase. This could result in a double line-to-ground fault with serious flash hazard. |

**Disadvantages in Relation to:**

| | |
|---|---|
| Control of transient and steady-state over-voltages from neutral to ground. | The ungrounded system provides no effective control of such overvoltages. |
| Shock hazard, phase-to-ground, resulting from fault-path contact with a higher voltage system. | The ungrounded system phase-to-ground potential may be elevated as high as the normal phase-to-ground voltage on the higher voltage system. |

| | |
|---|---|
| Safety hazard, for ground faults in directly connected control circuits using line-to-line rated voltage contactor coils. | The first or second ground on such a control circuit may start the motor. |
| Effect of delayed removal of line-to-ground fault on the system (no escalation to line-to-line fault). | All unremoved ground faults put greater than normal voltage on system insulation. Certain unremoved ground faults may result in very severe overvoltage conditions, leading to increased shock hazard and eventually to extensive equipment and circuit outages. |
| Difficulty of locating the first line-to-ground fault. | Ground fault locating is usually very difficult. It may require much time and repeated shutdowns of unfaulted as well as faulted equipment. Special fault-locating equipment can facilitate pinpointing the fault site. |
| Cost of system maintenance. | Maintenance costs on the ungrounded system are relatively high because of reduced insulation life and the labor of locating ground faults. |
| Motor protection. | Ground fault in motor cannot be easily detected and removed until it has burned into another coil, resulting in greater damage. |

**Typical Area of Application**

The ungrounded system has been much used in general industry, and in the process industries, such as the paper, chemical and petroleum industry, and in certain other service or manufacturing operations where the ability of this system to avert immediate shutdown on the occurrence of the first ground fault was desired. The prevention of a non-scheduled shutdown in these instances was intended to avoid severe financial loss in production, substantial contingent damage to equipment, or grave danger to personnel.

**General Remarks**

The prominent favorable feature of the ungrounded system is its ability to avoid immediate interruption of service continuity when a single ground fault takes place. The vulnerability of the ungrounded power distribution system to insulation failures and increased shock hazard from transient and steady-state overvoltage conditions, however, has led to the gradual diminishment of its use, in favor of the solidly grounded and high-resistance grounded systems. Ungrounded systems with ground fault indicators are still used in specific plants and industries, but such installations require excellent maintenance and housekeeping procedures, and rigorous ground fault detection and removal practices in order to provide service reliability and continuity equivalent to that found in the solidly and high-resistance grounded neutral systems.

# THE SOLIDLY GROUNDED NEUTRAL SYSTEM

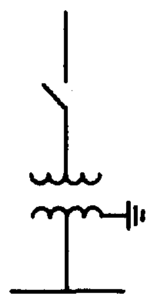
**Characteristic Features**

Definition

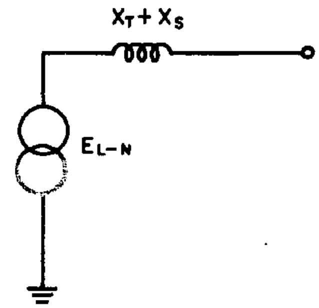
The solidly grounded neutral system has the neutral point directly grounded through an adequate ground connection in which no impedance has been inserted intentionally, except possibly in the case of low-voltage generator grounding.

---

Circuit schematic and Thevenin line-to-ground equivalent circuit diagram①.



Circuit




Thevenin Equivalent

---

Suitable for serving load circuits of the type indicated.

Two-wire, single phase.
Two-wire, single phase, 1 side grounded.
Three-wire, three-phase.
Four-wire, three-phase.

---

Grounding equipment required for this method of grounding④.

None for wye-system with neutral available. Grounding transformer is required for delta system⑤.

---

First cost, relative to a solidly grounded neutral system with phase relaying only.

This is the reference system, using a wye-connected transformer. Ground fault relaying adds to price.

---

Current for bolted line-to-ground fault, in percent of bolted three-phase rms fault current, for terminal fault at supply point.

Varies; may be 100 percent or more.

---

Probable level② of sustained single-phase line-to-line arcing fault current, in percent of three-phase bolted fault value.

Value is function of system voltage as well as of arc and restrike voltage values. For particular conditions, calculated values are:

| System Volts | Fault Current, Percent ③ | Arc Volts | Restrike Volts |
|---|---|---|---|
| 208 | 2 | 275 | 275 |
| 480 | 74 | 275 | 375 |
| 600 | 85 | 275 | 375 |

For footnotes see Page 33.

| | |
|---|---|
| Probability of sustained arcing for line-to-line fault on single-phase circuit extension (no escalation to three-phase fault). | 208-volt systems—small probability, but sustained arcing can occur.<br>480-, 600-volt systems—high probability; in the order of 1.0. |
| Rms current② for sustained single-phase line-to-ground arcing fault, in percent of three-phase bolted fault value. | Based on 140-volt arc and 375-volt restrike voltages (275 volts @ 208 Y):<br>208 V—0 percent⑧<br>480 V—40 percent*<br>600 V—50 percent* |
| Shock hazard, phase-to-ground, for<br>(a) No ground fault.<br>(b) Ground fault on phase conductor. | <br>(a) Phase-to-neutral voltage from each phase to ground.<br>(b) Phase-to-neutral voltage on two phases. |

**Advantages in Relation to:**

| | |
|---|---|
| Control of transient and steady-state overvoltages from neutral to ground. | The solidly grounded neutral system effectively controls to safe levels the overvoltages which become impressed on or self-generated in the power system by insulation breakdowns, resonant inductive-capacitive circuits, restriking ground faults, etc. |
| Automatic tripping by phase and/or ground overcurrent devices for first line-to-ground fault. | System is designed to provide automatic tripping by low-cost phase devices for first ground fault. Solid ground faults or high-level arcing faults to ground will operate the phase overcurrent devices. For low level arcing faults to ground, application of sensitive ground fault relays is required to assure disconnection of faulty circuit before burndown can occur. In many industries and conditions of service this rapid protection of equipment is necessary and desirable, to protect other services and personnel. |
| Ease of discrimination between an arcing line-to-line or line-to-ground fault and normal system load current. | Usual levels of arcing faults will cause tripping of phase devices. Use of zero-sequence type ground fault relaying is necessary for prompt discrimination between low-level ground faults and normal load currents. Line-to-line arcing faults usually involve ground quickly. Thus ground relays minimize the possibility of arcing-fault burndown. |
| Shock hazard, phase-to-ground, resulting from fault-path contact with a higher voltage system. | Limited to low-voltage system line-to-neutral voltage, approximately. |
| Shock hazard, from neutral to ground during line-to-ground fault. | Essentially zero voltage for low impedance common main grounding conductor. |

*Tentative; subject to further investigation. Minimum ground fault current value may be quite low, depending on ground circuit impedance and other factors.

For footnotes see Page 33.

| | |
|---|---|
| Safety hazard, for ground faults in directly connected control circuits using line-to-line rated voltage contactor coils. | Only 58 percent of line-to-line voltage appears on contactor coil. Motor start is not likely. |
| Difficulty of locating the first line-to-ground fault. | Generally not difficult. Fault is usually self-isolating via phase overcurrent device operation, but ground fault relaying is recommended to isolate very low level faults on high current circuits. Noise, smoke, and flash during fault aid in pinpointing fault site. |
| Cost of system maintenance. | Minimum, since insulation life is not shortened, and ground faults are readily located. |
| Motor protection. | A fault to ground in a motor winding can be quickly detected and removed, before extensive damage occurs, by means of phase overcurrent devices or ground sensor relays. |

**Disadvantages in Relation to:**

| | |
|---|---|
| Probability of sustained arcing for line-to-ground fault on single-phase circuit (no escalation). | 208-volt systems—small probability; near zero.*<br>480-, 600-volt systems—high probability; in the order of 1.0. |
| Probability of escalation of 1-phase, line-to-ground arcing fault into line-to-line or 3-phase arcing fault (in bare bus system). | High probability, in the order of 1.0, particularly for 480- and 600-volt systems. (Probability of escalation is zero in this system on single-phase circuits serving line-to-neutral connected loads.) |
| Safety hazard, for ground faults in directly connected control circuits using line-to-line rated voltage contactor coils. | A motor already running may not drop out when the "stop" button is pressed.<br>Pushing the "start" button with a ground fault in the control circuit may permit line-to-ground fault current to flow through the push button. This would cause a momentary personnel hazard until a protective device operates.<br>Protective contacts on energized equipment may be bypassed by an accidental ground, preventing equipment shutdown if safety limits are exceeded. |
| Effect of delayed removal of line-to-ground fault on system (no escalation). | Continuing low-level arcing fault may result in equipment burndowns and delayed restoration of service. Sensitive ground fault relaying can eliminate this problem. |
| Flash hazard to personnel arising from accidental line-to-ground fault (no escalation). | Severe flash hazard for ground fault on any phase of a high capacity system. |

* Not to be construed as being dependably self-extinguishing.

**Typical Area of Application**

The solidly grounded neutral system is the one most widely used in industrial and commercial service, for serving general industrial loads, and loads affecting public welfare and safety (lighting, elevators, fire pumps, ventilation, etc.) In particular, the solidly grounded neutral arrangement is the most effective in serving three-phase four-wire low voltage power distribution circuits. It has also been used effectively on critical process (so-called non-interruptible) loads.

**General Remarks**

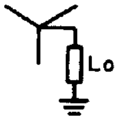
The prominent characteristics of the solidly grounded neutral system are its effective control of all overvoltage conditions and its immediate segregation of the faulty circuit, by means of economic phase overcurrent trips, on the occurrence of a **sensible** ground fault. Furthermore, the solidly grounded neutral system provides an **effective basis** for protection against destructive low-level arcing faults, since the addition of zero-sequence type relaying to such a system enables the easy detection and removal of such faults.

These characteristics of overvoltage control, immediate fault isolation, and practicable protection against arcing fault burndown help to account for the very extensive use of the solidly grounded neutral system in industrial and commercial power service. Its emphasis on prompt protection for faulty equipment and circuits, thereby increasing service restorability and reducing repair costs and downtime, make it suitable for use wherever extensive damage to electrical equipment and prolonged shutdown of processes or services is to be guarded against.

A particular shortcoming of the solidly grounded neutral system is the very severe flash hazard which exists on the occurrence of an arcing fault involving ground. Where a person may be in close proximity to the fault, or may have been directly instrumental in initiating the fault, a serious personnel hazard then exists. This hazard is sufficient to require that equipment and circuits be worked upon only when de-energized. This safe working practice is also required by the otherwise ever-present voltage hazard. Working on energized equipment requires specially trained crews and safety procedures not normally available in industrial plants or commercial buildings.

The solidly grounded neutral system generally isolates phase and ground faults promptly. In this system, however, equipment burndown may occur if a relatively low-level arcing fault occurs on a high-current circuit. Ground-fault relaying minimizes this possibility.

The prompt removal, in the solidly grounded neutral system, of a circuit in which a ground fault has occurred is considered by some system operators to be a singular imperfection. For these operators the requirement to avoid a disorderly and abrupt shutdown on the occasion of the first ground fault, and to continue to supply power to a critical process or service takes precedence over all other considerations. In situations of this sort high resistance in the neutral connection to ground to limit fault current and avoid tripping on the first ground fault has frequently been employed. See High-Resistance Grounding.




# LOW-RESISTANCE* GROUNDED NEUTRAL SYSTEM

**Characteristic Features**

Definition

The low-resistance* grounded neutral system is one in which a low-value resistor has been inserted in the neutral connection to ground to limit the current under ground-fault conditions to a level significantly reducing the fault-point damage but still permitting automatic detection and isolation of the fault by ground-fault protection devices.

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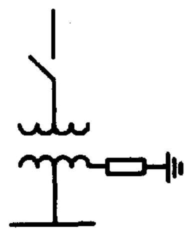
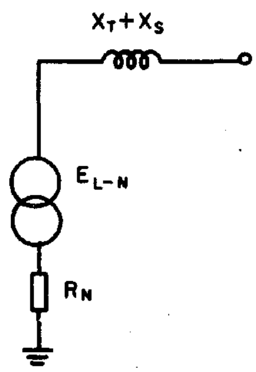
Circuit schematic and Thevenin line-to ground equivalent circuit diagram ①.



Circuit




Thevenin Equivalent

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Suitable for serving load circuits of the type indicated.

Two-wire, single-phase.
Three-wire, three phase.

Footnote ⑥

---

Grounding equipment required for this method of grounding ④.

Neutral resistor for wye systems. Neutral resistor and grounding transformers for delta systems ⑤.

---

First cost, relative to a solidly grounded neutral system with phase relaying only.

Higher, because of neutral resistor, and because sensitive ground fault relaying is necessary to insure that no ground faults remain unremoved.

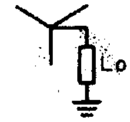
---

Current for bolted line-to-ground fault, in percent of bolted three-phase rms fault current, for terminal fault at supply point.

20 percent and downward to 1000 ampere. Installations with special safety requirements against shock hazard, such as mine power systems, may go as low as 25 amperes.

* Not yet defined quantitatively. See entry for "Current for bolted line-to-ground fault . . ." for range of resistor current values.

For footnotes see Page 33.



Probable level ② of sustained single-phase line-to-line arcing fault current, in percent of three-phase bolted fault value.

Value is function of system voltage as well as of arc and restrike voltage values. For particular conditions, calculated values are:

| System Volts | Fault Current, Percent ③ | Arc Volts | Restrike Volts |
|---|---|---|---|
| 208 | 2 | 275 | 275 |
| 480 | 74 | 275 | 375 |
| 600 | 85 | 275 | 375 |

---

Probability of sustained arcing for line-to-line fault on single-phase circuit extension (no escalation to three-phase fault).

208-volt systems—small probabilty, but sustained arcing can occur.
480-, 600-volt systems—high probability; in the order of 1.0.

---

Rms current② for sustained single-phase line-to-ground arcing fault in percent of bolted line-to-ground fault values.

Based on 140 1-1/1-1 volt arc and 375 volt restrike voltages.
208 V—*
480 V—*
600 V—*

---

Shock hazard, phase-to-ground, for
(a) No ground fault.
(b) Ground fault on phase conductor.

(a) Phase-to-neutral voltage from each phase to ground.
(b) Approximately line-to-line voltage on two phases.

### Advantages in Relation to:

Control of transient and steady-state overvoltages from neutral to ground.

The low-resistance grounded neutral system effectively controls to safe levels the overvoltages generated in the power system by resonant capacitive-inductive circuits, static charges, and restriking ground faults. It may not control certain steady-state overvoltages arising from physical contact with a higher voltage system, from autotransformer extended winding failures, or from faulty series capacitor-welder circuits ⑦.

---

Automatic tripping by phase and/or ground overcurrent devices for the first ground fault.

System is designed to provide automatic tripping by ground overcurrent devices for first ground fault. Phase overcurrent devices may also operate, depending on their ratings relative to the resistance-limited fault current. To many power system operators fast tripping on ground faults, which limits fault damage and prevents equipment burndown, is advantageous to system service reliability.

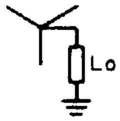
---

Ease of discrimination between an arcing line-to-line or line-to-ground fault and normal system load current.

Required use of sensitive zero-sequence type relaying permits prompt discrimination between low-level ground faults and normal load currents. Line-to-line arcing faults usually involve ground quickly. Thus ground relays minimize the possibility of arcing-fault burndowns.

* Currently under examination.

For footnotes see Page 33.




| | |
|---|---|
| Safety hazard, for ground faults in directly connected control circuits using line-to-line rated voltage contactor coils. | Less than line-to-neutral voltage appears on contactor coil. Motor will not start. |
| Shock hazard, from neutral to ground, during line-to-ground fault. | Essentially zero shock hazard, since the neutral is not run with the phase conductors. |
| Difficulty of locating the first line-to-ground fault. | Usually not difficult. The smaller circuit phase overcurrent devices will provide self-isolation. The larger circuits must be equipped with ground-fault relaying and will provide rapid fault isolation. Noise, smoke, and flash during fault aid in pinpointing fault site. |

**Disadvantages in Relation to:**

| | |
|---|---|
| Probability of sustained arcing for line-to-ground fault on single-phase circuit extension (no escalation). | 208-volt systems—small probability; near zero.*<br>408-, 600-volt systems—high probability; in the order of 1.0. |
| Probability of escalation of single-phase line-to-ground arcing fault into line-to-line or three-phase arcing fault (in bare bus system). | High probability, in the order of 1.0, particularly for 480- and 600-volt systems. |
| Shock hazard, phase-to-ground, resulting from fault-path contact with a higher voltage system. | May be as high as normal line-to-neutral voltage on the primary system[7]. |
| Safety hazard arising from ground faults in directly connected control circuits, using line-to-line rated voltage contactor coils. | Pushing "start" button with ground fault on control circuit will permit line-to-ground fault current to flow through push button, causing momentary personnel hazard until protective device operates. |
| Effect of delayed removal of line-to-ground fault on system (no escalation). | Continuing presence of a ground fault could cause burndown or serious damage of equipment, but ground fault relaying required by this system of grounding should avoid this situation. |
| Cost of system maintenance. | May be higher than for solidly grounded system, because of shortened insulation life arising from certain types of overvoltage not effectively controlled by this method of system grounding. |
| Flash hazard to personnel, arising from accidental line-to-ground fault (no escalation). | Serious flash hazard, but less severe than on solidly grounded neutral system. Reduction in hazard is proportional to reduction in bolted line-to-ground fault current. Escalation, which is probable in bare bus system, would cancel any reduction in line-to-ground fault flash hazard. |

* Not to be construed as being dependably self-extinguishing.

For footnotes see Page 33.


**Typical Area of Application**

The low-resistance grounded neutral system to date has been used largely in special situations, such as mine power systems, where extraordinary protection against shock hazard on portable equipment is required.

Although the reduction in burning damage and in flash hazard offered by this type of system grounding is significant, it has been infrequently applied in general industrial and commercial building service. In the latter instance the unsuitability of this type of system to serve four-wire three-phase loads has been responsible for its not being used. For general industrial service the application of this system grounding method has been hampered by the lack of sensitive, small, inexpensive ground-fault detectors which can be applied to circuit interrupters on branch circuits and small feeder circuits. Adequate ground-fault protective devices for the larger circuit interrupters on load center substations and distribution switchboards have been available, but not for the smaller circuit interrupters. Consequently, a completely selective operation for ground faults in low-resistance grounded neutral systems would be difficult to achieve economically. Hence applications in general industry have been of the solidly grounded neutral system, to secure maximum probability of selectivity in operation.

It is to be expected that the development of small, sensitive, inexpensive ground-fault protective devices which are compatible with currently available circuit protective devices for low-rated circuits will result in the increased use of low-resistance grounded neutral power systems.

**General Remarks**

The low-resistance grounded neutral system, when augmented with sensitive ground fault relaying, will provide most of the benefits of solid neutral grounding, plus reduced damage at the fault point, decreased flash hazard, and lower voltage dip on the occurrence of a ground fault.

With this type of system neutral grounding the current under ground fault conditions may be severely limited in comparison with the solidly grounded neutral system, making detection of such faults by the larger phase overcurrent devices either impossible or very long delayed. Since a ground fault unremoved from the system will likely cause severe damage or even burndown, the low-resistance grounded neutral system requires the use of ground fault relaying to make its application practicable.

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# THE HIGH-RESISTANCE GROUNDED NEUTRAL SYSTEM

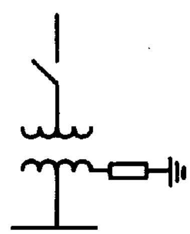
**Characteristic Features:**

Definition

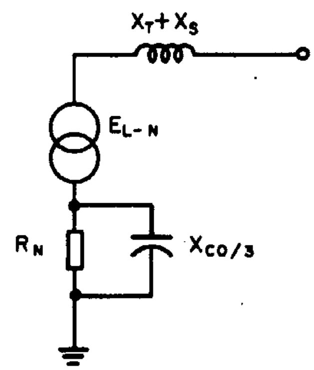
The high-resistance grounded neutral system is one in which a high value resistor has been inserted in the neutral connection to ground to limit the resistor current under ground-fault conditions to a value not less than the total system charging current, resulting in a total ground fault current of approximately $\sqrt{2}$ times the charging current. An objective of high-resistance grounding is to avoid automatic tripping of the faulty circuit for the first ground fault.

---

Circuit schematic and Thevenin line-to-ground equivalent circuit diagram.



Circuit




Thevenin Equivalent

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Suitable for serving load circuits of the type indicated.

Two-wire, single-phase
Three-wire, three-phase
Footnote [4]

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Grounding equipment required for this method of grounding [1].

Neutral resistor for wye systems. Neutral resistor and grounding transformer for delta systems [5]. Ground fault indication, which is recommended, requires relay and indicating lights or alarm.

---

First cost, relative to a solidly grounded neutral system with phase relaying only.

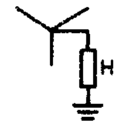
Higher, because of neutral resistor and ground fault indicating equipment.

---

Current for bolted line-to-ground fault, for terminal fault at supply point.

Determined by neutral resistor ohmic value, but should not be less than $\sqrt{2}$ times system charging current ($3E_{LN}/X_{co}$); generally less than 1 ampere. System charging current rarely exceeds 5 amperes, except on systems having surge capacitors.

For footnotes see Page 33.




Probable level[2] of sustained single-phase line-to-line arcing fault current, in percent of three-phase bolted fault value.

Value is function of system voltage as well as of arc and restrike voltage values. For particular conditions calculated values are:

| System Volts | Fault Current, Percent[3] | Arc Volts | Restrike Volts |
|---|---|---|---|
| 208 | 2 | 275 | 275 |
| 480 | 74 | 275 | 375 |
| 600 | 85 | 275 | 375 |

Probability of sustained arcing for line-to-line fault on single-phase circuit (no escalation to three-phase fault).

208-volt systems—small probability, but sustained arcing can occur.
480-, 600-volt system—high probability; in the order of 1.0.

Shock hazard, phase-to-ground, for
(a) No ground fault.
(b) Ground fault on phase conductor.

(a) Phase-to-neutral voltage from each phase to ground.
(b) Approximately line-to-line voltage on two phases.

**Advantages in Relation to:**

Control of transient and steady-state overvoltages from neutral to ground.

The high-resistance grounded neutral system effectively controls to safe levels the overvoltages generated in the power system by resonant capacitive-inductive circuits, static charges, and repetitive restrike ground faults. It does not control certain steady-state overvoltages such as those arising from physical contact with a higher voltage system, from autotransformer extended winding failures, or from faulty series capacitor-welder circuits.

Probability of sustained arcing for line-to-ground fault on single-phase circuit extension (no escalation).

Extremely low probability, near zero. Arcing line-to-ground fault would be difficult to initiate and would very likely be self-extinguishing.

Rms current value for sustained single-phase line-to-ground arcing fault.

Very low current value, if fault could be sustained. Single phase line-to-ground arcing fault in high resistance grounded neutral system would likely be self-extinguishing.

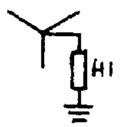
Probability of escalation of single-phase line-to-ground arcing fault into line-to-line or three-phase arcing fault, in bare bus system.

Very small probability. Escalation probability would be prominently influenced by closeness of phase conductors.

Automatic tripping by phase overcurrent devices for the first ground fault.

No automatic tripping for the first ground fault occurs, provided a second line-to-ground fault on another phase does not occur before the first one is removed. The faulty circuit continues in operation; in certain process industries and conditions of service this procedure is considered necessary and advantageous.

For footnotes see Page 33.




| | |
|---|---|
| Safety hazard, for ground faults in directly connected control circuits using line-to-line rated voltage contactor coils. | Less than line-to-neutral voltage appears on contactor coil. Motor will not start. |
| Shock hazard from neutral to ground, during line-to-ground fault. | Essentially zero shock hazard, since the neutral is not run with the phase conductors. |
| Flash hazard to personnel arising from accidental line-to-ground fault (no escalation). | Basically no flash hazard exists, unless the system has an unremoved ground fault on another phase. This could result in a double line-to-ground fault with serious flash hazard. |

#### Disadvantages in Relation to:

| | |
|---|---|
| Shock hazard, phase-to-ground, resulting from fault-path contact with a higher voltage system. | May be as high as normal line-to-neutral voltage on the primary system. |
| Ease of discrimination between line-to-ground or line-to-line arcing faults and normal system load currents. | Line-to-ground arcing faults are indistinguishable from load currents, but are very likely to be self-extinguishing. Arcing line-to-line faults would usually cause tripping of phase-overcurrent devices. At times their current level may be so low, however, as to go undetected and cause equipment burndown. |
| Effect of delayed removal of line-to-ground fault on the system (no escalation to line-to-line fault). | All unremoved ground faults put greater than normal voltage on the system's insulation. System continues in operation, but with continued damage at the point of fault. While this damage is greatly limited, in a relative sense, its prolongation in equipment with multi-turn coils may cause eventual turn-to turn or phase-to-phase failures and result in severe damage, requiring motor restacking and/or rewinding. |
| Difficulty of locating the first line-to-ground fault. | Frequently as difficult as for the ungrounded system. May require many hours and repeated shutdown of faulty zone equipment. Special fault-locating equipment can facilitate pinpointing the fault site. |
| Cost of system maintenance. | Will be somewhat higher than for the solidly grounded neutral system because of the adverse effect of greater than normal voltage (during presence of ground fault) on insulation life and because locating ground faults increases maintenance costs. |

#### Typical Area of Application

The high-resistance grounded neutral system has been applied in the process industries and in other situations where control of transient overvoltages is desired but an immediate service interruption on the first ground fault is to be avoided. In these instances the objective is to prevent a disorderly shutdown of equipment which might result in severe financial losses, or hazards to personnel or equipment. A collateral benefit lies in the virtual elimination of personnel flash hazard arising from accidental faults to ground.

**General Remarks**

The underlying reasons for the application of high-resistance neutral grounding (see typical Area of Application) are the same as those for the use of an ungrounded system, except that transient overvoltage control is also a prime objective when employing the resistance method of grounding. Any advantages to the power system user which exist in the ungrounded method of operation may also be secured, along with transient overvoltage control, when using the high-resistance grounded neutral system.

In comparison to the solidly grounded neutral system during ground faults, high-resistance grounding affords essentially zero flash hazard, arc blast and voltage dip during ground faults, provided simultaneous ground faults on different phases do not occur. The difficulty of locating ground faults on this system, however, increases the probability of a second ground fault shutting down two circuits simultaneously.

Since unremoved ground faults in this type of system continue to liberate energy at the fault point which may eventually cause further breakdown in the insulation system, it is essential to monitor the high resistance grounded neutral system for ground faults and to remove them with all possible expediency. Furthermore, while a ground fault remains on this system it loses its original characteristics and becomes essentially a "corner-of-the-delta" grounded system with serious flash hazard, arc blast, voltage dip, and the probability of fault escalation should a second ground fault occur.

As the neutral point is elevated to essentially normal line-to-neutral voltage above earth during a ground fault, this grounding method is not suited to 4-wire 3-phase systems with line-to-neutral connected loads.

# THE HIGH-RESISTANCE GROUNDED NEUTRAL SYSTEM WITH TRACEABLE SIGNAL TO FAULT

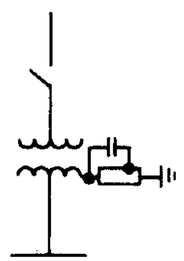
**Characteristic Features:**

**Definition**

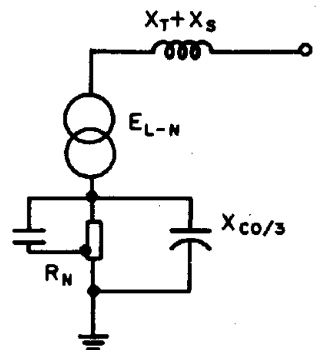
The high-resistance grounded neutral system with traceable signal to fault, is one in which a high-value resistor has been inserted in the neutral connection to ground to limit the resistor current under ground-fault conditions to a value not less than the total system charging current, resulting in a total ground fault current of approximately $\sqrt{2}$ times the charging current. An objective of this type of grounding is to avoid tripping of the faulty circuit for the first ground fault. In addition this system is equipped with ground-fault indicators and a means of pulsing a traceable signal onto a grounded phase to aid in rapid location of system faults to ground while the system is energized.

---

**Circuit schematic and Thevenin line-to-ground equivalent circuit diagram.**



Circuit




Thevenin Equivalent.

---

**Suitable for serving load circuits of the type indicated.**

Two-wire, single-phase.
Three-wire, three-phase.
Footnote ⑥.

---

**Grounding equipment required for this method of grounding④.**

Neutral resistor for wye systems. Neutral resistor and grounding transformer for delta systems⑤. Ground fault indicating equipment, plus signal pulsing and tracing equipment are required for either wye or delta system arrangements.

---

**First cost, relative to a solidly grounded neutral system with phase relaying only.**

Higher, because of neutral resistor and ground fault indicating, pulsing and tracing equipment.

---

**Current for bolted line-to-ground fault, for terminal fault at supply point.**

Determined by neutral resistor ohmic value, but should not be less than $\sqrt{2}$ times system charging current ($3E_{LN}/X_{co}$); generally less than 1 ampere. System charging current rarely exceeds 5 amperes, except on systems having surge capacitors. The pulsing current used for fault tracing may be two or more times the normal ground fault current.

For footnotes see Page 33.

Probable level[2] of sustained single-phase line-to-line arcing fault current, in percent of three-phase bolted fault value.

Value is function of system voltage as well as of arc and restrike voltage values. For particular conditions, calculated values are:

| System Volts | Fault Current, Percent[3] | Arc Volts | Restrike Volts |
|---|---|---|---|
| 208 | 2 | 275 | 275 |
| 408 | 74 | 275 | 375 |
| 600 | 85 | 275 | 375 |

---

Probability of sustained arcing for line-to-line fault on single-phase circuit extension (no escalation to three-phase fault).

208-volt systems—small probability, but sustained arcing can occur.
480-, 600-volt systems—high probability; in the order of 1.0.

---

Shock hazard, phase-to-ground for

(a) No ground fault.
(b) Ground fault on phase conductor.

(a) Phase-to-neutral voltage from each phase-to-ground.
(b) Approximately line-to-line voltage on two phases.

### Advantages in Relation to:

Control of transient and steady-state overvoltages from neutral to ground.

The high-resistance grounded neutral system effectively controls to safe levels the overvoltages generated in the power system by resonant capacitive-inductive circuits, static charges, and restriking ground faults. It does not control certain steady-state overvoltages such as those arising from physical contact with a higher voltage system, from autotransformer extended winding failures, or from faulty series capacitor-welder circuits.

---

Probability of sustained arcing for line-to-ground fault on single-phase circuit extension (no escalation).

Extremely low probability, near zero. Arcing line-to-ground fault would be difficult to initiate and would very likely be self-extinguishing.

---

Rms current value for sustained single-phase line-to-ground arcing fault.

Very low current value, if fault could be sustained. Single-phase line-to-ground arcing fault in high-resistance grounded neutral system would likely be self-extinguishing.

---

Probability of escalation of single-phase line-to-ground arcing fault into line-to-line or three-phase arcing fault, in bare bus system.

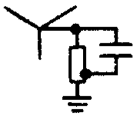
Very small probability. Escalation probability would be prominently influenced by closeness of phase conductors.

---

Automatic tripping by phase overcurrent devices for the first ground fault.

No automatic tripping for the first ground fault occurs provided a second line-to-ground fault on another phase does not occur before the first one is removed. The faulty circuit continues in operation; in certain process industries and conditions of service this procedure is considered necessary and advantageous.

For footnotes see Page 33.



| | |
|---|---|
| Safety hazard, for ground faults in directly connected control circuits using line-to-line rated voltage contactor coils. | Less than line-to-neutral voltage appears on contactor coil. Motor will not start. |
| Shock hazard, from neutral-to-ground, during line-to-ground fault. | Essentially zero shock hazard, since the neutral is not run with the phase conductors. |
| Flash hazard to personnel arising from accidental line-to-ground fault (no escalation). | Basically no flash hazard exists, unless the system has an unremoved ground fault on another phase. This could result in a double line-to-ground fault with serious flash hazard. |
| Difficulty of locating the first line-to-ground fault. | Very little difficulty. Pulsed signal aids in locating fault with system energized, but some skill in use of tracing equipment is required. |
| Cost of system maintenance. | Approximately the same as solid grounding. Tracing ground faults adds cost, and insulation life is reduced by unremoved ground faults, but fault damage arising from ground faults is reduced. |

### Disadvantages in Relation to:

| | |
|---|---|
| Shock hazard, phase-to-ground, resulting from fault-path contact with a higher voltage system. | May be as high as normal line-to-neutral voltage on the primary system. |
| Ease of discrimination between line-to-ground or line-to-line arcing faults and normal system load currents. | Line-to-ground arcing faults are indistinguishable from load currents, but are very likely to be self-extinguishing. Arcing line-to-line faults would usually cause tripping of phase-overcurrent devices. At times their current level may be so low, however, as to go undetected and cause equipment burndown. |
| Effect of delayed removal of line-to-ground fault on the system (no escalation to line-to-line fault). | All unremoved ground faults put greater than normal voltage on the system's insulation. System continues in operation, but with continued damage at the point of fault. While this damage is greatly limited, in a relative sense, its prolongation in equipment with multi-turn coils may cause eventual turn-to-turn or phase-to-phase failures and result in severe damage, requiring motor restacking and/or rewinding. This possibility is minimized by the use of ground fault tracing equipment, which facilitates locating the fault site and helps to lessen the time that the ground fault remains on the system. |

**Typical Area of Application**

The high-resistance grounded neutral system with tracing pulse has been applied in the process industries and in other situations where control of transient overvoltages, coupled with a reduction in flash hazard, is desired but where an immediate service interruption on the first ground fault is to be avoided, and a means of subsequently tracing the fault location with the system energized is wanted. The objectives in these instances are to prevent a disorderly shutdown of equipment which might result in severe financial losses or hazards to personnel or equipment, and to minimize personnel injuries from arc flash during accidental line-to-ground faults.

**General Remarks**

The fundamental objectives in the use of the high-resistance grounded neutral system with a fault-tracing pulse are several: The avoidance of an immediate service interruption on the occasion of the first ground fault, the minimizing of flash hazard to personnel arising from accidental ground faults in equipment, a substantial reduction in the risk of equipment burndown arising from ground faults, and the ability to trace the location of a ground fault without de-energizing the system. An additional benefit is a reduction in voltage dip during ground faults, provided simultaneous ground faults on different phases are not encountered.

The facility of quickly locating ground faults with the pulsing and tracing equipment on this system tends to lessen the probability of a second ground fault shutting down two circuits simultaneously.

Since unremoved ground faults in this type of system continue to liberate energy at the fault point which may eventually cause further breakdown in the insulation system, it is essential to monitor the high-resistance grounded neutral system for ground faults, to trace them promptly with the fault locating equipment, and to remove them with all possible expediency. While a ground fault remains on this system it loses its original characteristics and becomes essentially a "corner-of-the delta" grounded system, with serious flash hazard, arc blast, voltage dip and the probability of fault escalation should a second ground fault occur.

As the neutral point is elevated to essentially normal line-to-neutral voltage above earth during a ground fault, this grounding method is not suited to 4-wire, three-phase systems with line-to-neutral connected loads.

# CORNER-OF-THE-DELTA GROUNDED SYSTEM

**Characteristic Features:**

Definition

The corner-of-the-delta grounded system is one in which an identified phase conductor is directly grounded through an adequate ground connection in which no impedance has been inserted intentionally.

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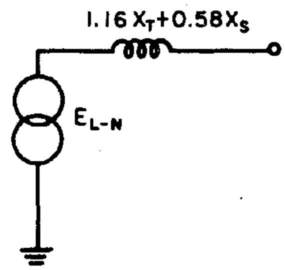
Circuit schematic and Thevenin line-to-ground equivalent circuit diagram.

Circuit




Thevenin Equivalent

---

Suitable for serving load circuits of the character indicated.

Two-wire, single-phase.
Two-wire, single-phase, 1-side grounded.
Three-wire, three-phase.

---

Grounding equipment required for this method of grounding④.

None, but grounded-phase identification is necessary throughout the system.

---

First cost, relative to a solidly grounded neutral system with phase relaying only.

Approximately the same, as wye and delta transformers cost about the same.

---

Current for bolted line-to-ground fault, in percent of three-phase rms fault current, for terminal fault at supply point.

Varies; may be as high as 87%.

---

Probable level④ of sustained single-phase line-to-line arcing fault current, in percent of bolted three-phase fault value.

Value is function of system voltage as well as of arc and restrike values. For particular conditions, calculated values are:

| System Volts | Fault Current, Percent③ | Arc Volts | Restrike Volts |
|---|---|---|---|
| 208 | 2* | 275 | 275 |
| 480 | 74 | 275 | 375 |
| 600 | 85 | 275 | 375 |

* Corner-of-the-delta grounding is not likely on 208-volt systems, but value is given to permit estimating current for 240-volt systems, for which calculations were not made.

For footnotes see Page 33.

| | |
|---|---|
| Probability of sustained arcing for line-to-line fault on single-phase circuit extension (no escalation to three-phase fault). | 208-volt systems—small probability, but sustained arcing can occur.<br>480-, 600-volt systems—high probability; in the order of 1.0. |
| Rms current② for sustained single-phase line-to-ground arcing fault, in percent of three-phase bolted fault value. | Based on 275 volt arc and restrike voltages of 275 volts (208-volt system) or 375 volts (480-, 600-volt systems)<br>208 V— 2 percent③*<br>480 V—74 percent<br>600 V—85 percent |
| Probability of escalation of single-phase line-to-ground arcing fault into three-phase arcing fault (in bare bus system). | Probability is high, but fault starts as line-to-line fault and escalation to 3-phase fault produces only moderate current increase. |
| Shock hazard, phase-to-ground, for<br>(a) No ground fault.<br>(b) Ground fault on phase conductor. | (a) Line-to-line voltage on two phases.<br>(b) Line-to-line voltage on unfaulted phase, zero volts on others. |
| Control of transient and steady-state overvoltages from neutral to ground. | The corner-of-the-delta grounded system effectively controls to safe levels the overvoltages which become impressed on or self-generated in the power system by insulation breakdowns, resonant inductive-capacitive circuits, restriking ground faults, etc. It continuously impresses, however, 1.73 times normal line-to-neutral voltage between two conductors and ground. |
| Automatic tripping by phase and/or ground overcurrent devices for the first line-to-ground fault. | System is designed to provide automatic tripping by phase devices for the first ground fault. For very low level arcing faults to ground the application of sensitive ground fault relays will help assure disconnection of the faulty circuit before burndown can occur. In many industries and conditions of service this rapid protection of equipment, service, and personnel is necessary and desirable. |
| Ease of discrimination between arcing line-to-line or line-to-ground fault and normal system load current. | Usual levels of arcing faults will cause tripping of phase devices. Line-to-line arcing faults usually involve ground quickly. Thus use of ground fault relays permits prompt discrimination between low-level arcing faults and normal load currents, minimizing the possibility of arcing-fault burndown. |
| Shock hazard, phase-to-ground, resulting from fault-path contact with a higher voltage system. | Limited to secondary line-to-line voltage, approximately. |
| Shock hazard, from neutral-to-ground during line-to-ground fault. | Essentially no hazard, since neutral of system voltage triangle is not normally run with this system. |

* Value for 208-volt system is given to permit estimating current for 240-volt corner-of-the-delta grounding systems, for which calculations were not made.

For footnotes see Page 33.

| | |
|---|---|
| Difficulty of locating the first ground fault. | Generally not difficult. Fault is usually self-isolating via phase overcurrent device operation, but ground fault relaying may be advisable to isolate low-level faults on high current circuits. Noise, smoke, and flash during fault aid in pinpointing fault site. |
| **Disadvantages in Relation to:** | |
| Probability of sustained arcing for line-to-ground fault on single-phase circuit extension (no escalation). | 240-volt systems—small probability.* 480-, 600-volt systems—high probability; in the order of 1.0. |
| Safety hazard, for ground faults in directly connected control circuits using line-to-line rated voltage contactor coils. | Pushing the "start" button with a ground fault in the control circuit may permit line-to-line fault current to flow through the push button, causing a momentary personnel hazard until the protective device operates. On properly wired control circuits an accidental ground will not start the motor or prevent its shutdown if running. |
| Effect of delayed removal of line-to-ground fault on system (no escalation). | Continuing low-level arcing fault to ground may result in equipment burndown and delayed restoration of service. |
| Flash hazard to personnel arising from accidental line-to-ground fault (no escalation). | Severe flash hazard, equivalent to arcing line-to-line fault, for accidental ground on a "hot phase." |
| Cost of system maintenance. | Somewhat above that for the solid neutral grounding method, because of 73 percent higher insulation stress on two phases. Ground faults are easily located. |

**Typical Area of Application**

The corner-of-the-delta method of grounding is not widely used in industrial systems. Its application generally has been made only in delta systems⑤ where the benefits of a grounded system are desired to be secured at minimum cost.

**General Remarks**

For new systems the corner-of-the delta grounding method offers no special advantages, since the solidly grounded neutral system provides the same and additional benefits at the same or less cost, and without many of the disadvantages of corner-of-the-delta grounding.

This method of grounding requires positive identification of the grounded phase throughout the distribution system. In addition, all instrumentation, metering and motor overload relays must be connected to the "hot" phases to avoid having accidental grounds upset their registration or operation. A ground fault on the grounded conductor cannot be readily detected but will result in stray ground currents even in the absence of additional faults on the system.

* Not to be construed as being dependably self-extinguishing.

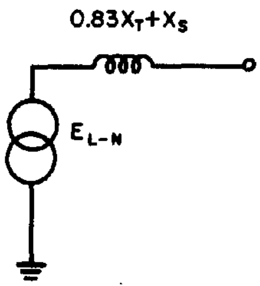
# THE MID-PHASE GROUNDED SYSTEM

## Characteristic Features

| | |
|---|---|
| Definition | The mid-phase grounded system is a delta system in which the mid-point of one phase of the supply transformer has been tapped and solidly grounded. |

Circuit schematic and Thevenin line-to ground equivalent circuit diagram.

Circuit




Thevenin Equivalent

| | |
|---|---|
| Suitable for serving load circuits of the type indicated. | Two-wire, single-phase.<br>Two-wire, single-phase, 1-side grounded.<br>Three-wire, single-phase, mid-phase grounded.<br>Three-wire, three-phase. |
| Grounding equipment required for this method of grounding ④. | None, but the mid-point of one phase of the power source must be available, and the highest voltage conductor must be identified at any point where a connection is to be made. |
| First cost, relative to a solidly grounded neutral system with phase relaying only. | Approximately the same. |
| Current for bolted line-to-ground fault in percent of three-phase rms current, for terminal fault at supply point. | Varies; may be as high as 120 percent. |
| Probable level② of sustained single-phase line-to-line arcing fault current in percent of bolted three-phase fault value. | Value is function of system voltage as well as of arc and re-strike voltage values. For particular conditions calculated vaues are: |

| System Volts | Fault Current, Percent③ | Arc Volts | Restrike Volts |
|---|---|---|---|
| 208 | 2* | 275 | 275 |
| 480 | 74 | 275 | 375 |
| 600 | 85 | 275 | 375 |

* Mid-phase grounding is not likely on 208-volt systems, but value is given to permit estimating for 240-volt systems, for which calculations were not made.

For footnotes see Page 33.

| | |
|---|---|
| Probability of sustained arcing for line-to-line fault on single-phase circuit (no escalation to three-phase fault). | 240-volt systems—small probability, but sustained arcing can occur.<br>480-, 600-volt systems—high probability; in the order of 1.0. |
| Rms current[2] for sustained single-phase line-to-ground arcing fault, in percent of bolted three-phase fault value. | Based on 275 volt arc and restrike voltages of 275 volts (208-volt system) or 375 volts (480-, 600-volt system).*<br>240 V— 2 percent.<br>480 V—64 percent.<br>600 V—74 percent. |
| Probability of escalation of single-phase line-to-ground fault into three-phase arcing fault (in bare bus system). | Probability is high, but fault starts as relatively high level line-to-mid-phase fault, and escalation to three-phase fault produces only moderate increase in fault current. |
| Shock hazard, phase-to-ground, for<br>(a) No ground fault.<br>(b) Ground fault on phase conductor. | <br>(a) 1.5 times line-to-neutral (geometric) voltage on one phase; .87 times line-to-neutral on other two phases.<br>(b) .87 times line-to-neutral voltage on one phase; line-to-line volts on the other. |
| **Advantages in Relation to:**<br>Control of transient and steady-state overvoltages from neutral-to-ground. | Mid-phase grounding effectively controls to safe levels the overvoltages which become impressed on or self-generated in the power system by insulation breakdowns, resonant capacitive-inductive circuits, restriking ground faults, etc. It continuously impresses, however, 1.5 times normal line-to-neutral voltage between one conductor and ground. |
| Automatic tripping by phase and/or ground overcurrent devices for the first line-to-ground fault. | System is designed to provide automatic tripping by phase devices on the first ground fault. For very low-level arcing faults to ground the application of sensitive ground fault relays will help assure disconnection of the faulty circuit before burndown can occur. In many industries and conditions of service this rapid protection of equipment, service, and personnel is necessary and desirable. |
| Ease of discrimination between arcing line-to-line or line-to-ground fault and normal system load current. | Usual levels of arcing faults will cause tripping of phase devices. Line-to-line arcing faults usually involve ground quickly. Thus use of ground-fault relays permits prompt discrimination between low-level arcing faults and normal load currents, minimizing the possibility of arcing fault burndowns. |
| Shock hazard, phase-to-ground, resulting from fault-path contact with a higher voltage system. | Limited to .87 times secondary line-to-line voltage, approximately. |
| Shock hazard, from neutral-to-ground during line-to-ground fault. | Essentially no hazard, since neutral of system voltage triangle is not normally run with this system. |

* Tabulated values are estimates based on line-to-line fault calculations for 208-, 480- and 600-volt systems.

For footnotes see Page 33.

| | |
|---|---|
| Difficulty of locating the first ground fault. | Generally not difficult. Fault is usually self-isolating via phase overcurrent device operation, but ground fault relaying may be advisable to isolate very low-level faults on high current circuits. Noise, smoke, and flash during fault aid in pinpointing fault site. |

**Disadvantages in Relation to:**

| | |
|---|---|
| Probability of sustained arcing for line-to-ground fault on single-phase circuit extension (no escalation). | 240-volt systems—small probability.* 480-, 600-volt systems—high probability; in the order of 1.0. |
| Safety hazard, for ground faults in directly connected control circuits using line-to-line rated voltage contactor coils. | Situation depends on how control is wired with respect to the "high" leg. In worst case approximately 87 percent of line-to-line voltage could appear on the contactor coil, causing a motor start. In other cases an accidental ground may create a hazard to personnel by causing a momentary short-circuit through the "start" button when it is pressed, or by preventing a running motor from being shut down by the "stop" button or by a safety contact. |
| Effect of delayed removal of line-to-ground fault on system (no escalation). | Continuing low-level arcing fault to ground may result in equipment burndown and delayed restoration of service. |
| Flash hazard to personnel arising from accidental line-to-ground fault (no escalation). | Serious flash hazard for accidental ground on any phase. |
| Cost of system maintenance. | Somewhat above that for the solid neutral grounding method, because of 50 percent higher insulation stress on one phase. Ground faults are easily located. |

**Typical Area of Application**

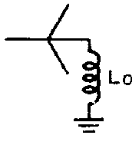
The mid-phase method of system grounding is infrequently used in industrial systems. Its application has been made largely in systems made up of banks of single-phase transformers with a mid-tap available.

**General Remarks**

For new systems the mid-phase grounding method offers no special advantages, since the solidly grounded neutral system provides the same and additional benefits at the same or less cost.

This method of grounding requires positive identification of the "hottest" phase throughout the system.

* Not to be construed as being dependably self-extinguishing.




# THE LOW-REACTANCE GROUNDED NEUTRAL SYSTEM

**Characteristic Features:**

Definition

The low-reactance grounded neutral system is one in which a low-value reactor has been inserted in the neutral connection to ground to limit the current under ground-fault conditions to a value not less than 25 percent nor more than 100 percent of the three-phase bolted fault value.

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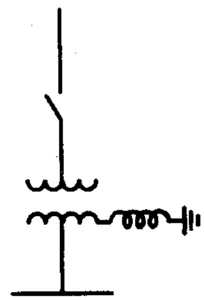
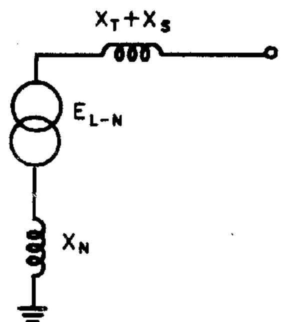
Circuit schematic and Thevenin line-to-ground equivalent circuit diagram.



Circuit




Thevenin Equivalent

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Suitable for serving load circuits of the type indicated.

Two-wire, single-phase.
Three-wire, three-phase.
Four-wire, three-phase.*

---

Grounding equipment required for this method of grounding④.

Neutral reactor is required.

---

First cost, relative to a solidly grounded neutral system with phase relaying only.

Higher, because of neutral reactor.

---

Current for bolted line-to-ground fault, in percent of bolted three-phase rms fault current, for terminal fault at supply point.

System is designed to produce current in the range 25–100 percent of three-phase value.

---

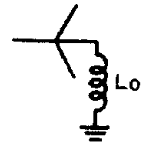
Probable level② of sustained single-phase line-to-line arcing fault current, in percent of three-phase bolted fault value.

Value is function of system voltage as well as of arc and restrike voltage values. For particular conditions, calculated values are:

| System Volts | Fault Current, Percent③ | Arc Vots | Restrike Volts |
|---|---|---|---|
| 208 | 2 | 275 | 275 |
| 480 | 74 | 275 | 375 |
| 600 | 85 | 275 | 375 |

* Only in exceptional cases, where ground fault current $\cong 100$ percent of three-phase bolted fault value and $X_N << X_O$, where $X_O$ = total system zero sequence reactance.

For footnotes see Page 33.



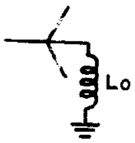

| | |
|---|---|
| Probability of sustained arcing for line-to-line fault on single-phase circuit extension (no escalation to three-phase fault). | 208-volt systems—small probability, but sustained arcing can occur.<br>480-, 600-volt systems—high probability; in the order of 1.0. |
| Rms current② for sustained single-phase line-to-ground arcing fault, in percent of bolted line-to-ground fault values. | Based on 140 1-1/1-1 volt arc and 375 1-1/1-1 volt restrike voltages—<br>208 V—*<br>480 V—*<br>600 V—* |
| Shock hazard, phase-to-ground, for<br>(a) No ground fault<br>(b) Ground fault on phase conductor. | (a) Phase-to-neutral voltage from each phase to ground.<br>(b) Varies; maximum would be approximately line-to-line voltage on two phases. |

### Advantages in Relation to:

| | |
|---|---|
| Control of transient and steady-state overvoltages from neutral to ground. | The low-reactance grounded neutral system effectively controls to safe levels the overvoltages generated in the power system by resonant capacitive-inductive circuits, static charges, and restriking ground faults. It may not control overvoltages arising from physical contact with certain higher voltage systems. |
| Automatic tripping by phase and/or ground overcurrent devices for the first ground fault. | System is designed to provide automatic tripping by ground overcurrent devices for the first ground fault. The phase overcurrent devices may also operate, depending on their ratings, relative to the reactance-limited fault current. To many power system operators, fast tripping on ground faults, which limits fault damage and prevents equipment burndown, is advantageous to system service reliability. |
| Ease of discrimination between an arcing line-to-line or line-to-ground fault and normal system load current. | Usual levels of arcing faults will cause tripping of phase devices. Use of zero-sequence type relaying will permit prompt discrimination between low-level ground faults and normal load currents. Line-to-line arcing faults usually involve ground quickly. Thus ground relays minimize the possibility of arcing-fault burndown. |
| Safety hazard, for ground faults in directly connected control circuits using line-to-line rated voltage contactor coils. | Less than line-to-neutral voltage appears on contactor coil. Motor start is not likely. |
| Difficulty of locating the first line-to-ground fault. | Generally not difficult. Fault is usually self-isolating via phase overcurrent device operation, but ground fault relaying is recommended to isolate low level faults on high current circuits. Noise, smoke, and flash during fault aid in pinpointing the fault site. |
| Cost of system maintenance. | Probably somewhat higher than for solid neutral grounding, because insulation may be subjected to higher than normal voltage stresses for certain fault conditions. |

For footnotes see Page 33.

* Currently under examination.




**Disadvantages in Relation to:**

| | |
|---|---|
| Probability of sustained arcing for line-to-ground fault on single-phase circuit extension (no escalation). | 208-volt systems—small probability.* 480-, 600-volt systems—high probability; in the order of 1.0. |
| Probability of escalation of single-phase arcing line-to-ground fault, into line-to-line or three-phase arcing fault (in bare bus system). | High probability, in the order of 1.0, particularly for 480- and 600-volt systems. |
| Shock hazard, phase-to-ground, resulting from fault-path contact with a higher voltage system. | May be as high as normal line-to-neutral voltage, approximately, on the higher voltage system. |
| Safety hazard, for ground faults in directly connected control circuits using line-to-line rated voltage contactor coils. | Pushing "start" button with ground fault in control circuit may permit line-to-ground fault current to flow through push button, causing momentary personnel hazard until the protective device operates. A motor already running may not drop out when the "stop" button is pressed, or protective contacts on energized equipment may be bypassed by an accidental ground, preventing equipment shutdown if safety limits are exceeded. |
| Effect of delayed removal of line-to-ground fault on system (no escalation). | Continuing presence of ground fault may result in equipment burndown and delayed restoration of service. |
| Flash hazard to personnel, arising from accidental line-to-ground fault (no escalation). | Severe flash hazard for ground fault on any phase. |

**Typical Area of Application**

The low-reactance method of system grounding is not very often used. It is basically designed for systems where the limited mechanical or electrical capability of equipment requires reducing ground-fault current. In particular it is applied to local generators at 600 volts or less to limit the ground fault current contribution of the generator to a value no greater than the bolted three-phase fault-contribution value.

**General Remarks**

To avoid transient overvoltages the low reactance neutral grounding method must not reduce ground fault current below 25 percent of the three-phase fault value. This is generally higher than the minimum fault current desired in a resistance grounded system and reactance grounding is therefore not usually considered an alternative to resistance grounding.

This type of system grounding may interfere with normal four-wire system operation if the ground fault current is limited to a value much below 100 percent of three-phase fault current.

* Not to be construed as being dependably self-extinguishing.

# FOOTNOTES

①On a line-to-neutral basis, $X_T$=reactance of source generator or transformer, $X_S$=low voltage distribution system reactance, $X_N$=reactance of grounding reactor, and $R_N$=resistance of grounding resistor. $X_{CO}$=system line-to-ground capacitive reactance, including surge capacitors, if present.

②These values are of interest to establish minimum sensitivity requirements for relaying. Even greater sensitivities are desirable to account for situations where the current is suppressed to lower values. The percentage figures in the tables are the calculated theoretical values for the system, arc and restrike voltages indicated. Actual fault current values may be greater or less than those calculated, because of differences in driving voltage, arc voltage and/or restrike voltage, and because of the influence of physical factors not included in the theoretical calculations.

③The low current value at 208 volts results from the relatively high arc voltage and restrike voltage used in the calculation. Experimental data and field reports indicate that arcing faults of much higher current value may be produced in 208-volt systems. The use of lower arc and restrike voltage values in the calculation would increase the calculated 208-volt current value.

④All grounded systems require a grounding electrode and common main grounding conductor as basic equipment for grounding the system.

⑤A "delta" system is one in which the neutral is not available. New systems should use wye-connected source, with the neutral brought out.

⑥While certain resistance- and reactance-grounded systems may meet the NEC requirement for a "grounded" system (NEC 250-51), they do not provide the limitation of voltage from phase-to-ground and from grounded conductor (neutral) to ground which are commonly expected of "grounded" systems. Therefore such impedance-grounded systems have not been indicated as suitable for serving single-phase load circuits with one-side grounded or four-wire, three-phase circuits.

⑦Use of recommended practices in the primary and secondary systems, such as 400 amp grounding at 13.8 kV and 1000 amp or higher at 600 volts and below, will avoid excessive overvoltage in the secondary system when physical contact with the primary system occurs. In such cases the secondary phase-to-ground voltages will not exceed those present during a line-to-ground fault in the secondary system. A high voltage-low voltage crossover will result in dangerous overvoltage on the low-voltage system if the high-voltage system is solidly grounded. 13.8 kV utility systems are frequently solidly grounded, and all higher voltage systems are almost always solidly grounded.

⑧The zero value at 208 volts results from the high restrike voltage used in the calculation. The use of a considerably lower restrike voltage would permit the calculation of a non-zero rms current value.

# APPENDIX

## PRINCIPAL METHODS OF LOW-VOLTAGE SYSTEM GROUNDING

The preceding material makes no recommendations for the application of specific system grounding methods, because this is dependent upon the particular system involved. As the introductory comments indicate, the "sales and/or application engineer is best qualified to consult with the customer and advise him on the choice of grounding method for his specific conditions and objectives."

From a practical viewpoint, however, it should be recognized that two methods of system grounding — the solidly grounded neutral and the high-resistance grounded neutral (with or without tracing pulse) methods—are those which are most frequently applied. Very often, the choice of a method of grounding comes down to a selection between these two methods. For that reason, it is appropriate to re-emphasize certain ideas and provide additional information regarding these particular grounding techniques, to aid in the selection process. Furthermore, the table on page 38 provides a useful quick reference for comparing the main features of these two grounding methods with one another and with the ungrounded system.

## SOLIDLY GROUNDED NEUTRAL SYSTEM

This system has the neutral point directly grounded through an adequate ground connection in which no impedance has been inserted intentionally. By proper selection and setting of its circuit protective devices, the solidly grounded neutral system is intended to provide automatic disconnection of faulty circuits on the occurrence of line-to-ground or line-to-line faults. Most often, in conventional practice, this automatic segregation of defective circuits is provided by the phase overcurrent devices. More and more, however, it is being recognized that this type of system may justify supplementary ground fault relaying to detect and remove low-level arcing faults to ground which, if unremoved, could cause extensive burndown of equipment. No instances are known of such burndowns having occurred on solidly grounded neutral systems equipped with sensitive ground fault relaying.

An important feature of the solidly grounded neutral system is that it has essentially zero shock hazard on the neutral conductor during a line-to-ground fault, and is thus satisfactory for serving four-wire three-phase distribution systems with line-to-neutral connected loads.

### Application Area

The solidly grounded neutral system has been applied most satisfactorily in general industrial and commercial power distribution systems (including those serving "critical" loads) where one or more of the following characteristics prevail:

1. Four-wire three-phase power service is required.
2. Automatic tripping for isolation and removal of ground faults is desirable and acceptable.
3. Maximum possible system insulation life is to be secured through effective control of transient and steady-state overvoltages.
4. Competent operating and maintenance personnel are not continuously available for tracing ground faults and scheduling their removal from the system with minimum deliberate delay.
5. There is an unusual possibility of a high voltage-low voltage crossover.

### Requirements for Securing Maximum Benefits

To secure the maximum in benefits from the use of a solidly grounded neutral system, the following items are essential:

1. Proper equipment grounding conductors installed to insure adequate ground fault current for tripping.
2. Properly set and maintained phase overcurrent protective devices.
3. Properly set and maintained ground fault protective devices where this requirement is not served by the phase devices.
4. Observance of the limitations of single-pole interrupters. (See GER-2253, "Application Limitations of Single-pole Interrupters in Polyphase Industrial and Commercial Building Power Systems," R. H. Kaufmann.)

The observance of the limitations of single-pole interrupters is necessary to prevent an undesirable reduction in fault current level during arcing line-to-ground or line-to-line fault conditions. Preventing such a reduction helps to assure prompt removal of these faults by ground- or phase-overcurrent protective devices.

## HIGH - RESISTANCE GROUNDED NEUTRAL SYSTEM

The neutral point of this system is connected to ground through an impedance, the principal element of which is resistance. Although an official definition is lacking, it is to be understood here that "high resistance grounding" implies the use of a neutral resistor which limits the resistor current during a bolted line-to-ground fault to not less than ($3I_{co}$), the total system charging current ($3E_{LN}/X_{co}$). Furthermore, in a well-designed high-resistance grounded system the resistor current under ground fault conditions will not be greatly in excess of the total system capacitive charging current to ground with the result that the total maximum current in a solid fault to ground will be approximately $\sqrt{2}$ times the neutral resistor current. Only very rarely, on systems having a great many surge capacitors, will the total ground fault current exceed 5 amperes when the neutral resistor is chosen as indicated; in general, the total fault current will be less than one ampere.

The high resistance grounded system generally is designed so that automatic segregation of the faulty circuit does **not** take place on the occurrence of the first ground fault. Thus when a ground fault occurs there is no immediate interruption of service, and loads on the faulty circuit are continued in operation. This is often a desirable operating characteristic for certain critical loads to permit an orderly shutdown and/or to avoid the severe financial penalty arising from loss of production or from contingent equipment damage following an unscheduled outage. It is imperative to get the first ground fault removed from high-resistance grounded systems as quickly as possible, however, because while the initial ground fault remains on, the occurrence of another ground fault will result in flash hazard to personnel and possibly in the shutdown of two circuits, instead of only one. Thus, the continued presence of a ground fault constitutes a substantial peril both to personnel and to system service continuity. Furthermore, in equipment with multi-turn coils turn-to-turn failure may follow, with possibly greater resultant damage than if the system were soldily grounded.

For the foregoing reasons any purchaser choosing a high-resistance grounded system should be alerted to the need for ground fault detection and alarm equipment, continuously available equipment and personnel for tracing and locating ground faults with the system energized, and operating instructions that require the removal of such faults with all the urgency that conditions permit.

### Application Area

The high-resistance grounded neutral system has been applied with the most favorable results in industrial systems—particularly in the process-type industries—where one or more of the following characteristics are prevalent:

1. Automatic tripping on the first ground fault is not desirable or acceptable.
2. The minimizing of ground-fault flash hazard for personnel is an objective.
3. A substantial reduction in the risk of equipment burndown arising from ground faults is desired.
4. Competent operating and maintenance personnel are available for promptly tracing ground faults and scheduling their removal with minimum deliberate delay.
5. 4-wire 3-phase service is **not** required.
6. Control of system transient overvoltages is required, but the avoidance of certain possible steady-state overvoltage conditions is of secondary importance to avoiding automatic tripping on the first ground fault.

### Requirements for Securing Maximum Benefits

The attainment of maximum benefits from the use of the high-resistance grounded neutral system is dependent on the following:

1. The selection of a grounding resistor to provide a resistor ground-fault current only slightly greater than the line-to-ground system charging current ($3E_{LN}/X_{co}$).
   This means the total ground fault current will be approximately $\sqrt{2}$ times the system charging current.
2. The application of procedures and fault-tracing equipment for quick detection, location, and removal of ground faults.*
3. The proper setting and maintenance of phase-overcurrent devices.
4. Consideration of the use of ground overcurrent protective devices for backup protection.
5. The installation of proper equipment grounding conductors.
6. The observance of the limitations of single-pole interrupters. (See GER-2253, "Application Limitations of Single-pole Interrupters in Polyphase Industrial and Commercial Building Power Systems," R. H. Kaufmann.)

The limitations of single-pole interrupters should be observed to avoid a reduction in fault current level during line-to-line fault conditions and during the existence of sequential-occurrence line-to-ground faults at different locations. This procedure facilitates the prompt removal of such faults by ground- or phase-overcurrent protective devices acting upon three-phase interrupters.

### Evaluation of These Alternative Grounding Methods

There are many possible criteria against which to measure the suitability of a particular method of system grounding. While nontechnical factors, such as the need to minimize the disorderly shutdown of certain critical loads, may be the predominant influence in the choice of a grounding method, it is appropriate to weigh other factors in the process of making a decision. Among these other factors the following are particularly important:

1. Control of Overvoltages.
   The sources of overvoltage which may occur on a power distribution system are many. Inasmuch as the method of system grounding may be effective in relieving such overvoltages, the most significant are (see Industrial Power Systems Data Book, Section .22):
   A. Physical contact with a higher voltage system.
   B. Resonance in series inductive-capacitive circuits.
   C. Repetitive restrike (intermittent ground faults).
   D. Autotransformer connections.

   The solidly grounded neutral system effectively controls to safe levels the overvoltages which tend to be impressed on or self-generated in the power system by the above situations. The high-resistance grounded system, on the other hand, is able to effectively control to acceptable levels only the overvoltages in categories B. and C. above. Overvoltages arising from physical contact with higher voltage systems, from faults in systems interconnected with an ungrounded autotransformer, or from autotransformer extended winding failures, are not satisfactorily controlled by the high-resistance grounded system.
2. Shock Hazard.
   Serious, perhaps lethal, electrical shock caused by accidental contact with energized phase conductors is a hazard common to almost all power distribution systems, grounded as well as ungrounded. Since the human body presents a relatively high impedance fault-to-ground, only extremely sensitive ground fault detection, coupled with very rapid fault isolation and near-perfect dependability, can significantly improve the present incidence of injuries or deaths attributable to such contacts. Unfortunately, detector-interrupter combinations of the required sensitivity and speed are presently applicable only in the smallest of power systems—as in residential or pool-side service—and are not currently practical in industrial and commercial power systems. Thus avoidance of injury or death from shock in these systems is essentially a matter of avoiding working on energized equipment, the observance of safe work habits, the proper maintenance and repair of equipment, and the installation of an adequate grounding network. Despite these measures, however, accidental contact with energized conductors or with the frames or enclosures of faulted equipment or circuits improperly grounded will continue to occur. For these reasons, comment on the difference between solidly grounded neutral and high-resistance grounded neutral systems under such conditions is appropriate.
   In the absence of a circuit fault to ground, the solidly grounded neutral and the high-resistance

*See GER-2375 "High-resistance Grounding of . . . delta systems with ground-fault alarm and traceable signal to fault," F. K. Fox, H. J. Grotts, C. H. Tipton.

# APPENDIX

grounded neutral systems both present direct-contact shock hazard; line-to-neutral voltage exists from each phase to ground, and the neutral point is at essentially ground (zero) potential.

In the presence of a solid line-to-ground fault, normal line-to-neutral voltage continues to be present on two of the three-phase conductors to ground in the solidly grounded system, while in the high-resistance grounded system essentially normal line-to-line voltage appears on two of the phase conductors (to ground) for the duration of the fault, thus increasing the shock potential on these phases. Of greater importance, however, is the fact that the neutral conductor of the solidly grounded neutral system remains at essentially ground potential during the line-to-ground fault interval, while in the resistance-grounded system the neutral point assumes a potential above ground approximately equal to the value of the normal line-to-neutral voltage. Stated another way, the ground fault current flow in the neutral resistor elevates the neutral point above ground potential by about the normal line-to-neutral voltage value. It is essentially for this reason that the resistance-grounded system is not satisfactory for general four-wire power distribution, since the neutral conductor during line-to-ground faults would be energized to about normal line-to-neutral voltage. On four-wire systems, line-to-neutral connected loads are served by single-pole interrupters, the disconnection of which in a resistance grounded system would not prevent the appearance of hazardous shock potential between the "white" wire and ground during line-to-ground faults. Thus the safety of electricians working on supposedly de-energized circuits would be jeopardized during line-to-ground faults in four-wire systems served from resistance-grounded sources, unless two-pole interrupters were used to serve the line-to-neutral connected loads. This, however, would be a costly change from present practices and requirements.

In the presence of an adequate equipment grounding network, the shock potential presented by the frame of an equipment or device having an internal line-to-ground fault is less in the high-resistance grounded system than in the solidly grounded neutral system. In either case, however, the shock potential is low. Under the same fault conditions, but in the absence of an adequate equipment grounding network, no difference in shock hazard exists between the two systems described.

3. Flash Hazard.

Whenever a phase-to-phase or phase-to-ground fault takes the form of a flashover through air (an arcing fault) the release of energy in the fault may cause the violent generation of hot gases and arc plasma, accompanied by incandescent metallic vapors. The site of the fault, when a relatively high fault current flows—say, a thousand amperes or more—becomes a flaming eruption with considerable blasting and burning effect. Such a fiery explosion represents an extreme peril to persons working at or near the fault location, and may realistically be referred to as a **flash hazard.**

In the solidly grounded neutral system it is possible for several thousand amperes to flow during a line-to-ground arcing fault. Obviously, the flash hazard associated with such a fault would be severe. With high current flow in the arc there is a strong probability that instantaneous overcurrent protective devices will promptly remove the fault. If the arcing fault current occurs at reduced levels the flash hazard, though still serious, will be correspondingly reduced in severity. Under these restricted flow conditions supplementary ground fault relaying may be required to detect and extinguish the fault, at least on the larger circuits.

The extent of the flash hazard in solidly grounded neutral systems clearly is of sufficient degree, at its best, to make it a safety requirement that equipment and circuits be worked upon only when de-energized, thus eliminating the risk of fault initiation. The voltage hazard always present in energized systems also imposes this same requirement.

The high-resistance grounded system is not free from flash hazard and warrants similar rules regarding working on energized equipment. The flash hazard in this type system on the occurrence of a first **ground** fault, however, is minimal, provided escalation does not occur. The restriction in current flow is so great that limited energy is released in the arc. Also, the arc itself is difficult to sustain. Little flash and spark are produced and the tendency, at the point of contact between conductor and ground, is for the arc to extinguish or for a slight "tack" welding action to be produced.

The serious flash hazard situation in high-resistance grounded systems occurs when a line-to-ground fault escalates into a line-to-line fault, or when the fault occurs as a line-to-line or double line-to-ground fault. The latter two events may be brought about, respectively, through an electrician's error or from the occurrence of a **second** ground fault on the system. The flash hazard from a line-to-line fault is a danger associated with the solidly grounded neutral system also, but the occurrence of a double line-to-ground fault is a peril associated largely with the high-resistance grounded system. In a line-to-line arcing fault on a high-resistance grounded system the flash hazard may be as great as for a line-to-ground fault on a solidly grounded neutral system. Thus the resistance grounded system is not secure from very serious flash hazard. This is one reason that application of this type of system grounding should be bolstered by ground-fault indicating and tracing equipment, and by the requirement that ground faults be removed as promptly as operations permit.

4. Detection of Arcing Faults.

The need for rapid detection and removal of arcing faults in low-voltage systems has been well covered in the technical literature in the past few years. Fundamentally, the objective is to control arc burning damage to an acceptable degree and avoid or minimize equipment burndowns. The use of sensitive zero-sequence type relaying may permit prompt detection and subsequent removal of arcing faults, especially in the solidly grounded neutral system. This kind of system commonly includes ground itself in the fault circuit, even though the fault may be initiated line-to-line. With sensitive ground fault relays, even low-level arcing faults may be quickly detected and removed before extensive damage is incurred at the fault site. Thus the solidly grounded neutral system provides an effective **basis** for protection against destructive arcing fault burndowns.

In the high-resistance grounded system little if any threat of burndown is presented by a single fault to ground, provided it is not left on for prolonged periods. Line-to-line arcing faults, however, will cause severe equipment damage if not removed within a few cycles. When the arcing fault current is relatively high, the conventional phase overcurrent devices will function to detect and remove the faults. Under certain conditions, however, the rms current value associated with an arcing line-to-line fault may be so low as not to operate conventional phase overcurrent devices, or to operate them only after a prolonged interval; then burndown may occur. This is possible, for instance, when single-pole interrupter operation has only partially disconnected the faulty circuit, when a double line-to-ground fault on separate circuits introduces substantial impedance into the fault circuit or when the arc resistance lowers the current. In the double line-to-ground fault case sensitive ground fault relays can detect and remove one or both faults provided they are on different circuits. If the low level arcing fault involves only one circuit, however, on either a line-to-line or double line-to-ground basis, ground fault relaying will be ineffective and burndown can occur unless the fault current level increases sufficiently to operate the phase overcurrent devices. Such escalation is not certain and thus, in contrast to the solidly grounded neutral system, the high-resistance grounded system does not provide a simple, economical means to assure detection and removal of low-level arcing faults regardless of where they occur. Also, the high-resistance grounded system does not offer as good rotating machine protection as solid grounding **with ground fault relaying,** since ground faults are not quickly detected and removed, and may burn into turn-to-turn faults creating greater damage to the machine. This compromise in rotating machine protection is inbuilt in the "non-interruptible" design concept of high resistance neutral grounding.

### Summary Remarks

There is, obviously, no single method of system grounding which will prove to be most satisfactory in all possible situations. Each application problem must be resolved on the basis of its individual requirements and constraints, leading usually to a compromise choice in which something is gained at the expense of something else. The solidly grounded neutral system with ground fault relaying will provide acceptable performance. In other instances, the high-resistance grounded neutral system with tracing pulse may have user preference. For each of these system grounding methods the typical application areas are suggested in preceding paragraphs, while concluding statements may be made as follows:

#### Solid Neutral Grounding

The solidly grounded neutral system provides transient overvoltage control and a means for automatic easy detection and selective isolation of system faults, as well as the possibility of good rotating machine protection. To secure greater benefits from its use, however, and to improve personnel safety and system service reliability, this type of system grounding may require the use of supplementary ground fault relaying.

In the solidly grounded neutral system arcing line-to-ground faults can produce violent local eruption which could result in personnel injuries and severe damage to equipment if not quickly removed. Most line-to-line faults, however, will promptly involve ground and will be removed without significant delay by phase overcurrent devices or supplementary ground fault relays. This method of system grounding is the one most widely used at present in industrial and commercial power distribution, and is required on four-wire systems.

#### High-resistance Neutral Grounding

High-resistance neutral grounding has frequently been applied in process and similar industries in the belief that delayed tripping of a faulted critical process circuit will improve over-all service continuity by permitting an orderly shutdown under ground fault conditions. The basic objective is to secure control of the self-generated system transient overvoltages while minimizing the possibility of having a service interruption arising from a first ground fault. Since the prolonged existence of a ground fault increases the probability of a second ground fault shutting down two circuits simultaneously, it is advisable to complement this grounding method with ground detection and alarm devices and fault-tracing equipment, to help in securing maximum benefits from this type of grounding.

High resistance neutral grounding, on a first ground fault, avoids the arc blast and minimizes the fault damage associated with arcing line-to-ground faults. Such faults, however, may escalate into line-to-line faults or, if unremoved, may be compounded by a similar fault on another phase, with subsequent arc damage quite like that with a solidly grounded neutral system. Furthermore, unremoved ground faults continue to produce some damage at the fault point and may eventually escalate to more serious character. On equipment with multi-turn coils, such as motors, such unremoved faults may cause eventual turn-to-turn failures and consequent severe damage (turn-to-turn currents are not limited by the grounding resistor).

This method of neutral grounding is not satisfactory for general four-wire service, since the elevation in voltage of the neutral conductor during any line-to-ground fault may result in a severe shock hazard to personnel. To minimize this would require the use of two-pole interrupters on single-phase circuits. Even then, there might be other problems in the safe use of portable tools or appliances. The high resistance method of system grounding is, however, gaining increased acceptance on three-wire systems with plant operators in process and other industries who are desirous of securing control of transient overvoltage while avoiding a disorderly shutdown of electrical equipment and/or the presence of a severe flash hazard on the occurrence of a first ground fault.

# PRINCIPAL CHARACTERISTICS OF MAJOR METHODS OF GROUNDING LOW-VOLTAGE SYSTEMS

**PRINCIPAL CHARACTERISTICS OF MAJOR METHODS OF GROUNDING LOW-VOLTAGE SYSTEMS**

| System Property | Type of System Grounding | | |
|---|---|---|---|
| | Solid * | High Resistance ** | Ungrounded |
| Immediate Shutdown of Faulty Circuit on Occurrence of First Ground Fault | Yes | No | No |
| Control of Transient Overvoltages Due to Arcing Ground Faults | Yes | Yes | No |
| Control of Impressed or Self-generated Steady-state Overvoltages | Yes | No | No |
| Flash Hazard to Personnel During Ground Fault (No Escalation of Fault) | Severe | Essentially zero | Essentially zero |
| Arcing Fault Damage to Equipment During Ground Fault (No Escalation) | May be severe unless fault is promptly removed | Usually minor unless fault removal is so prolonged as to cause fault escalation | Usually minor but transient overvoltages may cause fault escalation or multiple insulation failures |
| Shock Hazard, Unfaulted Phases to Ground, During Ground Fault | Line-to-neutral voltage | Approximately line-to-line voltage | May be several times line-to-neutral voltage |
| Shock Hazard, Equipment Frame to Ground During Solid Internal Line-to-Ground Fault | Moderate | Minimum | Small |
| Detection of Arcing Faults | L-L or L-G arcing faults readily detected, esp. with ground fault relaying | Ground detectors and fault locating equipment required for L-G arcing faults. L-L faults readily detected by phase overcurrent devices unless fault current is severely limited | Ground detectors and fault locating equipment required for L-G arcing faults. Transient overvoltages may meanwhile cause additional insulation breakdowns. L-L faults readily detected by phase overcurrent devices unless fault current is severely limited |
| Suitable for Four-wire, Three-phase Service | Yes | No | No |

* For optimum results, use of solid grounding method should include sensitive ground fault relaying.

**For optimum results, use of high resistance grounding method should include equipment and procedures for alarming, tracing and removing the ground fault promptly.

# NOTES

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GENERAL ELECTRIC

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# The impact of arcing ground faults on low-voltage power system design

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# CONTENTS

# 1. INTRODUCTION

The neutral grounding and ground fault protection practices as they relate to low-voltage a.c. systems appear to be under renewed scrutiny primarily because of a genuine concern about recurring reports of arcing faults and their destructive consequences.

As a related development, the National Electrical Code Committee has under consideration a proposal to include an art 230-95 in the 1971 edition which would make at least one step of ground fault protection on circuits rated 1000 ampere or above mandatory and on smaller circuits desirable.

This publication presents a review of the general subject of low-voltage neutral grounding and ground fault protection. Coupled to historical developments which led to the present state-of-the-art, the emerging understanding should be helpful in evaluating neutral grounding and ground fault protection practices.

The material presented herein pertains primarily to the options and practices as they relate to neutral grounding for the purpose of system service continuity as well as circuit and equipment protection. Grounding for "Personnel Safety," which is aimed at reducing shock hazards by limiting accidental ground currents to a few milliamperes is outside the scope of this publication.

This publication brings together the various aspects of arcing ground faults, which to a certain extent have been discussed in published technical literature. This composite treatise of the subject matter may prove helpful in the further development of protection philosophies and equipments.

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August 1, 1970

*The author acknowledges his indebtedness to the earlier writers in the field, in particular Messrs. R. H. Kaufmann and F. J. Shields for their useful suggestions and review of the manuscript.*

# 2. REVIEW OF LOW VOLTAGE SYSTEM GROUNDING PRACTICES

## GROUNDING OF THE 3-PHASE, 3-WIRE SYSTEM

The early 3-phase, 3-wire systems, predominantly serving industrial plants, were historically ***ungrounded*** 240, 480 and 600V systems for the reason that they required the fewest number of wires to connect. Freedom from unscheduled equipment shutdowns in the event of a single ground fault was not the basic reason for the early use of ungrounded systems. Fault locating was not only cumbersome but at times was neglected at the risk of developing a second ground fault. More severe faults and unscheduled outages on a larger scale were consequently experienced.

When disastrous multiple insulation failures began to emerge and were analytically proven to be caused by transient overvoltages due to intermittent ground faults and the resonant effects in series inductive-capacitive circuits, this early practice of not grounding power systems rapidly lost its popularity. These analytical studies further showed that solid grounding of the system neutral provided a simple and effective means to suppress the damaging transient line-to-neutral overvoltages.

As a result, industrial systems are now, with very few exceptions, operated with ***solidly grounded*** neutrals. On properly designed low voltage systems, a solid line-to-ground fault, in magnitude approaching the 3-phase fault current, is usually rapidly removed by phase overcurrent protective devices thus negating the need for separate ground fault protection. The major operational disadvantage of solidly grounded systems, however, is that essential equipments will be shut down when they develop a line-to-ground fault.

Where electrical service continuity is considered to be an overriding consideration, ***high resistance*** neutral grounding is considered an acceptable compromise. By limiting the neutral resistor current to a magnitude no less than the capacitive charging current of the low voltage system, generally between .5 and 5A, several types of severe transient overvoltages can be limited to safe values. The resultant small magnitude of ground fault current is relatively harmless until a second ground fault occurs which increases the fault current to much greater magnitudes, requiring two circuits to be opened by phase overcurrent trip devices. Therefore, the success and effectiveness of high-resistance grounded systems depend largely on the early location and removal of a ground fault. To aid in the location of ground faults, the neutral resistor, in more recent applications is arranged to provide a pulsating ground fault, generally from 1 ampere to 20 ampere. Now, a simple portable fault locator can more easily pin-point the fault location against "noise," usually introduced by stray ground currents.

Note that ***low resistance*** grounding, so popular in medium voltage systems, has not found wide acceptance in low voltage systems. The need for a complete and separate series of coordinated ground responsive trips on sprawling multi-circuit low voltage systems made this mode of grounding unattractive. Mining service systems however, have long been grounded through a low resistance because of unique protection problems.

## GROUNDING OF THE 3-PHASE, 4-WIRE SYSTEM

The 4-wire neutral grounded systems are operated to supply a line-to-neutral voltage and require that one of the power conductors, such as the neutral of a wye-connected transformer be ***solidly grounded.*** Typical areas of application are the downtown networks as well as large apartment and commercial building systems.

It is important to note that the early 4-wire systems operated on a 208 wye/120 voltage. Increasing load densities gradually made the 480 wye/277 volt system the more attractive distribution voltage.

The operational record of these systems was generally considered to be excellent until reports of severe burndowns of equipments became more frequent, especially on 480 wye/277 volt systems which relied heavily on fuses to provide protection. Studies and tests brought to light that these severe burndowns were caused by *"arcing faults"* as opposed to *"bolted faults,"* the latter being the usual criterion used to size interrupters. The growing number of arcing fault incidents further appeared to coincide with a corresponding growth of the 480 wye/277 volt systems (replacing the 208 wye/120 volt systems) and a corresponding increase in the use of higher rated breaker trip coil and fuse ratings.

## GROUNDING FOR SAFETY OF PERSONNEL

This form of grounding has been receiving increasing attention. In essence, the objective is to limit the flow of accidental ground currents in both time duration and magnitude, to levels of a few milli-amperes, considered to be non-lethal to the human body. Electrical service to hospital operating rooms for instance, oftentimes rely on this form of grounding. Although no national standards have been finalized for non-lethal boundaries, the following limits have been suggested:

100 ma for 1 second and a constant $I^2t$ value for other time intervals, with less than 5 ma as a permanent sustained current value limit.

Such a low level of ground fault current can not be attained in the usual low-voltage system, where just the normal charging ground current can easily exceed the 100 milli-amps level. A special form of protection to be applied at the branch circuit level, characteristically the 20A or 30A single pole breaker or fuse in conjunction with isolating transformers and monitoring equipment, is promoted to provide such personnel safety grounding. The effectiveness of such protection is presently under active deliberation as is the alternative of emphasizing the need for a low impedance ground return circuit.

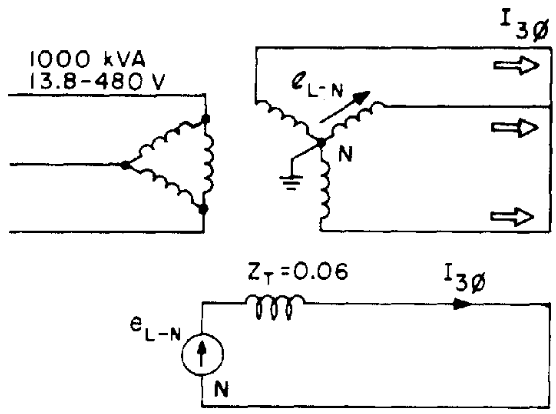
The subject will not be discussed in further detail since it is considered outside the scope of this publication.

# 3. THE NATURE OF FAULTS

## THE BOLTED FAULT

The study of fault conditions is usually aimed at the determination of the theoretically *maximum* fault current magnitudes by assuming close-in bolted fault conditions. The selection of the interrupting rating of protective devices in three-phase systems is based on *bolted three-phase faults. Bolted line-to line faults* and *bolted line-to-ground faults* (on solidly grounded systems) should in specific cases also be considered. External to the interrupter, the physical evidence of the flow of the maximum fault current is minimum; only a movement of conductors may be observed. Because of the high magnitude of these short circuit currents, the usual phase-overcurrent protective devices should interrupt these close-in bolted faults without unnecessary delay.

In preparation for an approximate quantitive comparison of the magnitude of various types of faults, Fig. 3-1, 3-2 and 3-3 display the bolted three-phase, line-to-line and line-to-ground fault equivalents. The calculation of fault currents further illustrates the typical magnitudes for a 1000 kva, 480V substation.




In per unit: $1\,^{\circ}\!/_1$ Amp = Transf. FLA

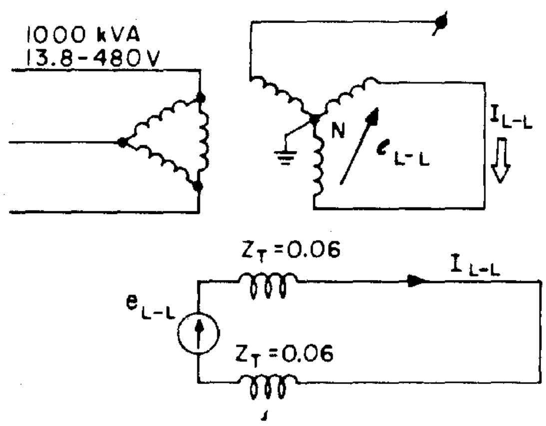
$$= \frac{1000}{480\sqrt{3}} = 1203 \text{ Amp.}$$

$$I_{3\phi} = \frac{e_{L\text{-}N}}{Z_T} = \frac{1.0}{.06} = 16.6 \text{ per unit}$$

$$= 16.6 \times 1203 = 20{,}000 \text{ Amp.}$$

Note: $3\phi$ fault appears symmetrical as viewed from neutral. Can thus be calculated on single-phase basis. Each line-neutral voltage drives its phase current through one transformer winding.

**Figure 3-1: Calculation of bolted 3-phase short-circuit current magnitude.**




$1\,^{\circ}\!/_1$ = Transf. FLA = 1203A @ 480V

$$I_{L\text{-}L} = \frac{e_{L\text{-}L}}{2X_T} = \frac{e_{L\text{-}N} \times \sqrt{3}}{2X_T}$$

$$= \frac{\sqrt{3}}{2} \times \frac{e_{L\text{-}N}}{X_T} = .877 \times I_{3\phi}$$

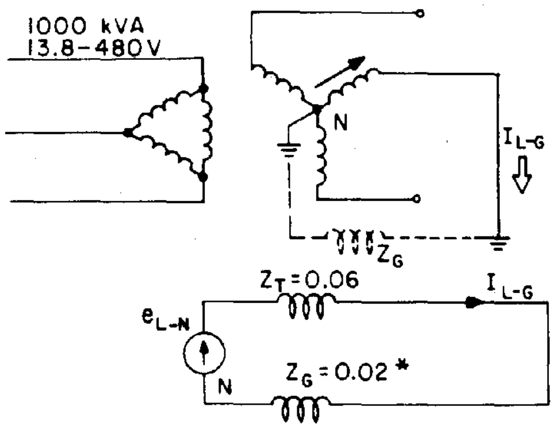
$$= .877 \times 20{,}000 = 17{,}540 \text{ Amp.}$$

**Figure 3-2: Calculation of bolted line-to-line short-circuit current magnitude.**

The line-to-ground fault case requires further study. The significant variation in the ground return circuit *impedance* is primarily the result of the *inductive reactance* ($X_L$) component[2*]. The $X_L$ value is minimal if the ground current returns to the transformer neutral through a path in close proximity to the outgoing power conductors. Since currents seek a path of lowest impedance, the return current has a natural tendency to flow in a proximal path to the outgoing current. In Fig. 3-4, a ground fault in the motor winding will thus return almost completely through the conduit. Absence of such a return circuit may force dangerous (10,000A) stray currents in an unpredictable path through building steel, waterpipes etc. At the locations where the current jumps from one metallic member to another, considerable arcing will be evident. In hazardous areas, such sparks could cause disastrous explosions.

From a protective device point of view, the need for a low impedance ground return circuit should be evident. Both the path and the magnitude of the

* Superscript indicates bibliography reference.




1 $^{\circ}/_{1}$ Amp. = Transf. FLA = 1203A @ 480V

$$I_{L\text{-}G}=\frac{e_{L\text{-}N}}{Z_T+Z_G}=\frac{1.0}{.06+.02}$$

$$=\frac{1.0}{.08}=12.5 \text{ per unit}$$

$I_{L\text{-}G}=12.5\times1203=15{,}000$ A

IF $Z_G=0$ then, $I_{L\text{-}G}=I_{3\phi}=20{,}000$ A

Note: The line-neutral voltage drives the fault current thru one transformer winding and ground path.

*The ground path impedance ($Z_G$) can vary considerably. For minimum $Z_G$ provide ground return circuit in close proximity to outgoing power conductors.

**Figure 3-3: Calculation of bolted line-to-ground short-circuit current magnitude.**

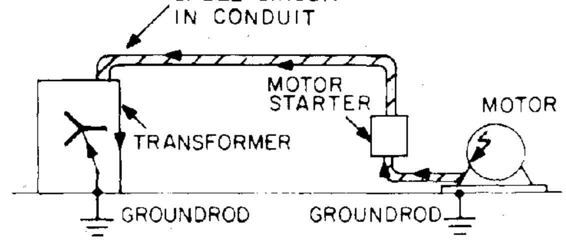



**Figure 3-4: Ground fault originating in motor will return almost completely through conduit or interstitial ground wire. Ground rod is not very effective in conducting ground fault current to transformer neutral but essential to provide "equipment ground."**

ground fault are predictable within reasonable limits. This knowledge will indicate whether fast detection and removal by phase overcurrent protective devices and interrupters is assured.

The unexpected shutdown of essential equipment due to a single ground fault is in certain application areas considered highly undesirable. The high resistance grounded neutral system allows a temporary continuity of service to such critical equipments at the risk of meantime developing a double line-to-ground fault with more widespread shutdown consequences.

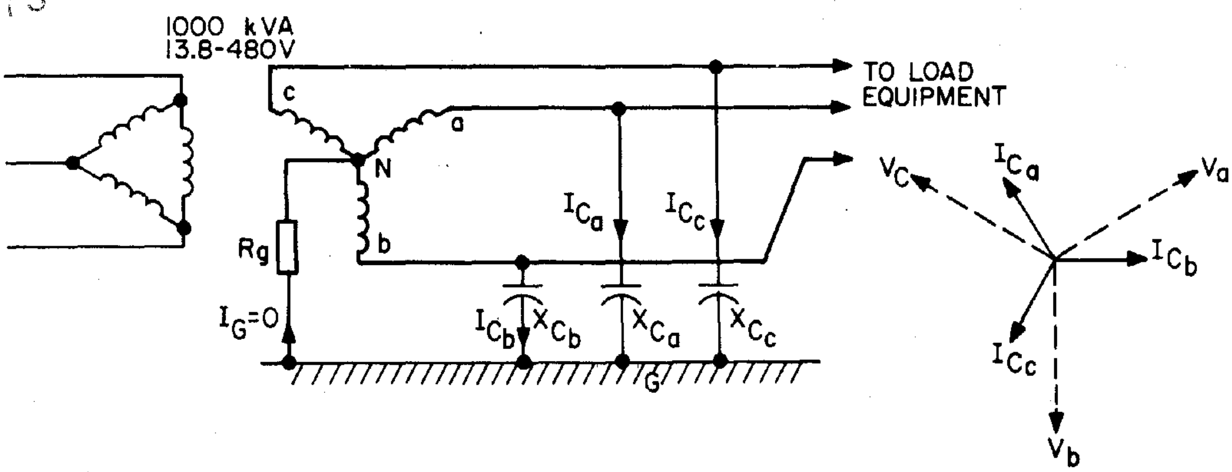
In Fig. 3-5, the system charging current is assumed to be 1 ampere. To suppress transient line-to-neutral overvoltages to acceptable levels, the grounding resistor must be sized so that the resistor current will equal or exceed the 1 ampere of charging current. Since both the transformer impedance and the ground fault impedance are negligible relative to the desired grounding resistor value, the required resistor can be calculated to be equal or less than 277 ohm (see Fig. 3-5).

### THE ARCING FAULT

While *bolted* faults are largely theoretical and rare in occurrence, *arcing* faults are more likely to materialize due to loose connections, conductive dust accumulation on insulators, insulation failure due to overloading, slippage of electrician's tools and "fish tapes," and unsuccessful interruption of short circuits causing conductive gases to emanate from circuit breakers or fuses.

Although smaller in magnitude, arcing faults are extremely turbulent in that the energy released by the arc can generate a tremendous amount of heat and arc pressures in a matter of cycles. Copper or aluminum bus and grounded parts can be melted away if these faults are allowed to persist.

Naturally, such faults are not allowed to persist intentionally. A study of the behaviour of arcing faults reveals that arcing faults may be considerably smaller in current magnitude than bolted faults. The fault magnitude may be so small that the usual phase overcurrent protective devices do not respond at all or only after a considerable time-delay. It is therefore appropriate to gain an understanding of the current-limiting effects of arcing faults. Once these effects are better understood, phase overcurrent devices can be examined in terms of their ability to sense arcing faults of the three-phase, line-to-line and line-to-ground variety. This knowledge can also be used profitably in optimizing the design of the power system in terms of its protective features.

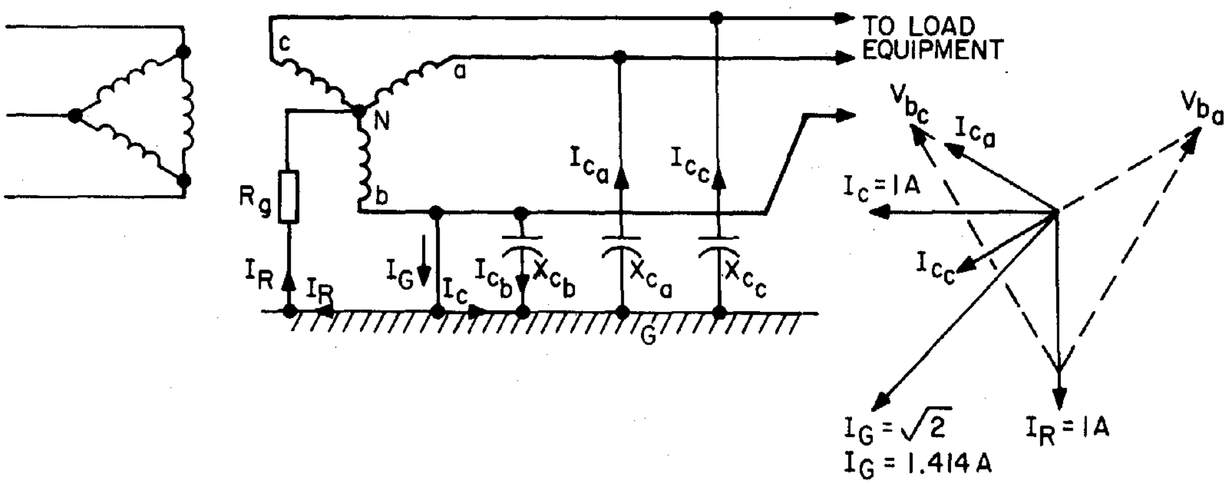



Ⓐ Normal Operation

For balanced capacitance: $X_{C_a} = X_{C_b} = X_{C_c}$

$I_{C_a} + I_{C_b} + I_{C_c} = 0$; therefore $I_G = 0$

Neutral "N" is at ground potential




Ⓑ Ground Fault on Phase b

$X_{C_b}$ is shorted; thus $I_{C_b} = 0$

High resistance criterion: $I_R \geq I_C$

Assume $I_C = I_R = 1$ amp; then $I_G = \sqrt{2}$ or 1.414 amp

Grounding resistor sees line-to-neutral voltage; therefore

$$R_g = \frac{277}{1} = 277 \text{ ohms}$$

**Figure 3-5: Illustration of high-resistance neutral grounding principle.**

# 4. THE BEHAVIOR OF ARCING FAULTS

The environment in which the arcing fault originates has a considerable influence on its subsequent behavior.

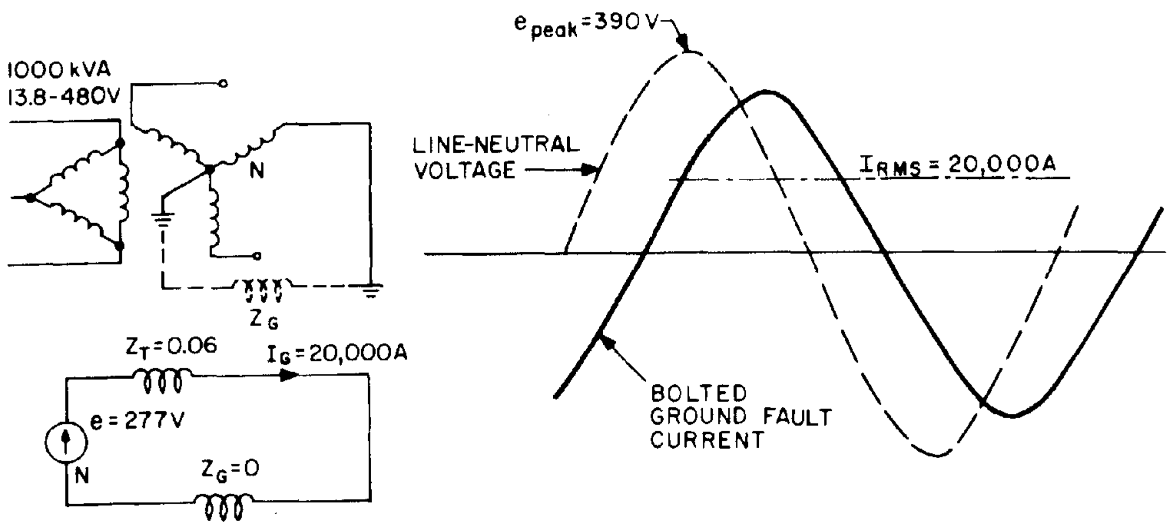
An arcing fault caused by *cable* insulation deterioration for instance usually originates as a sputtering ground fault. Temperature elevation accelerates carbonizing of the insulation rendering it semi-conducting. A continuing low level current may persist for a long time causing localized damage. A runaway condition may in time involve another phase. The considerably higher phase-to-phase fault current will then be detected by phase overcurrent devices and subsequently removed.

An arcing fault originating in a metal-enclosed *bare bus* arrangement usually involves ground. This fault can be expected to escalate quickly into a phase-to-phase or 3-phase arcing fault, unless the fault is detected and interrupted promptly; a matter of cycles. When allowed to persist, the resultant heat and arc pressures are likely to cause complete destruction of such equipments.

The precept appears to be: *apply sensitive ground fault protection in an attempt to sense and promptly interrupt an arcing ground fault before it escalates into the more severe forms of arcing faults or before it inflicts severe damage to equipments. The sensitivity required of such a device, however, in most cases can not be achieved by fuses or direct-acting trip devices with only long-time and instantaneous trip elements. Short-time trip elements may often times prove reasonably effective in securing ground fault removal.*

To further support this precept, the following analysis is presented to identify the mechanism which causes the relatively low levels of arcing fault currents. Inasmuch as the reduction in arcing fault current magnitudes is particularly significant in the event of a ground fault, this case will be used to explain the phenomenon.

The *bolted* line-to-ground fault current as identified in Fig. 3-3 (P. 7) is a 60 Hz sinusoidal current with a calculated RMS value of 20,000 Amperes, as shown in Fig. 4-1.




IF $Z_G = 0 \rightarrow I_G = I_{3\phi} = 20{,}000$ AMPERE

**Figure 4-1: Bolted line-to-ground fault current is essentially a sine wave.**

An arcing fault can be simulated by inserting in the solid connection between one phase and ground a sparkgap with a spark-over value of 375 volts (Fig. 4-2). Thus if the instantaneous voltage across the gap reaches or exceeds 375V, an arcing current will pass through the gap. Analytical studies and tests further show that the voltage across the conducting gap ($e_{arc}$) is reasonably constant but that its magnitude is a function of type of fault. For arcing *ground* faults the $e_{arc}$ value is approximately 140V; for *line-to-line* and *3-phase* arcing faults the $e_{arc}$ value is approximately 275V.

Referring to the right hand portion of Fig. 4-2, it becomes apparent that no current flows until the gap sparks over when the instantaneous line-to-neutral system voltage reaches 375V. At that instant an arcing current begins to build up, while the voltage across the gap remains relatively constant at about 140V. (This suggests that the arc resistance is inversely proportional to the arc current.) The arc current reaches its peak when the line-to-neutral voltage equals the arc voltage $e_{arc}$, after which the arc current attenuates. The arc is snuffed out when the line-to-neutral voltage reverses polarity and becomes equal but opposite to the arc voltage, $e_{arc}$.

This process is repeated every half cycle and results in an arcing ground current of a discontinuous, non-sinusoidal character.

Recognizing that overcurrent devices respond to RMS currents, this value of the arcing ground fault current is also indicated in Fig. 4-2. Although the determination of this value is quite complex, researchers were able to determine a relationship between this value and the bolted fault equivalents. In the case of the *arcing ground* fault, its RMS value is only 38% of the *bolted* 3-phase fault value. On this basis the RMS arcing ground fault must be about .38 x 20,000=7600 Ampere.

With a basic understanding of this phenomenon as it applies to line-to-ground faults, it suffices to say that line-to-line and 3-phase arcing faults can be similarly explained. The higher driving voltage (line-to-line rather than line-to-neutral voltage) causes the gap to conduct for a considerably longer time (Fig. 4-3). Although the arc voltage builds up to 275V (as compared 140V) the resultant arcing currents are considerably higher.

The importance of the system voltage can now also be visualized. On 208-volt systems, neither the peak line-to-neutral voltage (1.41 x 120=170V) nor the peak line-to-line voltage (1.41 x 208=295V) exceeds the 375V restrike voltage. On this theoretical basis, an arc could not be sustained. In practice however, not all 208 volt arc faults are known to have been self-extinguishing, in particular the 3-phase variety.

In summary: Arcing faults are considerable smaller in magnitude than the bolted varieties. The likely *minimum* values of arcing line-to-ground fault currents, governed by arcing and re-ignition voltage

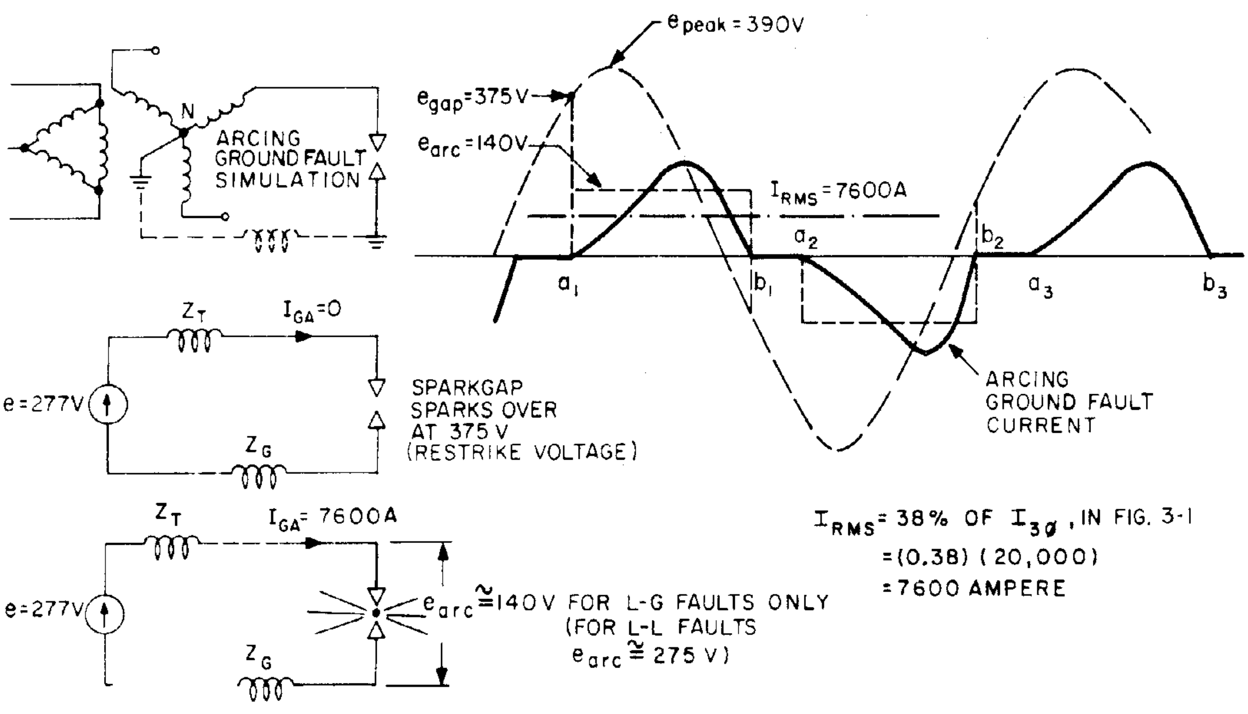



**Figure 4-2: Arcing line-to-ground fault current is a discontinuous, non-sinusoidal wave.**

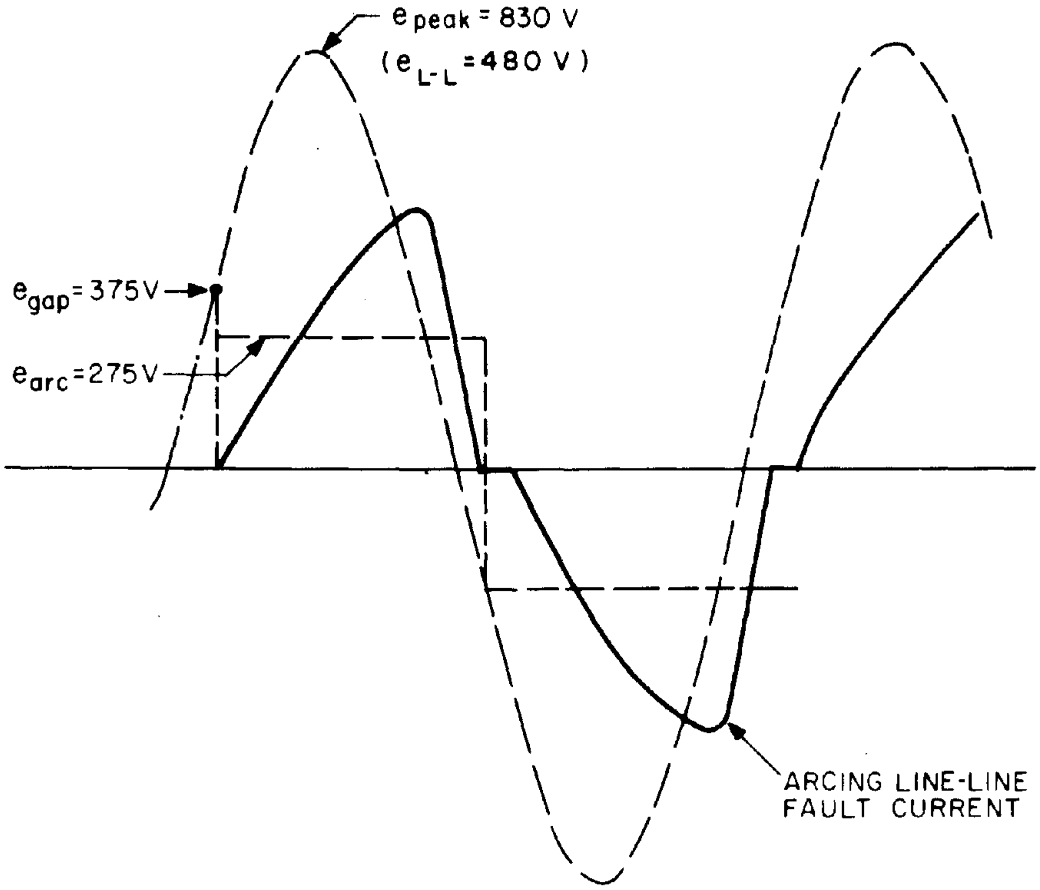



**Figure 4-3: Arcing line-to-line fault current is a discontinuous non-sinusoidal wave.**

magnitudes named in the previous paragraphs, are shown in table 4a.

| Type-of-arc fault | System Voltage | |
|---|---|---|
| | 480Y/277 | 208Y/120 |
| Three phase | 89% | 12% |
| Line-to-line | 74% | 2% |
| Line-to-ground | 38% | 0 |

*Table 4-a*

Approx. min. value of arcing fault current in per-cent of 3-phase bolted fault.

The relationships between arcing fault magnitudes and the bolted 3-phase fault allows a convenient generalization on the basis of the incoming circuit (transformer main secondary or service entrance) ampere rating. These magnitudes are presented in table 4-b.

| Incoming circuit Amp. rating | 1X | |
|---|---|---|
| Bolted close-in three-phase fault | 15—25X | |
| | @480V | @208V |
| Arcing three-phase fault | 13–23X | 2–3X |
| Arcing line-to-line fault | 11–19X | .3–.5X |
| Arcing line-to-ground fault | 5½–9½X | 0 |
| Suggested max. pick up of *short-time* trip on incoming line for arcing *phase* faults | 7½–12½X | 1–2X |
| Suggested max. pick up of *short-time* trip on incoming line for arcing *ground* faults. | 3½–6X | — |

*Table 4-b*

Generalized relationships between various types of arcing faults and interrupter ampere rating.

Reference to instantaneous trips has been omitted for the reason that incoming line protection in general requires selective trip characteristics, which rules out instantaneous elements. If such elements are used in lieu of short-time trips, the suggested instantaneous element settings may be those indicated for the short-time trips.

# 5. THE ART AND SCIENCE OF GROUNDING

The selecton of the type of neutral grounding for any specific low voltage systems is based on a variety of considerations. The following bar chart (Fig. 5-1) is an attempt to present in summary format a qualitative comparison of the modes of grounding low voltage systems. Characteristic features are unpretentiously evaluated as a function of four arbitrary ground fault current levels related to *ungrounded, high-resistance* grounded, *low-resistance* grounded and *solidly* grounded neutrals.

Although the merits of each characteristic feature relative to the mode of grounding cannot be evaluated in only two (black or white) categories, this form of presentation should appeal to the practical industrial or consulting engineer.

On the basis that a white bar indicates a favorable condition, a black bar an unfavorable condition, it follows that the grounding mode showing a plurality of white bars should be favored for the first consideration. Ignoring weighting factors (which should be applied to each feature), it appears that the high-resistance grounded neutral is the optimum mode of grounding, except that it cannot be used on systems serving single-phase, line-to-neutral loads (480Y/277) so popular in commercial buildings.

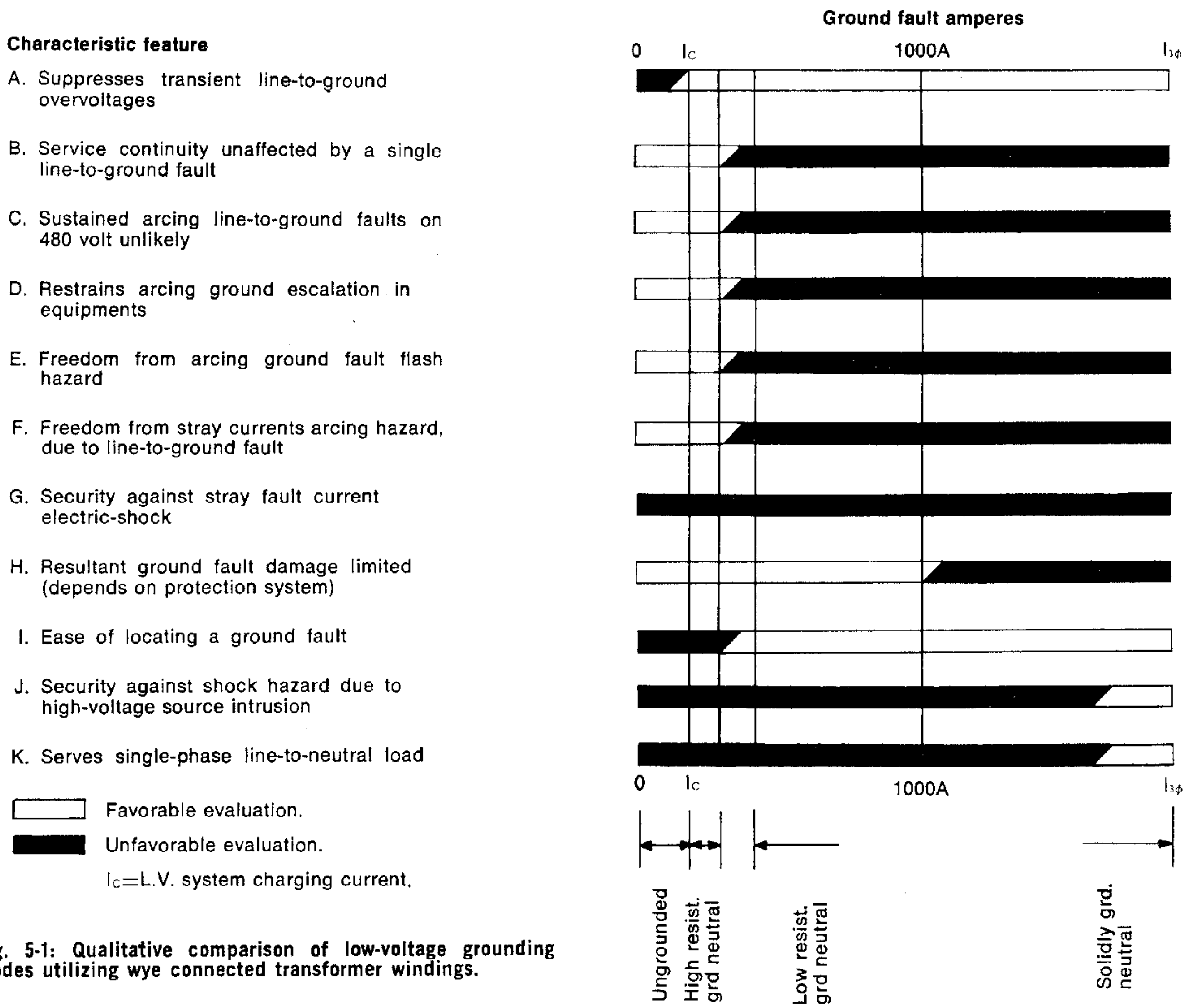



**Fig. 5-1: Qualitative comparison of low-voltage grounding modes utilizing wye connected transformer windings.**

No attempt will be made to present a detailed discussion pertinent to each of the characteristic features. The bibliography lists an excellent article[6] for further study. Instead a short topical summary will be provided here merely to define and illustrate the nature of each feature.

## CHARACTERISTIC FEATURE

### A. Suppresses transient line-to-ground overvoltages

The *ungrounded system* is shown to be susceptible to these overvoltages. The basis cause is the lack of neutral stability, meaning that the neutral can assume any value between zero and 6 to 10 times the line-to-neutral voltage relative to ground potential. Only when the capacitive coupling between each phase conductor and ground is balanced, will the neutral assume a zero potential relative to ground (Fig. 5-2). A *close-in bolted ground fault* will force the c-phase to assume ground potential with the result that the neutral will be elevated by 277V, while the a and b phase voltages will increase to 480V relative to ground (Fig. 5-3). This is not too dangerous an overvoltage, but it is potentially sufficient to break down already weakened insulation to ground.

The generation of more severe overvoltages finds its origin in the inherent capacitance of all cables, capacitors, and other insulations to ground.

If a *remote bolted ground fault* or more realistically a magnetic coil breakdown to ground occurs which interposes between line and ground an inductive reactance equal to the capacitive reactance of the grounded phase, the line-to-ground voltage may become as much as 6 to 10 times normal. Fig. 5-4 clearly shows the make-up of the notorious $X_L - X_C$ resonant circuit, which is responsible for the severe voltage transients. Note that the voltage between phases at the transformer is not affected and that only the ground insulations are severely overstressed. The stage is set for multiple ground faults!

also shown in Fig. 5-5 for the value of $X_L = 1/3\ X_C$ as

This series resonant overvoltage magnitude is also shown in fig. 5-5 for the value of $X_L = 1/3\ X_C$ as well as varying ratios of these system constants. It appears that overvoltages are relatively mild for any $X_L$ over $1/3\ X_C$ ratio greater than 2, if the frequency is 60 Hz. Any appreciable third harmonic voltage, not uncommon in power systems, will cause the series inductive capacitive circuit to resonate when the $X_L$ over $1/3\ X_C$ ratio calculated at 60 Hz is 9. Other harmonic frequencies similarly affect the resonant condition but their significance is usually considerably reduced because of the lesser magnitudes of higher harmonic frequencies in power systems.

If the bolted ground fault were resistive in nature, the magnitude of line-to-ground overvoltages on ungrounded systems would be significantly reduced as illustrated in Fig. 5-6.

Intermittent or *arcing ground faults* on low voltage ungrounded systems are known to have generated phase-to-ground potentials in excess of 1200V due to the *repetitive restrike* nature of such a ground fault.

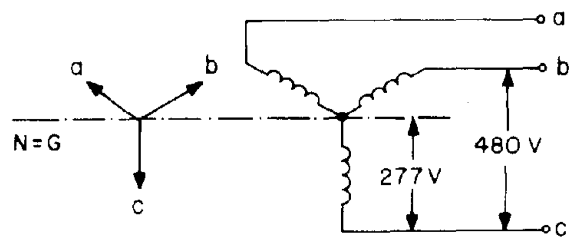



**Figure 5-2: Ungrounded system under balanced operating conditions. Neutral and ground are at same potential.**

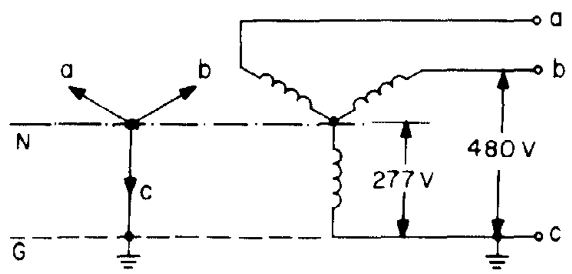



**Figure 5-3: Ungrounded system with close-in ground fault on c-phase. Neutral is elevated above ground by 277V.**

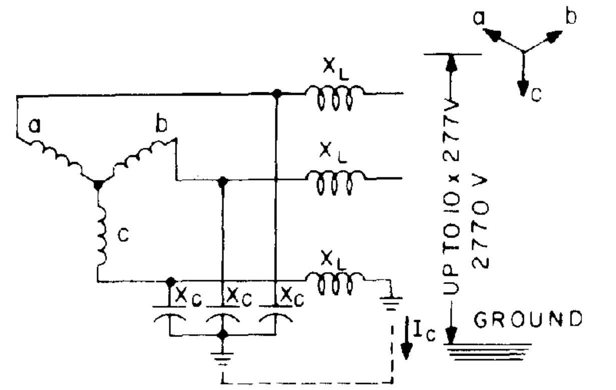



**Figure 5-4: Ungrounded system with remote ground fault on c-phase neutral may be elevated as high as (10) (277)=2770V due to resonant effect of series inductive ($X_L$)—capacitive ($X_C$) circuit.**

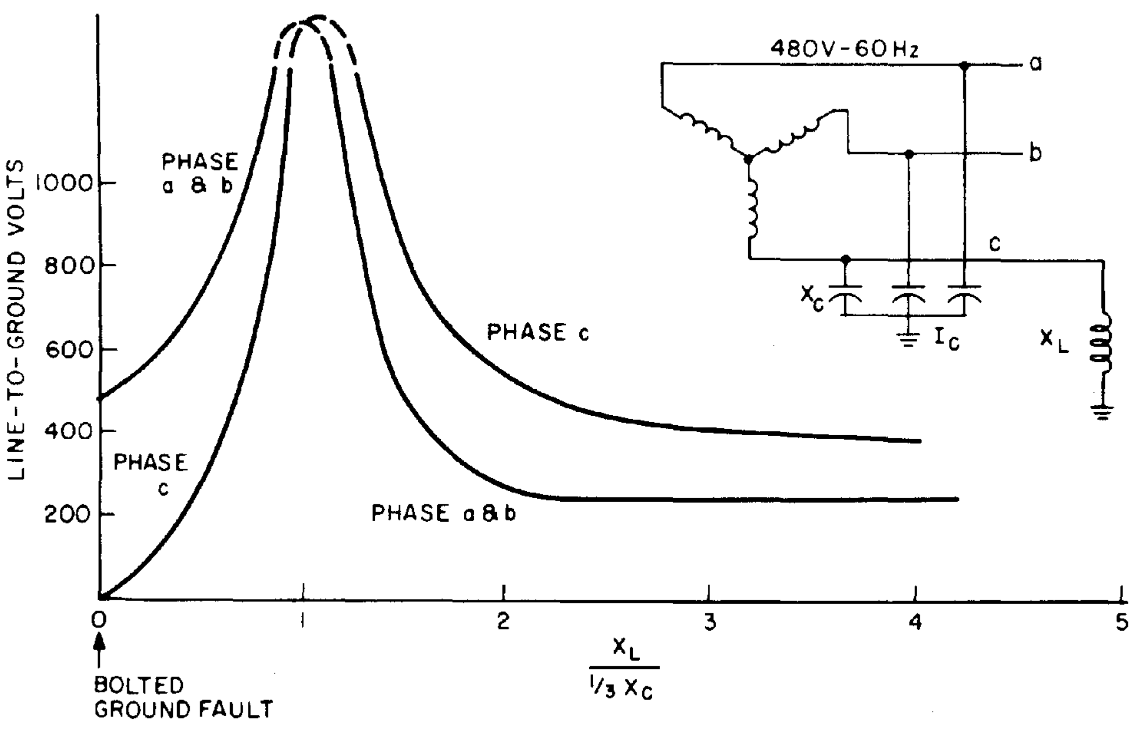
Many other mechanisms can cause overvoltages, which appear between phase(s) and ground. In most cases the line-to-line voltages are not affected. In the majority of cases, the offending agent is the capacitive coupling between phases and ground, which in effect unintentionally "loosely" grounds the neutral.

These transient overvoltages can usually be effectively curbed by intentionally grounding the neutral. The ultimate is a *solidly grounded neutral*. No appreciable voltage excursions can appear in this case between neutral and ground.

By inserting increasing magnitudes of resistance between the neutral and ground, the neutral will be allowed to assume an increasing voltage to ground under ground fault conditions. Analytical studies and tests have proven that transient overvoltages due to the series resonance and repetitive restrike effects can be restrained to acceptable levels by sizing the neutral resistor such that the ground fault current magnitude is slightly higher than the total 480V system charging current, (Fig. 3-5, P. 8) or about 1 to 1.5 amperes on the average low voltage system.

In the region of effective grounding the ground fault current magnitude will vary between a maximum of about the 3-phase fault magnitude (20,000A in Fig. 3-3, P. 7) to a minimum of about $\sqrt{2}$ times the charging current (1.414A in Fig. 3-5, P. 8). Operation in the region of maximum current requires the immediate separation of the ground fault from the system. A neutral resistance which limits the ground fault to essentially 1-2 amperes obviates separation. This current is sufficiently low to do no severe damage quickly, but expedient steps should be initiated to localize and orderly remove the fault from the system. Such systems are classified as *high resistance grounded* systems.

It should be noted that the low values of current are acceptable only if resistance limited. If reactance limited, the lower limit of ground fault is about 25% of the 3-phase value for reasons of controlling transient line-to-ground overvoltages.




$I_C = \frac{e_{L\text{-}N}}{1/3X_C} \rightarrow X_C = \frac{3\times e_{L\text{-}N}}{I_C}$ Typically $I_C = 1$ Ampere

$X_C = \frac{3\times 277}{1} = 830$ ohm at 60 HZ.

**Figure 5-5: Effect of $\frac{X_L}{1/3\,X_C}$ ratio on line-to-ground overvoltages.**

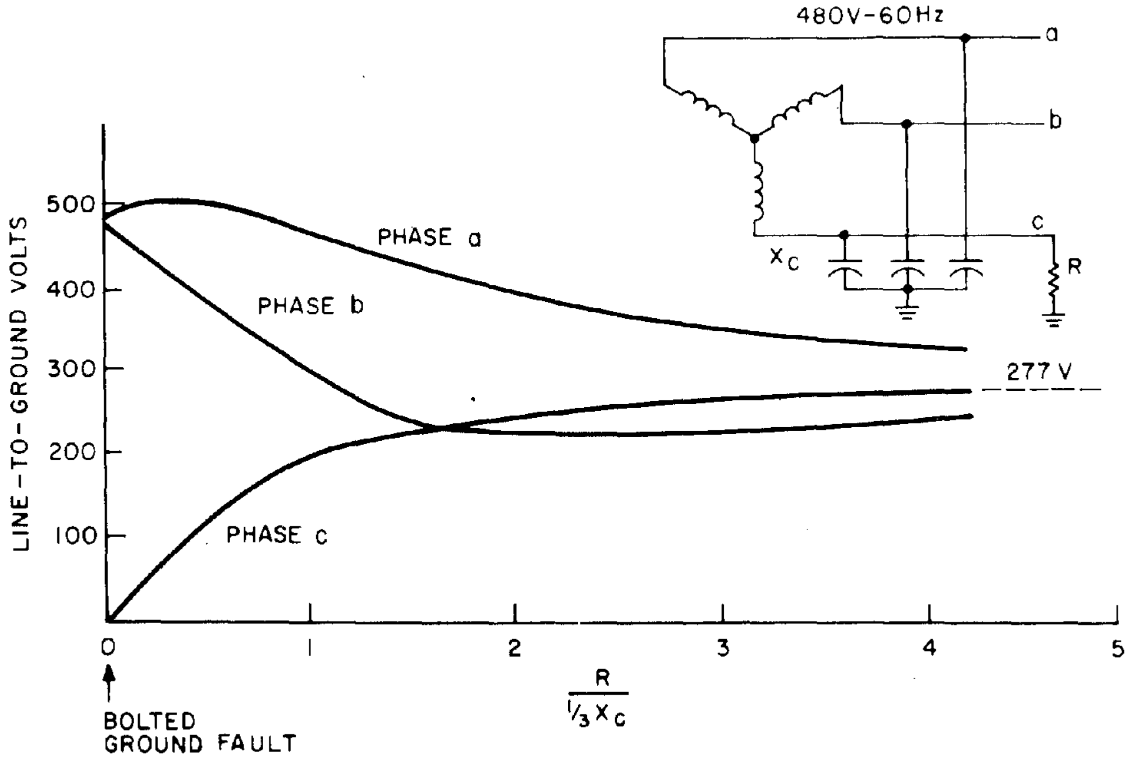



**Figure 5-6: Effect of $\frac{R}{1/3\,X_L}$ ratio on line-to-ground voltages.**

When selective ground fault relaying is desired, such as is used in medium voltage systems, the need for a higher magnitude of resistance limited ground fault current will be indicated.

A 400 ampere ground fault level for instance is popular in systems 2.4 through 13.8 KV because of available ground fault relay sensitivities. This so-called *low resistance grounded* neutral approach is not commonly used in low voltage system design for these reasons:

a. The first ground fault will still result in an unscheduled shutdown—if this is objectionable, the high resistance grounded neutral offers the desired continuity.

b. Separate ground responsive trips or relays are required in greater quantities to meet the basic desire for selectivity—the high resistance grounded system requires only one ground fault detection equipment.

It should be noted that users of single-phase one-side grounded circuits (277V in 480V and 120V in 208V systems) have no choice but to solidly ground the neutral conductor.

**B. Service continuity affected by ground fault**

The previous discussion indicates that by selecting a solidly grounded neutral mode, the ground fault should be removed promptly. In continuous process plants and for other extremely sensitive loads, the resulting unscheduled outages may have serious consequential effects. In such cases the system is grounded through a 150–300 ohm resistor. Now the ground fault is limited to about 1 ampere, which can be allowed to persist long enough to arrange for an orderly shutdown of the affected critical loads. All too often, however, delays in locating and clearing the first ground fault allows a second such fault to occur on a different phase, creating a line-to-line fault condition which defeats the basic objective of this operating mode.

**C. Probability of sustained arcing line-to-ground faults**

The *solidly grounded* system can potentially produce extremely high ground fault currents, especially in high fault capacity networks. Such an occurrence in an equipment causes considerable arc gases and pressures which if sustained, can produce devastating arcing burndowns especially on 480 volt systems. The proper application of ground fault protective devices will minimize burndowns.

The occurrence of a single line-to-ground fault on a *high resistance grounded* system however will create only a minor arc at the point of ground fault. The potential danger of escalation into a phase-phase or 3-phase arcing fault is therefore considerably reduced. Also, arc gases emanating from arc chutes of a circuit breaker during a fault current interruption are less likely to ignite a secondary fault within the switching equipment housing.

**D. Restrains arcing ground fault escalation in equipments**

The probability of escalating an arcing ground fault into phase-phase and 3-phase arcing faults in equipments is greatly enhanced when the initial ground fault produces considerable arcing, which ionizes the air surrounding bare buses. This may lead to a breakdown of the insulation properties of air and the escalation of the ground fault.

Fast fault removal, a matter of ½ cycle, is essential to help prevent this escalation on solidly grounded systems.

**E. Freedom from arcing ground fault flash hazard**

The arcing fault phenomenon described previously, unless properly controlled through suitable protection, can pose a real personnel hazard because of the explosive character of these faults.

**F. Freedom from stray current arcing hazard**

The discussion related to Fig. 3-4 (P. 7) illustrated the need for a continuous ground return circuit in close proximity to the outgoing power conductors. This requirement is of particular importance in solidly grounded systems. Careless installation practices could potentially result in discontinuities, which could be the cause of severe sparking during ground faults on solidly grounded systems. In areas of combustible mixtures these sparks could set off explosions or fires. The early detection and removal of these ground faults effectively reduces this hazard.

**G. Security against stray fault current electric shock hazard**

The lack of a continuous ground return circuit in solidly grounded systems results in the flow of stray ground currents through pipes, building steel etc. At the point where the current traverses these members, the IR drop across the point of resistive contact could rise to several hundred volts. Personnel straddling the resistive contact could be severely injured.

The high resistance grounded neutral suppresses ground currents and thus the potential of shock hazard in the presence of a single line-to-ground fault.

**H. Resultant fault damage limited**

Fault damage on solidly grounded systems can be effectively reduced by fast fault removal. The selection and setting of trip devices and relays must consider this aspect in the determination of the overall protective characteristics of the system.

Fault damage is inherently limited on high resistance grounded systems provided the first ground fault is removed before the second ground fault occurs. Once a fault escalates into a phase-to-phase or 3-phase fault, the rate of fault current damage will increase enormously.

**I. Ease of locating a ground fault**

The solidly grounded system is the most effective in this respect, while the ungrounded system presents severe problems. In the latter case, the crude approach is based on the process of elimination; sequential tripping of breakers until ground-voltmeters indicate the removal of the faulted circuit. More sophisticatedly, portable electronic monitoring devices can be used to trace the path of the ground fault current. The presence of even small stray currents of fundamental and harmonic frequency, however, may result in inconclusive readings. To establish a clear tracing signal, the grounding resistor can be arranged to be partially and intermittently shorted so as to produce a pulsating tracing signal. Even against the spurious stray currents, the monitoring device can then clearly identify the fault location (see Fig. 8-25, P. 49).

**J. Security against shock hazard due to high-voltage source intrusion**

The danger of medium or high voltage wires falling into or being accidentally brought in contact with low voltage circuits should be considered in selecting the desired grounding mode.

The ungrounded system is extremely vulnerable to this potential hazard. In Fig. 5-7 it is assumed that the A-phase of the solidly grounded 4.16 KV circuit has come in accidental contact with phase b of the ungrounded 480V system. The result will be that the low-voltage b-phase will assume the same potential as the high voltage A-phase conductor (2400 volts to ground). In other words, the tip of the b-phase voltage vector coincides with the rotating A-phase voltage vector tip. The neutral of the 480V system will thus be elevated from ground. The maximum excursion of the 480V system neutral with respect to ground may rise to about 2400+ 277 = 2677 volts maximum. This explains how the ground

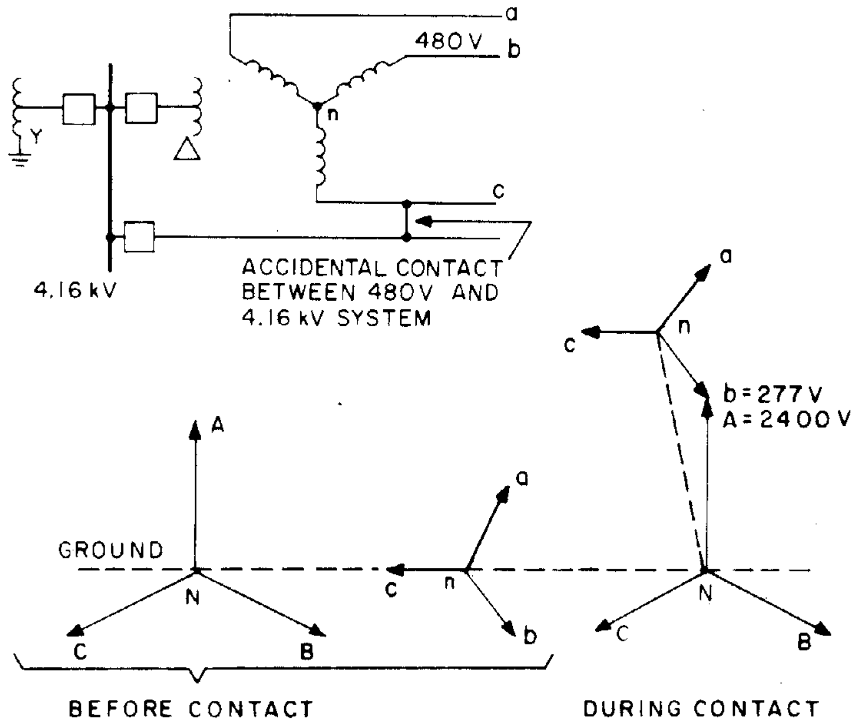



**Figure 5-7: Elevation of low-voltage system above ground due to accidental contact between 480V and 4.16 KV system.**

insulations of all phases of the 480 volts equipments will be seriously overstressed.

These dangerous overvoltages can be avoided by securely anchoring the neutral of the 480V system to ground. The solidly grounded neutral system accomplishes this objective.

**K. Serves single-phase load**

Those systems which supply single-phase one-side grounded loads (480 wye/277 volts or 208 wye/120 volts) must be solidly grounded to provide a stable neutral.

# 6. STATE AND FUTURE OF THE ART

The majority of low voltage systems are and will continue to be solidly grounded. These systems, *if properly designed with ground fault protection in mind,* do not usually require additional ground responsive devices to prevent burning damage due to arcing ground faults. These designs, in general are characterized by main secondary breakers using long time *and short time* trips rated 1200 to 2000 amperes. Feeder breakers are preferably 600 ampere rated *with short time* trips in addition to the usual long time and where appropriate, instantaneous trips.

However, too many system designs show the evidence of insufficient funds or foresight to establish distribution systems consistent with the minimum reliability requirements. Inferior design concepts advocating fewer larger breakers or worse, fewer larger fuses providing the barest arcing ground fault protection, if any at all, can set the stage for destructive arcing faults. When the number and extent of the fault damage incidences began to assume alarming dimensions a gradual up-grading in system design practices emerged.

Although basic agreement and understanding exist on the direction of design improvements, the complexity of the problem tended to obscure from the practicing engineer the real need for the higher degree of system protection.

The National Fire Protection Association has begun to lay the ground work for an acceptable *minimum* standard for the design and protection of low-voltage systems against the possibility of devastating arcing faults. The Board of Fire Underwriters is presently considering the acceptance of NEC article 230-95.

*"230-95. Ground Fault Protection. Ground-fault protection of equipment shall be provided for grounded electrical services of more than 150 volts to ground, but not exceeding 600 volts phase-to-phase for any service disconnecting means rated 1000 amperes or more. The ground-fault protection may consist of overcurrent devices or combination of overcurrent devices and current transformers or other equivalent protective equipment which shall operate to cause the service disconnecting means to open all ungrounded service entrance conductors of the faulted circuit within one second at fault current values of 1200 amperes or more.*

*"When a switch and fuse combination is used, the fuses employed shall be capable of interrupting any current higher than the interrupting capacity of the switch during a time when the ground-fault protective system will not cause the switch to open.*

*"Exception. Where equivalent ground fault protection is provided on the supply side of the service entrance conductors.* (See Fig. 7-11, P. 26, and text for limitations.)

*"Fine print note: It is recognized that ground fault protection may be desirable for service disconnecting means rated less than 1000 amperes on grounded systems having more than 150 volts to ground, not exceeding 600 volts phase-to-phase.*

*"Ground fault protection that functions to open the service disconnect means will not protect service conductors or the service disconnect means but will protect conductors and equipment on the load side of the service disconnect.*

*"It is recognized that ground-fault protection may be desirable for feeder and branch circuits for such systems, coordinated with the required service disconnect means where a maximum continuity of electrical service to the system is necessary.*

*"Each installation will have to be designed and equipment specified by knowledgeable personnel."*

The industry seems to support this proposal although some resistance has been registered against the presumed upgradng effect of the system protection standards. Rightly so, it can be claimed that the proposed one-step of ground fault protection required at the service entrance equipment will result in the shut-down of a complete low-voltage system following a ground fault. This indeed would soon discredit the perfectly sound philosophy of sensitive and fast arcing ground fault protection. However, instead of rejecting the whole concept because of this limitation, the proponents of 230-95 would not only accept the minimum NEC requirement but expand on the concept by providing selective ground fault protection based on the specific protection and continuity requirements.

A prediction of low voltage protection practice forecasts 3-phase 4-wire and 3-phase 3-wire industrial and commercial building systems with solidly grounded neutrals and selective phase and ground responsive trips, or relays.

The industrial 3-phase 3-wire system serving critical loads is expected to move toward the high-resistance grounded system with pulsating tracing signal facilities.

The continuing emphasis on arcing fault protection will be accompanied by increasing demands for electrical equipments designed to minimize the initiation as well as communication of arcing faults within switchgear and switchboards. In spite of such equipment features and improvements, the probability of arcing faults cannot be ignored. Back-up protection in the form of sensitive ground fault protection is expected to find acceptance.

The additional ground responsive relays and trips are likely to increase the cost of interrupters appreciably. The percentage increase is especially significant on smaller and lower priced equipments. The function-cost trade-off will establish a price level below which the ground fault protection feature can no longer be justified economically. This development will consequently require that *ground fault* protectors on the larger upstream interrupters be coordinated with downstream *phase overcurrent* direct-acting trips. The proper anticipation of compatibility between such devices in the early specification phase of the design activities requires an increasing intelligence and experience level on the part of the design engineer. As a result, selectivity studies on low voltage systems are expected to become the rule rather than the exception.

It would not be surprising if as a result of the current re-evaluation of ground fault practices many radical or minor deviations from those predicted will be proposed and utilized. Such proposals need to be carefully scrutinized to ascertain that not only specific problem areas are properly solved, but more importantly that no other unrecognized problems are inherently introduced.

# 7. GROUND FAULT PROTECTION PRINCIPLES

The renewed interest in ground fault protection will surely include a demand by users for equipments with the greatest possible freedom from arcing ground faults. Considerable progress has been made to provide such equipments within economic feasibility. AKD-5 switchgear, for instance, incorporates important safeguards against arcing faults by the use of compartmentation (Fig. 7-14). The patented application of this concept provides for the physical separation of the following components in AKD-5 switchgear:

1. The main bus from transformer to main secondary breaker.
2. The main secondary breaker itself.
3. The load bus.
4. Each feeder breaker.
5. The customer cable.

The resultant construction not only considerably reduces the probability of an arcing fault, but it also reduces the possibility of fault communication to other energized components. In spite of these precautions however, electrical failures cannot be ruled out. Proper system design practices recognize this possibility by incorporating supplemental back-up protection in the form of ground fault protection.

These voluntary or compulsory ground fault protection requirements eliminate from the list of options those interrupters and switches which cannot or should not be opened in the event of a ground fault in a solidly grounded system.

The implementation of adequate ground fault protection is dependent upon the interrupter (power circuit breaker, molded case breaker, fused switch), the equipments (switchgear, switchboard, individual enclosure), the type of circuit to be protected (cable, busway) and the economics of the acceptable options.

The addition of ground fault protection appears to be especially costly on the smaller, lower priced interrupters and switches. These smaller devces are as a result not likely to be equipped with ground fault relays unless a product development break-through produces a more economical ground responsive device. The evaluation of the economics of the functional equivalents *including* ground fault protection as a result may not always follow the established patterns pertaining to devices for phase protection only.

To clarify the discussion on the application aspects of the various options, it is essential to first develop an understanding of the operation of four distince modes of ground fault detection:

A. *Broken-delta ground fault protection,* (BDP) relies on the measurement of voltage across broken-delta-connected current sensors. In this arrangement a voltage will appear across the broken delta only when a ground fault develops in the system. The Power Sensor ground fault (PSG) option, available on type AK power circuit breakers, makes use of this method of detection by monitoring the outgoing ground fault current.

B. *Ground-sensor protection,* (GSP) is based on a combination of a donut-type current transformer which surrounds all 3 or 4 outgoing conductors *and a specific* overcurrent relay with either instantaneous or time-delay operating characteristics. The current transformer produces an output proportional to the ground fault component of the total *outgoing* current.

C. *Ground return protection,* (GRP) relies on a bar- or donut-type current transformer and a conventional time-delay or instantaneous relay. The current transformer measures the ground fault current as it *returns* to the source of power.

D. *Residual ground fault protection,* (RGP) measures the outgoing ground fault current in the residual circuit of three phase current transformers. Although frequently applied in medium voltage applications, this scheme is hardly ever used at low-voltage levels because of the need for three current transformers. Only for special applications may residual ground fault protection be practical. For this reason, no further reference will be made to this mode of ground fault protection.

Monitoring the *outgoing* ground fault current is the most reliable mode of ground fault sensing because the sensors respond to the *total* ground fault current. Thus the broken-delta (BDP) and ground-sensor (GSP) modes should be preferred. The broken-delta application is preferred for use with AK breakers equipped with static Power Sensors. The ground-sensor approach is applicable to molded-case breakers and AK power circuit breakers equipped with direct-acting EC trips.

The ground return protection (GRP option should be avoided whenever the possibility exists that a part of the total ground fault current might bypass the GRP function on its return path to the transformer neutral.

## BROKEN-DELTA GROUND FAULT PROTECTION (BDP)

This protection concept is incorporated in the new solid state ground fault protection available in the static Power Sensor (PSG) trip device (Fig. 7-1). The design is based on the measurement of the *outgoing* ground fault current in either 3 or 4 wire, 3-phase systems and is limited to 60 Hz applications. In the 3-wire system, three air-core transducers with linear characteristics (linear couplers) are connected in series or delta. A separate transducer in the neutral conductor at the location where it connects to the insulated neutral bus is needed when the system serves single-phase one side grounded loads as well as 3-phase loads.

Limiting the explanatory discussion to the ground fault protection circuit shown in Fig. 7-1, the air-core transducers are connected in series so as to measure the so-called broken-delta voltage. An understanding of the operation of this method of ground detection can be gained by the following discussion.

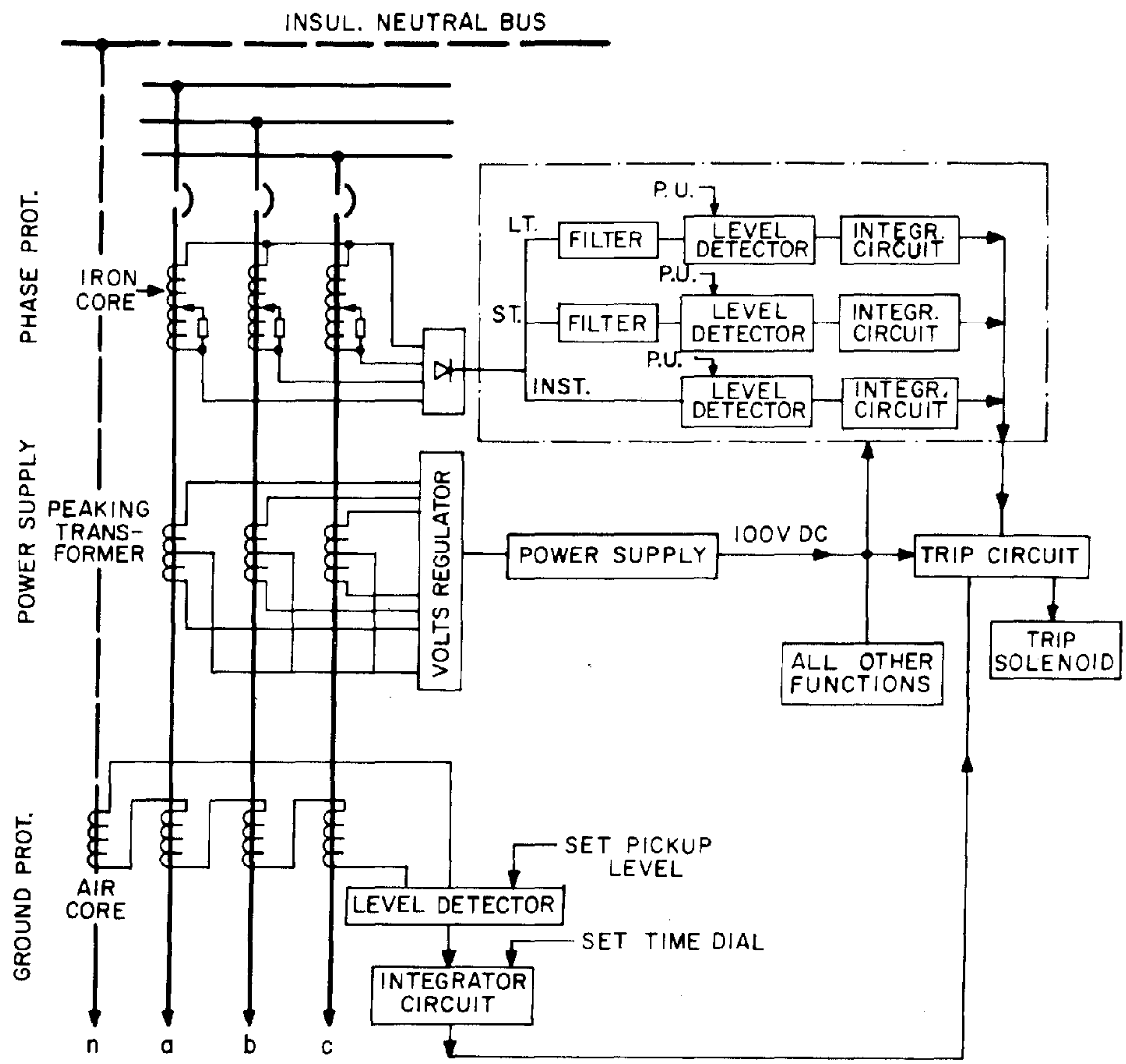



**Figure 7-1: Functional block diagram of Power-Sensor static trip device.**

In 3-phase 3-wire systems (Fig. 7-2) with normal *balanced* loads, the broken-delta voltage ($V_{\Delta 1}$) should be zero since the vectorial sum of the primary currents add up to zero. The secondary voltages are not only equal but also displaced by 120°. The series connection will force the voltages a, b and c to assume the vectorial positions shown. The broken-delta voltage ($V_{\Delta 1}$) is measured between the tail of vector "a" and the tip of vector "c". The vector diagram shows that this voltage is zero.

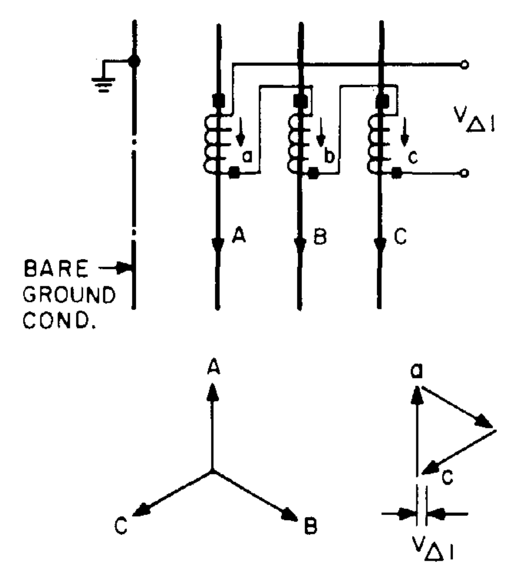



**Figure 7-2: For balanced 3-phase operation, in 3-phase, 3-wire system, $V_{\Delta 1}=0$.**

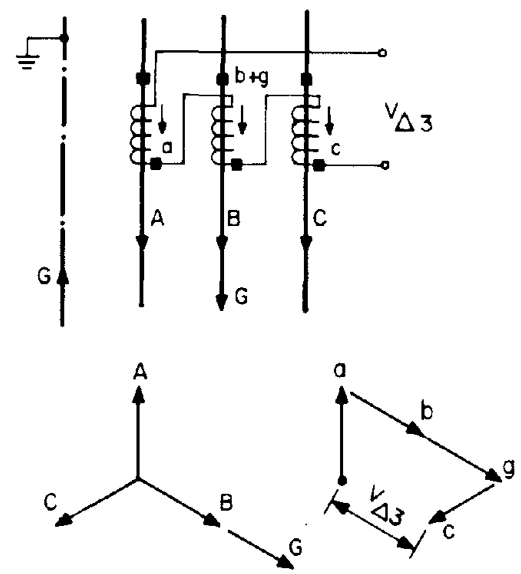



**Figure 7-4: For ground fault condition in 3-phase, 3-wire system, $V_{\Delta 3}$ not equal to 0.**

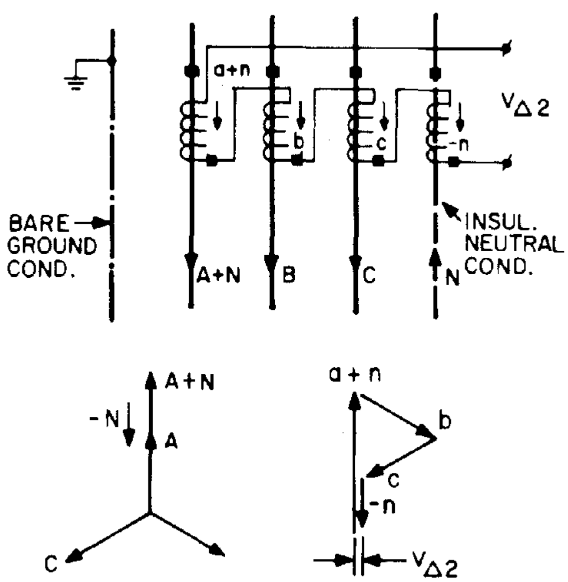



**Figure 7-3: For unbalanced (line-to-neutral) load operation in 3-phase, 4-wire system, $V_{\Delta 2}=0$.**

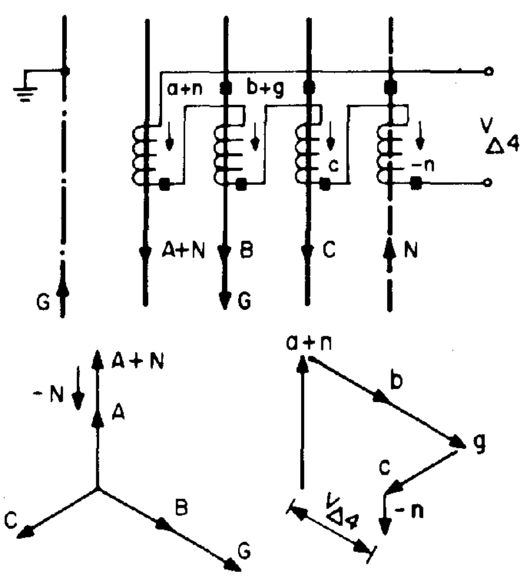



**Figure 7-5: For ground fault condition in 3-phase, 4-wire system and unbalanced load operation, $V_{\Delta 4}$ not equal to 0.**

Fig. 7-3 shows that under *unbalanced* load conditions the broken-delta voltage $V_{\Delta 2}$ still equals zero. This has been made possible by the addition of a linear coupler, measuring the neutral or unbalanced load current.

When a ground fault develops, in phase B for instance, an additional component of current G will flow out on phase B and returns through some external ground return circuit. (Fig. 7-4). In the vector diagram, ground current G shows up as an extension on the B-phase current. This higher current induces a corresponding higher voltage in the B-phase transducer. The net effect is that a voltage appears across the broken delta ($V_{\Delta 3}$). A voltage sensitive device could be made to respond to such voltages.

This principle works equally well on 3-phase 4-wire systems, provided an additional linear coupler is added to measure the unbalanced current flowing in the insulated neutral conductor. (Fig. 7-5).

In the broken-delta voltage scheme, the voltage signal used is the vectorial sum of the *individual* voltages induced in each of the current sensors. For this reason it is essential that the primary current in each phase be accurately transduced to a secondary voltage. To aid in this objective, air-core transformers are used. When so applied these transformers are also referred to as "linear couplers." Iron core transformers are likely to introduce inaccuracies in transducing the primary currents to secondary signals due to saturation of the iron core in the presence of relatively high current magnitudes especially those with d-c components or higher harmonic contents.

**GROUND SENSOR PROTECTION (GSP)**

This principle is based on the measurement of the total *outgoing* current by a toroid or donut type current transformer which surrounds the 3 power conductors and any neutral wire (on 4 wire systems). The magnetic flux produced by each of the 3 phases of the usually balanced load has a cancelling effect as observed by the donut-type current transformer. (Fig. 7-6).

Even an unbalanced load caused by a line-to-neutral load is not sensed by the donut-type current transformer and GSR relay since the outgoing and returning current are equal but in opposite direction. (Fig. 7-7). A ground fault, however, will go through the current transformer towards the fault but will return through a ground return circuit external to the donut-type current transformer (Fig. 7-8A).

For proper operation on any 3-phase, 4-wire system it is essential that the neutral conductor *not* be grounded on the downstream side of the ground-sensor. Therefore, circuits servicing ranges, cook tops etc. should not be protected with ground-sensors.

At this time it is essential to clarify the semantics related to *zero-sequence currents* and *ground-sensors*. The ground fault literature oftentimes refers to ground fault currents as zero-sequence currents. Similarly, donut-type current transformers surrounding all outgoing power conductors are labeled zero-sequence current transformers. These expressions have their origin in the "symmetrical component" analysis, a powerful tool to analyze the performance of a power system in terms of positive, negative, and zero sequence networks. In effect, the ground fault current is evaluated in terms of the zero sequence current component and is fixed by the relationship that the ground fault current equals three times the zero-sequence current ($I_G = 3I_O$). For the purpose of this publication, no knowledge of symmetrical component analysis is assumed.

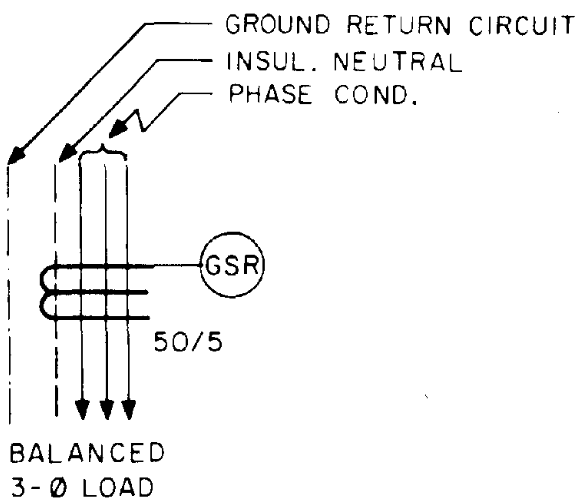



**Figure 7-6: Ground-sensor relay is insensitive to balanced 3-phase load currents.**

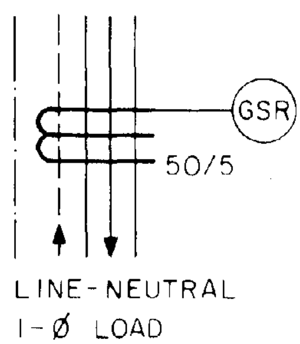



**Figure 7-7: Ground-sensor relay is insensitive to line-to-neutral load if neutral conductor is inserted in donut-type current transformer.**

The terms ground-sensing, ground-sensor and ground-sensor relay imply that ground fault protection relies on a *specific* and economical combination of the relay and donut-type current transformer which surrounds all power conductors. To attain sensitive ground fault protection only small (as low as 50/5; more commonly 500/5) CT ratios are considered. The small current transformer ratios are made possible by the fact that these current transformers are blind to the normal balanced or unbalanced load currents. Occasionally the use of even smaller current transformer ratios and/or extremely sensitive relays are proposed if ground fault sensitivities less than about 15 primary amperes are required.

The accuracy of economical current transformers of small ratios (50/5) in the presence of high ground fault currents is relatively poor but nevertheless acceptable. The poor performance is caused by the saturation of the transformer core in the presence of relatively high primary currents. As a result, most of the secondary winding current is absorbed in the form of excitation current ($I_e$). The equivalent circuit of Fig. 7-8B shows that only 9 amperes out of 80 amperes will be seen by the relay, an IAC53A relay set at 0.5 ampere. Under these conditions the relay exhibits an impedance of about 2 ohms. It is interesting to note that the current transformer saturation effect tends to protect the relay in that the voltage applied to the relay will not exceed about 20 volts for the JCB-0 current transformer and IAC53A3A relay combination. This limits the relay current to about 10 amperes, regardless of the magnitude of the primary current.

The phenomenon has of course a desensitizing effect on the relay. To illustrate the approximate extent of the "error" introduced by current transformer saturation, Fig. 7-9 shows the operating characteristic of an IAC53 relay set at 0.5 amp. tap and a 5 time dial. The difference between the operating curves with an ideal and a 50/5 ground-sensor current transformer is considerable but acceptable. As CT ratios increase, these differences tend to reduce.

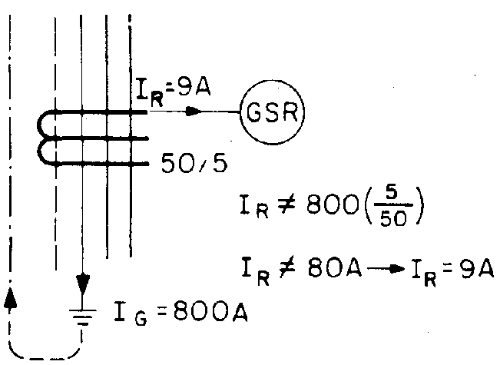



**Figure 7-8A: Ground-sensor relay operates for ground fault current not returning through the donut-type current transformer. Note CT ratio error.**

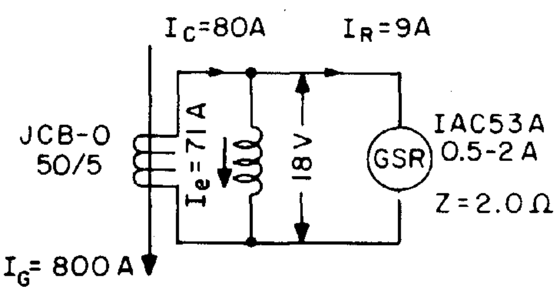



**Figure 7-8B: Approximate equivalent circuit of current transformer and relay.**

The determination of settings of selective steps of ground fault tripping must be based on the operating characteristics of the *specific* current transformer and relay combination. Considering the many possible current transformer and relay combinations, only a few combinations are actually tested and offered as a ground-sensor relaying scheme. Donut-type current transformers with larger and smaller openings are offered to accommodate larger and smaller conductors as well as bus bars.

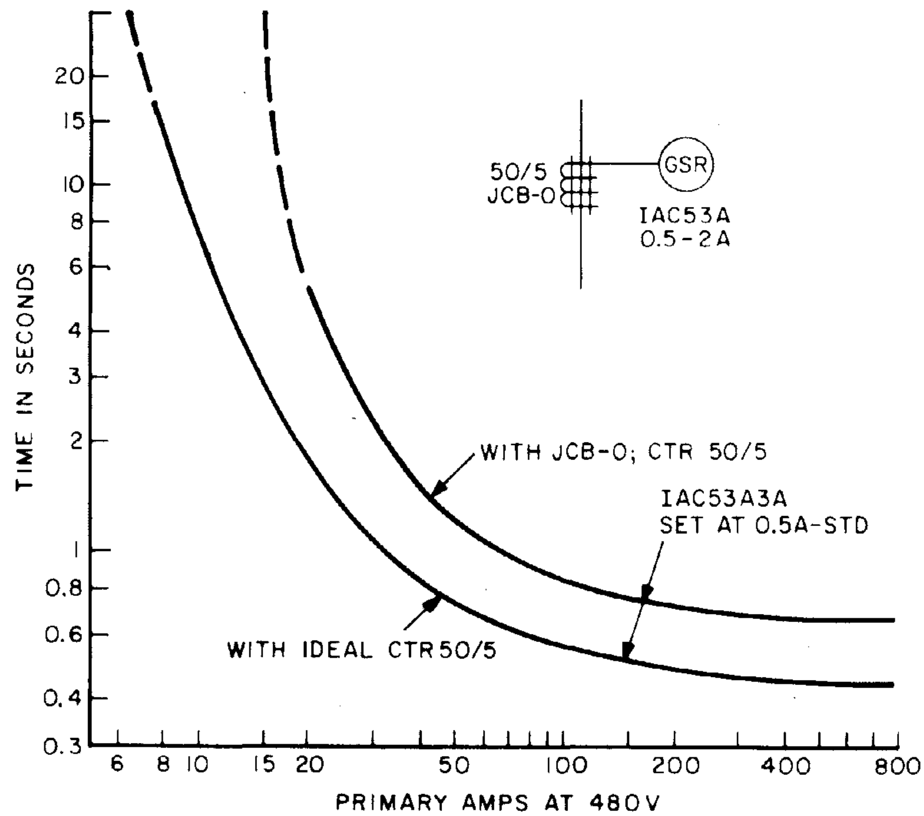



**Figure 7-9: Effect of CT saturation on relay operating characteristic. This effect reduces with increasing CT ratios.**

It should be noted that the relay input current is derived from the *outgoing* ground fault current only. The installation of these current transformers requires special care to help assure that the return current passes *outside* the ground-sensor current transformer.

Fig. 7-10 illustrates typical installations of ground-sensor current transformers using either cable in conduit or interlocked armor cable. The wrapping of a non-magnetic braid or tape helps to tightly bundle the 3 or 4 conductors thereby reducing the possibility of inducing small error currents in the current transformer in the presence of extremely large transients or load currents. The termination clamp used with interlocked armor cable must be isolated from ground for the purpose of sensing a ground fault in the segment between the current transformer and the termination clamp. In this event, the ground current must pass through the current transformer before it can seek a ground return path.

### GROUND RETURN PROTECTION (GRP)

Ground fault currents must return to the transformer neutral to complete the circuit. The GRP approach attempts to seek strategic locations in the system equipments which can be relied upon to pass all or most of these return currents. It goes without saying that at the time of installation and thereafter, proper safeguards must be taken not to alter the preferred path of the return current so as to render the GRP inoperative.

The most reliable application of the GRP principle is in the *transformer neutral connection to ground.* (Fig. 7-11). Installed in this location, all ground currents will be sensed by the transformer neutral ground relay (GRR). Operation of the GRR indicates that the ground fault may be on the bus, in the transformer winding or its extension to the line terminals of the main secondary breaker. To provide the proper protection, the relay should be wired to trip the main

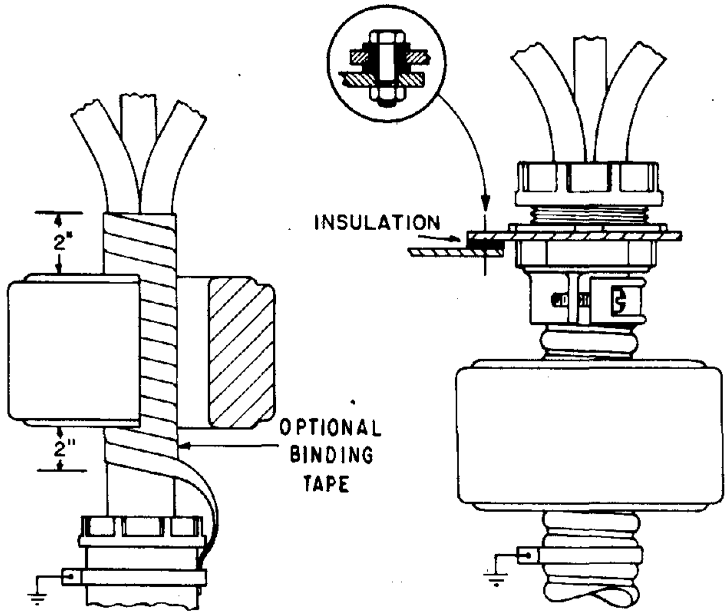



Figure 7-10: Typical installations of donut-type current transformers. Power source assumed to be at top.

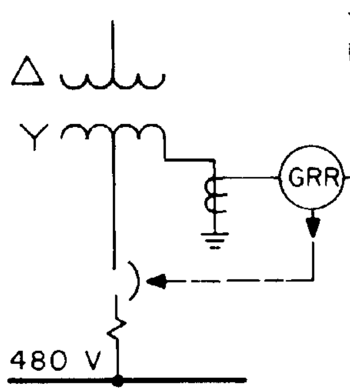



Figure 7-11: Transformer neutral ground fault protection.

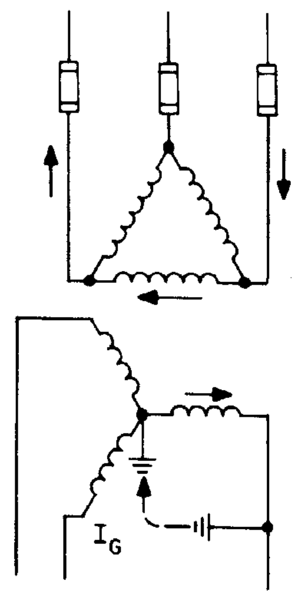



Figure 7-12: Ground fault appears as phase-to-phase overcurrent to primary fuse.

secondary breaker <u>and</u> to start a timer. If about 5 cycles after breaker operation, the fault is still sensed by the GRR, then the relay must signal the transformer primary protector to trip through a *transfer trip* arrangement.

A low voltage ground fault on a system fed through a delta-wye transformer is not reflected to the primary system conductors as ground fault current, but as a phase-to-phase overcurrent. (Fig. 7-12). The higher set and less sensitive *phase-overcurrent* protective devices however are not likely to sense the low voltage *ground fault* unless the ground fault is of the bolted variety. As a result, arcing ground faults are likely to go undetected by the transformer primary protectors, especially when they happen to be fuses.

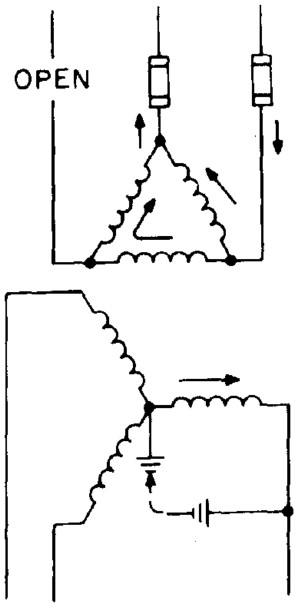



Figure 7-13: If fuse blows, ground fault current continues at low values of current.

Only a service entrance interrupter, properly equipped with arcing ground fault protection, can remove these faults on the load side of the interrupter. Protection for the incoming circuit down to the line side of the interrupter has to be provided by the utility company supplying the power. Arrangements for the proper form of protection needs to be made with the power company.

A bolted 480V ground fault could cause one of the primary fuses to blow (Fig. 7-13). The opening of one primary phase however does not remove the ground fault. The horizontal leg of the transformer (Fig. 7-13) is still energized. Even though the winding impedance has increased the ground fault is still very much in existence but at considerably lower current levels. (See fig. 8-14, P. 42, and text for details.)

The transfer trip function is relatively simple to implement if the transformer primary protector is physically close to the transformer. Remotely located protectors complicate the problem to the extent that it has often been ignored because of the degree of difficulty and for economic reasons. The risks associated with the absence of transfer tripping can be minimized by installing the transformer in the closest possible proximity to the main secondary breaker and to physically isolate this short bus section from all other compartments. This concept of *compartmentation* is being used effectively in AKD-5 load center unit substations. (Fig. 7-14A. Fig. 7-14B next page.)

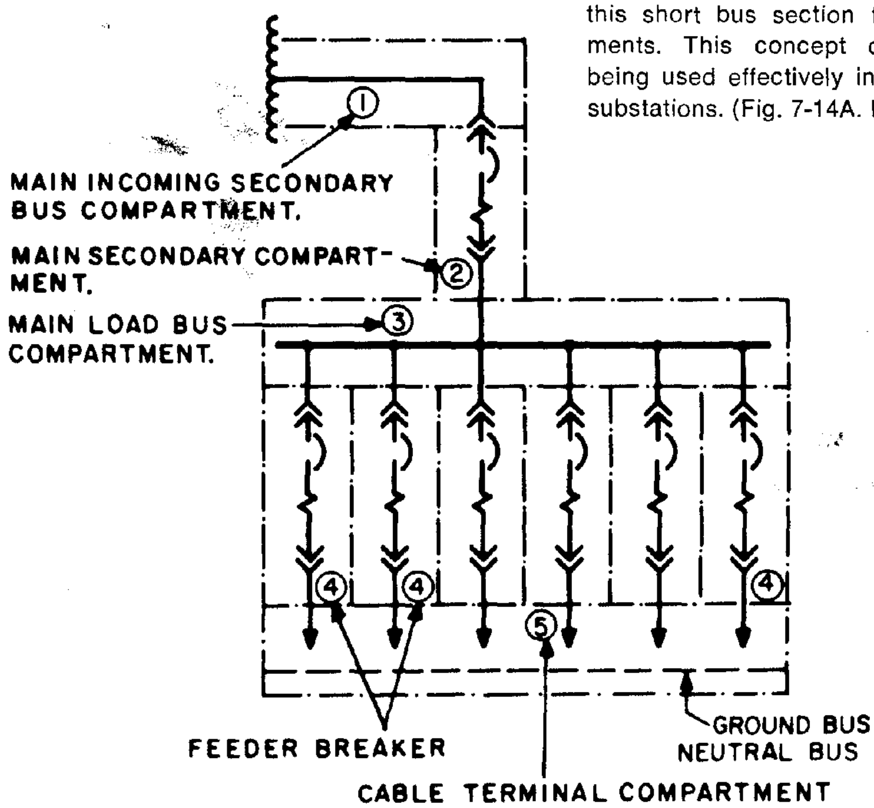



Figure 7-14A: One-line diagram showing patented AKD-5

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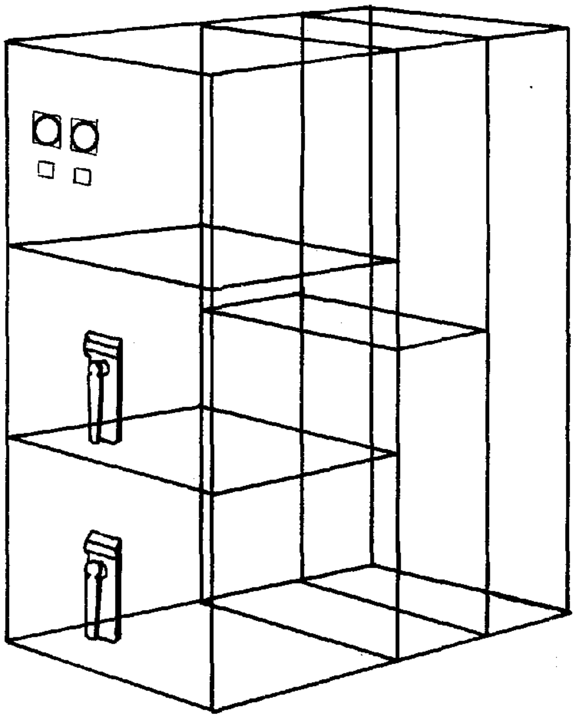

**Figure 7-14B: Isometric view of AKD-5 switchgear showing compartmentation principle.**

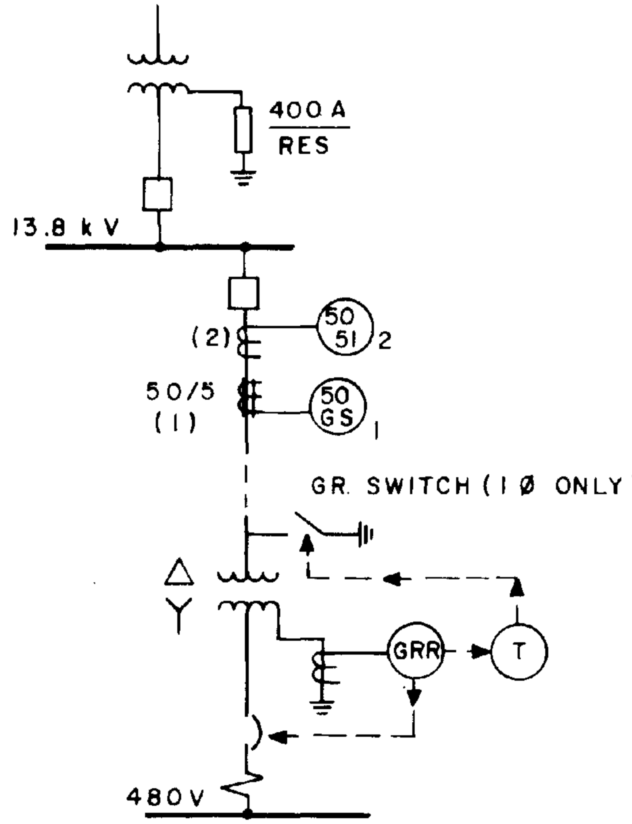


**Figure 7-15: One-line diagram showing use of electrically operated grounding switch on 400 amp resistance grounded 13.8 kV system to de-energize faulted 480 volt transformer.**

When a transfer trip function is required in the case of remotely located protectors, the use of a grounding switch should be considered (Fig. 7-15). Especially when the primary protection operates in a low resistance (400A) grounded medium voltage system, operation of the ground switch should cause minimum disturbance.

The effectiveness of the GRP principle becomes questionable when the transformer neutral is not available to monitor the ground fault current. In such instances the usefulness of the GRP option depends largely upon the low ground return circuit impedance meaning the transformer neutral wire should be installed in close proximity to the out-going power conductors, as described in Fig. 3-4 (P. 7). This helps assure that most of the ground fault current will follow a predictable path. A current transformer in this path will thus monitor most of the ground current.

# 8. APPLICATION OF GROUND FAULT PROTECTION

## ON SOLIDLY GROUNDED SYSTEMS

The application of ground fault protection on solidly grounded systems is relatively simple if a complete and separate set of ground fault relays is available with each interrupter. The main reason for the absence of these ground responsive devices is the cost of the addition of a ground fault protector; as high as about 25–40% of the basic interrupter price. As a result, system designers are expected to place a greater emphasis on system design practices which tend to produce conditions whereby the phase overcurrent protector has sufficient sensitivity and speed to provide arcing ground fault protection as well.

To underline this development, this chapter will deal with these considerations before presenting a detailed discussion on the various ground fault schemes.

### Limitation of phase-overcurrent devices

The usefulness of phase overcurrent devices in providing arcing ground fault protection was introduced in chapter 4, and summarized in table 4-b (P. 11). To pursue this concept in greater detail, Fig. 8-1 is presented to illustrate the approximate boundaries of effectiveness of the usual direct acting trip devices.

On the basis that the probable minimum arcing ground fault current magnitude is about 38% of the 3-phase bolted fault current; the uppermost dashed line (Fig. 8-1) represents this linear relationship. To help assure that a protective device will definitely respond to an arcing ground fault, the device should be set to pick-up at about two-thirds of the probable minimum arcing ground fault. It is further necessary that at pick-up, the device operate in less than 30 cycles.

These sensitivity and speed requirements can be met only with instantaneous and/or short-time trips in addition to the usual long-time trip characteristic. Instantaneous elements, of course, preclude selectivity with down-stream devices, making the short-time trip necessary where selectivity is desired.

To illustrate the use of Fig. 8-1, assume that a 150 HP, 460V motor is being considered. The starting equipment requires a breaker with a continuous current rating of 250 amp. The starting time and inrush allow a 10 x instantaneous setting. The phase overcurrent trips are expected to provide adequate ground fault protection if the bolted 3-phase short-circuit current at the starter location equals or exceeds 9800 amperes. These conditions may not always exist in 480V systems at the starter location.

As a second illustration of the use of Fig. 8-1, assume a 1600 ampere main secondary breaker is considered with a short-time trip set at 8 times. The phase-overcurrent trips will provide ground fault protection only if the 3-phase fault exceeds about 50,000 amperes. This short-circuit current exceeds the usual magnitudes associated with a 1600 ampere main secondary breaker. Therefore, additional ground responsive devices should be provided to prevent severe equipment burning damage due to undetected arcing ground faults.

Alternatively, if selectivity of phase overcurrent trips permit, the short-time trip on the 1600 amp breaker could be set at 3 times or 4800 amp. This combination should provide arcing ground fault protection on systems with a 3-phase available short circuit current of 18,000 amps or more.

Fig. 8-2A shows that a 1600A upstream interrupter with a Power Sensor long-time, short-time (LS) trip set at 3 times proves to be selective with a downstream interrupter with a 400 amp long-time, instantaneous (LI) trip set at 10 times or 4000 amps. However, loss of selectivity over a certain range must be expected when the downstream interrupter trip rating increases. (Fig. 8-2B). The lack of selectivity may not be as serious as it appears for the reason that the *minimum* arcing ground fault magnitude is about 7600 amps. Only in the presence of higher ground return path impedances will selectivity be lost in the current region between about 4800 and 6000 amps.

This discussion indicates that the usefulness and limitation of phase overcurrent trips are to a great extent determined by the relative characteristics and ratings of the interrupters operating in series as well as the available short-circuit current. When the conditions do not produce inherent arcing ground fault protection, additional ground responsive relays or trips should be considered.

### Combining phase and ground responsive trips

Ground responsive trips are required whenever the phase overcurrent trip is incapable of sensing the probable minimum arcing ground fault current and of interrupting such faults in less than 30 cycles.

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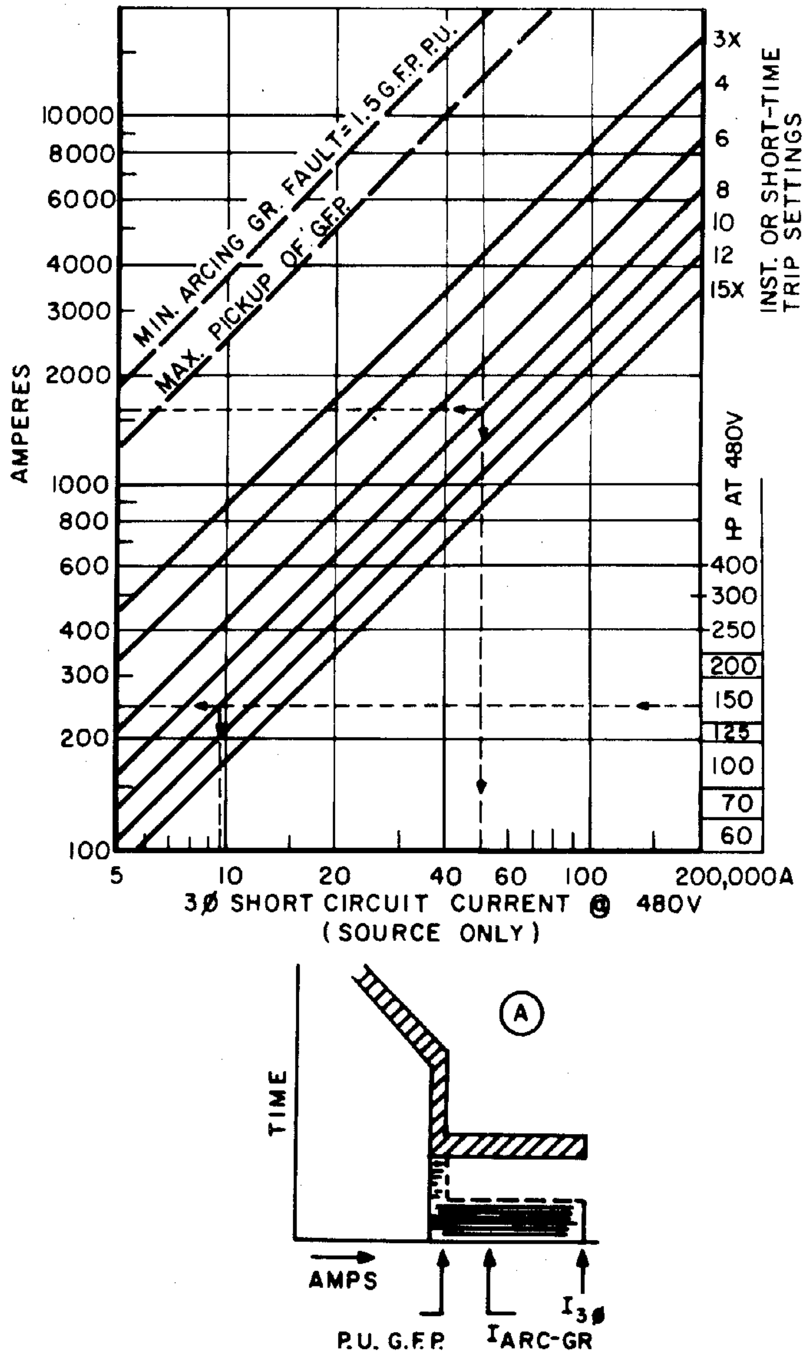


Figure 8-1 and 8-1A: Graph showing approximate effectiveness of short-time or instantaneous trips to provide arcing ground fault protection. Applies only to solidly grounded systems with low impedance ground return circuits.

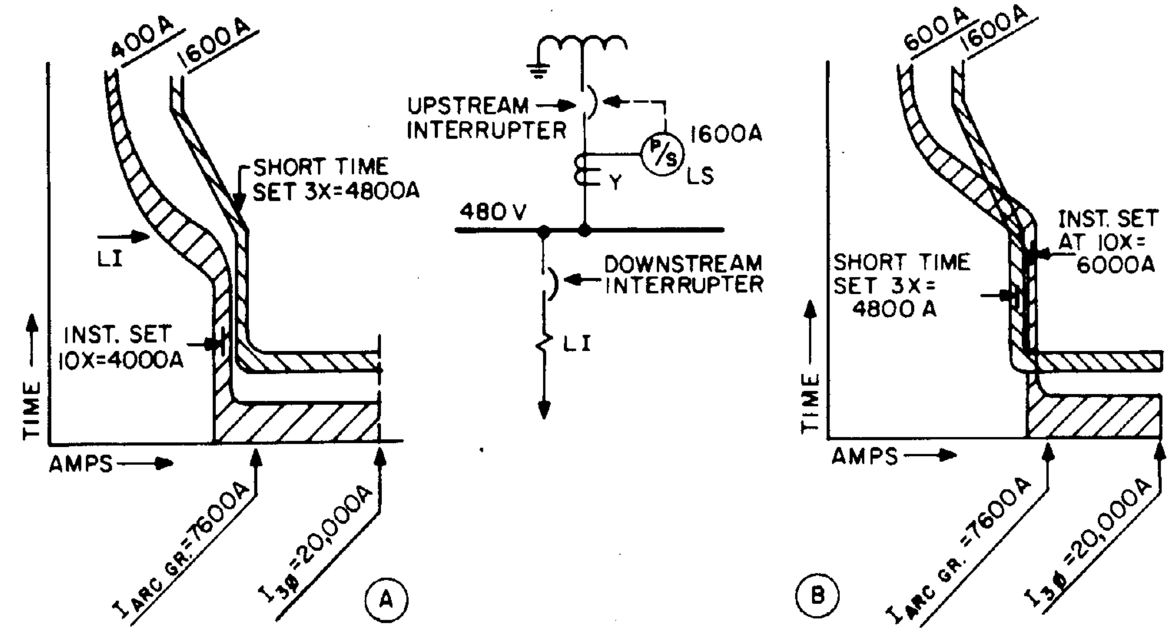


**Figure 8-2: Usefulness and limitation of long-time, short-time (LS) trips on upstream interrupter as an arcing ground fault protector.**

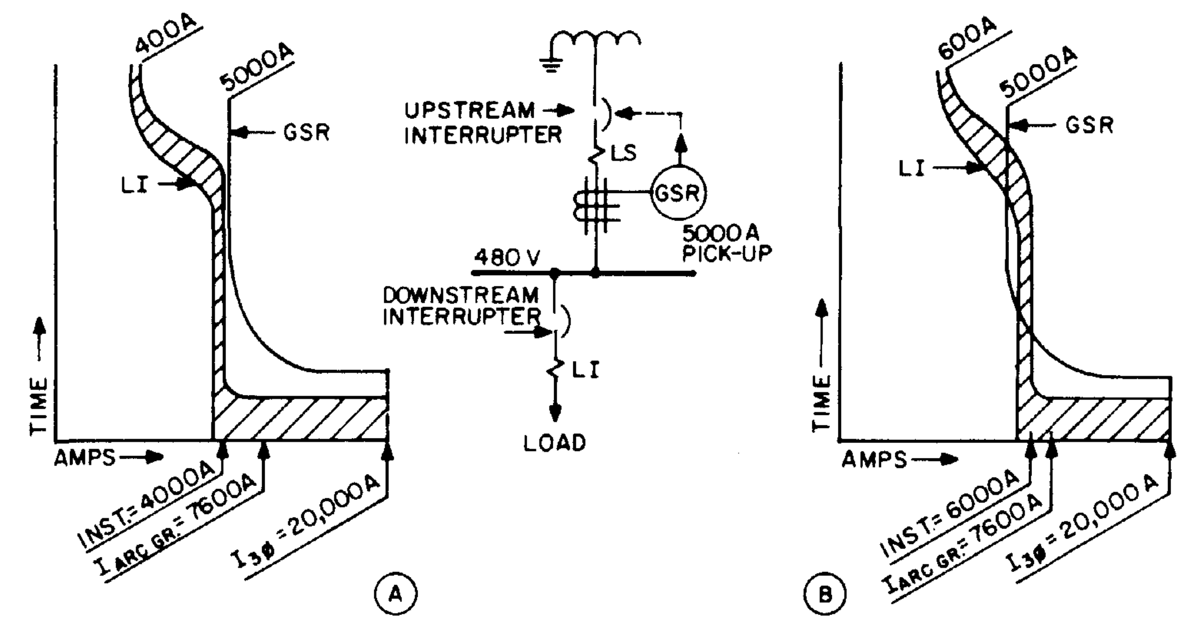


**Figure 8-3: Operating characteristics of 5000A GSR on 20,000A system shown in center, relative to 400A and 600A long-time, instantaneous (LI) direct acting trip.**

Fig. 8-3 again assumes a 20,000 amp, 480 system. Referring to Fig. 8-1 the minimum arcing ground fault is about 7600 amp, which requires a maximum pick up of about 5000 amp on the upstream interrupter (Fig. 8-3A). A ground-sensor relay set at 5000 amp and a low time-dial should provide full selectivity with the 400 amp downstream interrupter. However, a 600 amp breaker (Fig. 8-3B) with an instantaneous setting of 10 times or 6000 amp encroaches on the selectivity objectives. In this example, the apparent lack of selectivity may not be serious for the reason that the probable *minimum* arcing ground fault magnitude is about 7600 amps. Only when high ground return path impedances further limit the ground fault, will selectivity be lost.

Even though a 5000 amp ground fault sensitivity appears adequate, system designers tend to favor more sensitive ground fault protection. Minimum sensitivities of 400 to 600 amp have been suggested as a practical compromise. As expected, selectivity is being sacrificed to a greater degree as shown in Fig. 8-4B. This disadvantage is usually considered acceptable based on the small probability that the arcing ground fault is less than the calculated *minimum* level of 7600 amp on a 20,000 amp system. (See Fig. 8-1).

### Implementation of ground-sensor protection (GSP)

The ground-sensor principle is commonly used on molded-case breakers and on AK breakers equipped with EC trip devices. (The Power Sensor Ground option is preferred on AK breakers with P/S trips). The installation details for 3-phase 3-wire and 3-phase 4-wire systems are shown in one-line diagram format in Fig. 8-5. In the 4-wire case, the *insulated* neutral conductor must be carried from the switchgear neutral bus back to the transformer neutral. The *bare* ground return conductor on closely coupled transformers is usually carried back to the transformer neutral. If the transformer is remote, this bare ground wire should be connected at Q rather than at N (Fig. 8-5B). Note that Q is located *between* the GSR current transformer and the transformer neutral.

The insulated neutral wire must *not* be grounded on the downstream side of the GSR in the feeder circuit to help assure the proper operation of this GSR function.

The GSR will *not* operate on a ground fault between the GSR CT and the transformer. The probability of such faults can be considerably reduced by minimizing this spacing *and* by mounting this cable or bus section in a separate enclosure (see Fig. 7-14, P. 27). Additional protection can be installed as shown in Fig. 8-6. The ground return relay must be wired to trip the main secondary *and* to start a timer which in turn signals the transformer primary interrupter to trip when the fault exceeds the set time on the timing relay. The GRR function can be performed by an IAC53A relay and a bar type CT. The CT ratio should be selected such that the GRR will pick up at a current slightly higher

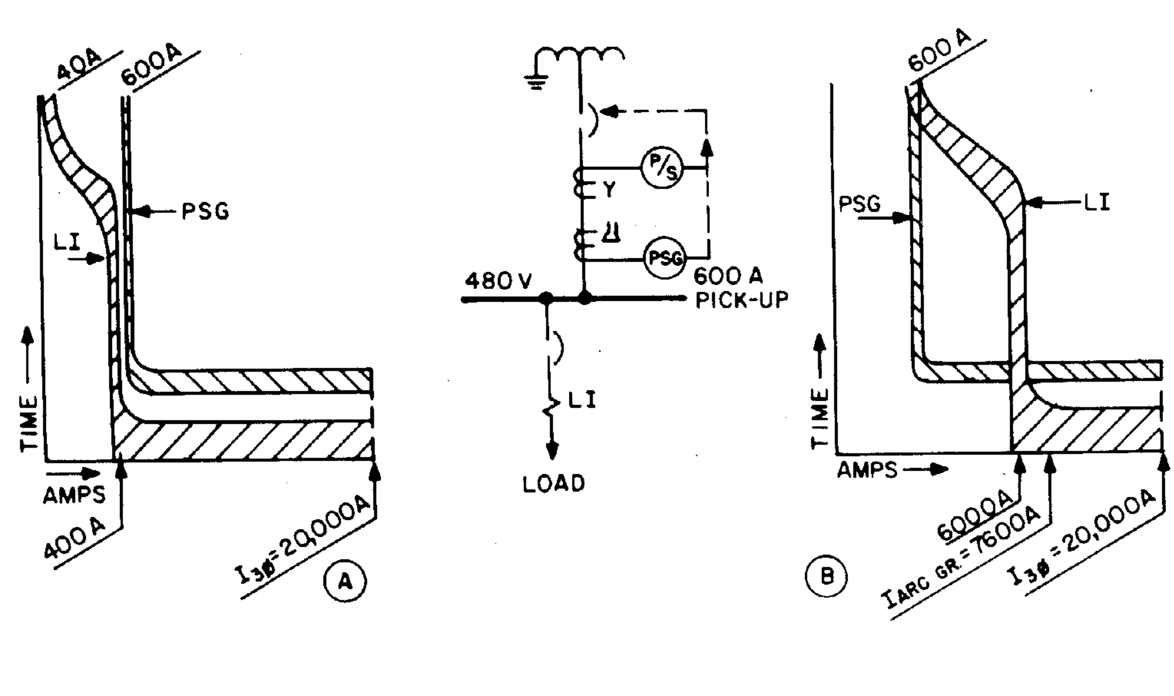


**Figure 8-4: Operating characteristics of 600A PSG on 20,000A system shown in center relative to 40A and 600A LI direct acting trip.**

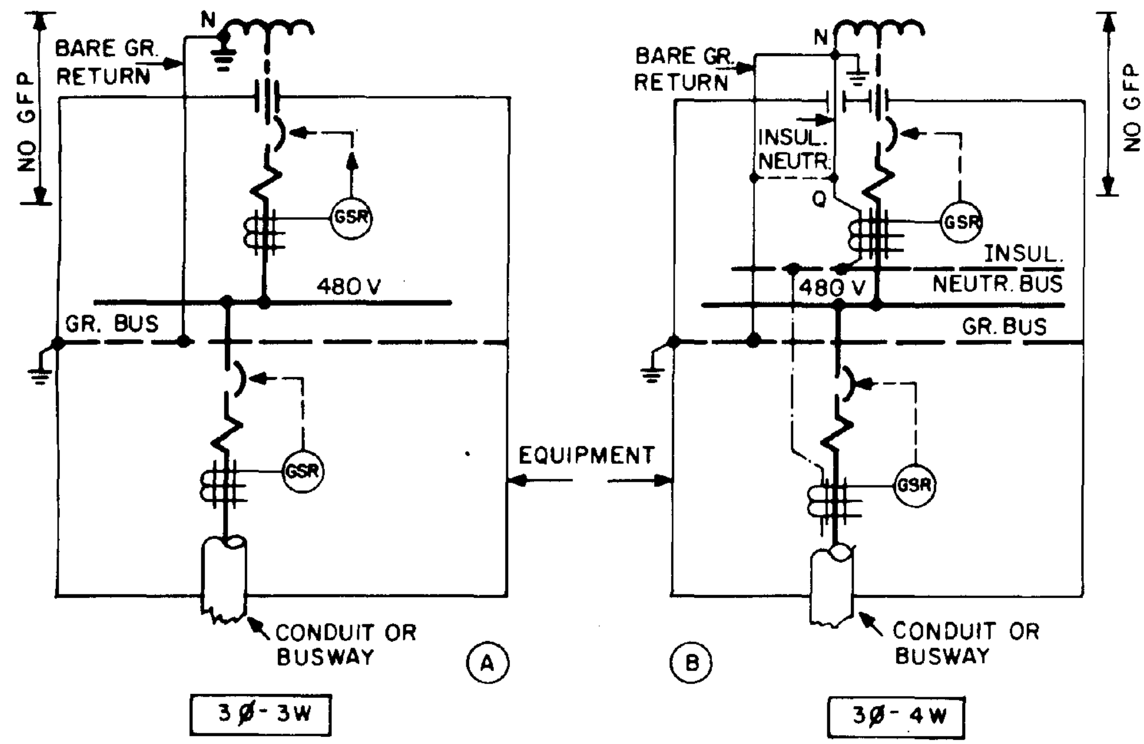


Figure 8-5: Implementing ground fault protection using the ground-sensor principle (GSP) in conjunction with direct-acting trips.

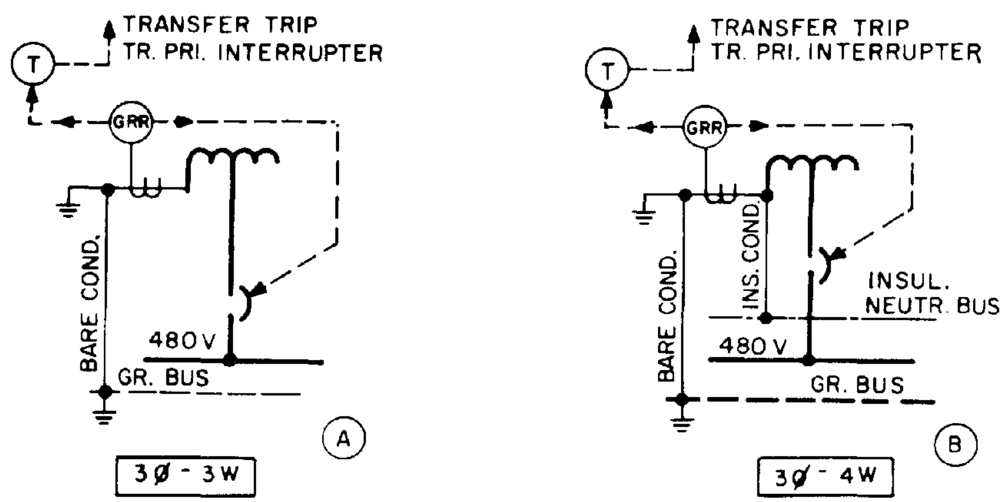


Figure 8-6: Implementing ground fault protection for transformer secondary winding and circuit to main secondary breaker.

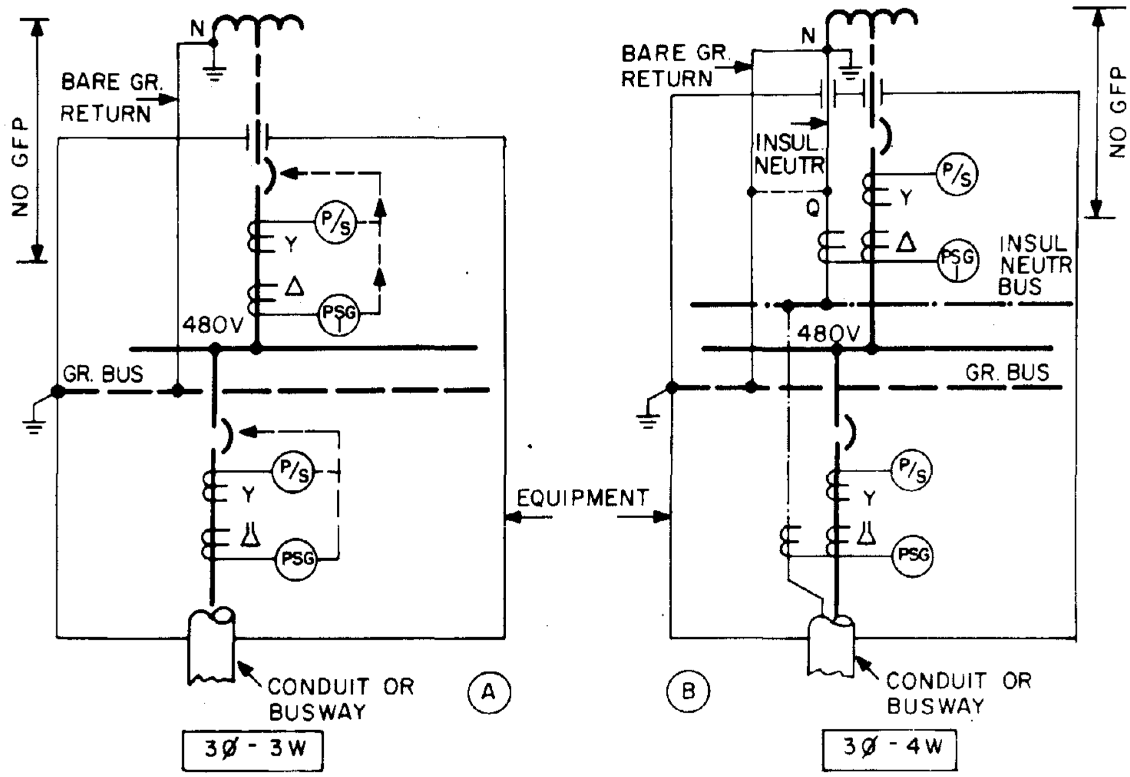


**Figure 8-7: Implementing ground fault protection using the Power Sensor Ground (PSG) option.**

than the sensitivity of the GSR relay in the transformer main secondary breaker circuit (Fig. 8-5).

**Implementation of Power Sensor ground protection (PSG)**

When AK breakers in conjunction with Power Sensors are used, the PSG option can be implemented as shown in Fig. 8-7. In the 3-phase 4-wire case, an additional linear coupler (air-core CT) is inserted between the insulated neutral bus and the neutral conductor (see Fig. 7-4 and 7-5 P. 22). If no additional ground fault protection, as shown in Fig. 8-6 is required, the bare ground return conductor in Fig. 8-7B can be connected at Q instead of at N. The insulated neutral conductor must *not* be grounded downstream from the PSG.

**Implementation of ground return protection (GRP)**

The implementation of the GRP principle is shown in Fig. 8-8A for 3-phase, 3-wire circuits fed from a solidly grounded service system. The GRR-O (instantaneous ground return) function on the conduit or busway feeder circuit will trip the feeder breaker in case of a ground fault in a feeder. Any stray ground current ($I_{SG}$) will be very small. The GRR-1 (time delay ground return) relay not only backs up the GRR-O function, but also responds to a ground fault in the equipment bus structure or feeder breakers.

Fig. 8-8B illustrates the GRP principle applied to 3-phase, 4-wire systems. The difference is that here the GRR-1 relay is installed between the ground bus and the insulated neutral bus rather than the transformer neutral. Now the GRR-1 relay will <u>not</u> sense unbalanced neutral currents but should properly sense ground return currents passing from the ground bus to the neutral bus.

*While the GRP principle is theoretically sound, the practical application is vulnerable due to the possibility of shorting the insulation separating the equipment enclosure and conduits and/or busways. Water pipes, instrument air tubing etc. installed by unsuspecting craftsmen present a continuous risk to the integrity of the insulation and therefore to the ground return protection principle.*

**The effect on combination motor starters**

By definition, a combination starter consists of a contactor and another interrupter; either a fuse or

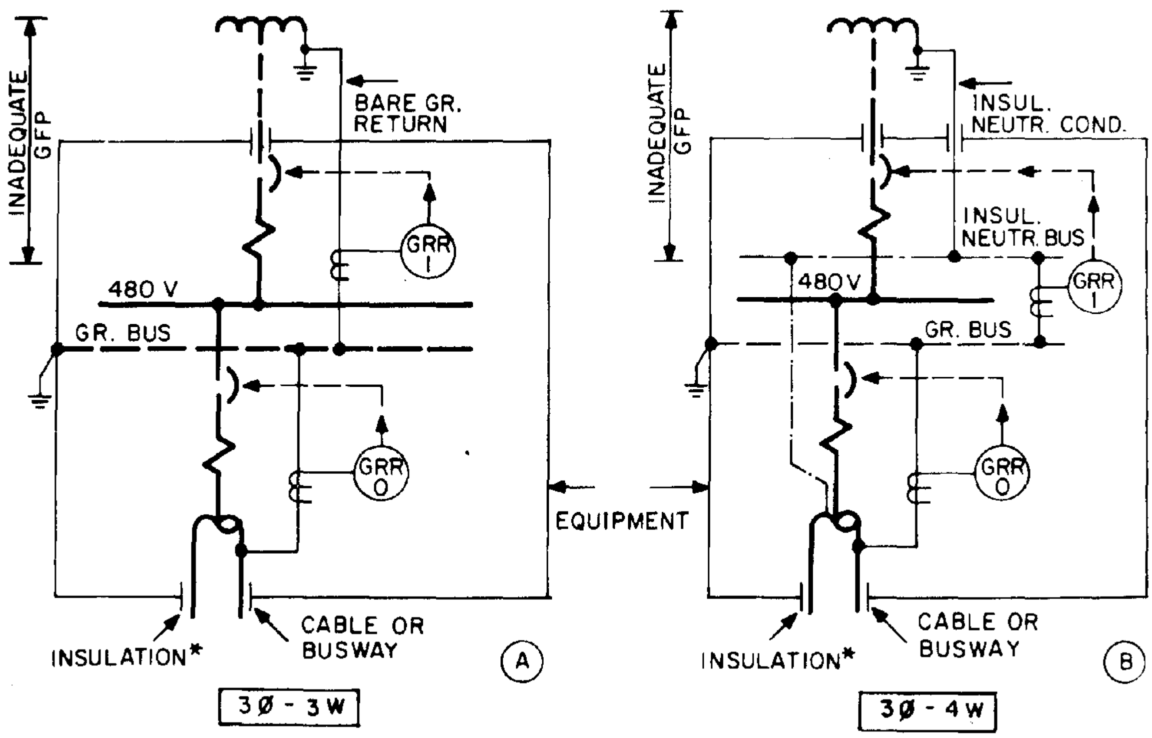


**Figure 8-8: Implementing ground fault protection using the ground fault return principle (GRP) in conjunction with direct acting trips. *Caution: *guard against accidental shorting of insulations.***

breaker, usually a molded case breaker.

The majority of combination starters utilize breakers of a range of ratings which inherently provide arcing ground fault protection. Increasing motor horsepower ratings however require breakers which may become insensitive to arcing ground faults. When the need for additional ground fault protection is required, these breakers need to be equipped with shunt trips and an appropriate control power supply.

The easiest solution would be to allow the ground fault protector to de-energize the starter holding coil. The probability that the contactor will be called upon to interrupt a current in excess of its 10 times starter size rating, however, prohibits this apparent solution.

Mindful of this limitation, the fused combination starter should be avoided whenever additional ground fault protection is mandatory.

### The effect on fused switches

Fused switches rely on fuses to interrupt phase overcurrents in excess of about 6 to 7½ times the switch rating. The switch is usually operated by a manual stroke or by electrical operation initiated by operators.

Ground fault relays require that fused switches be equipped with an electrical trip to remove a ground fault of a predetermined magnitude either instantaneously or after a set time delay (Fig. 8-9A). Under these circumstances the switch cannot be permitted to await the operation of the fuse because, especially on larger fuses, the arcing ground fault will persist too long. The devastating results of prolonged arcing ground faults have been explained in chapters 3 and 4.

Furthermore, it should be recognized that an arcing fault may be initiated as an *arcing line-to-ground* fault with a magnitude below the switch interrupting rating (Fig. 8-9B). Assume that either instantaneously or after some time delay, the switch receives the signal to open. Because of its turbulent nature the fault could, in bare bus equipments, easily escalate into an *arcing line-to-line* fault. The fault current magnitude could then increase rapidly above the switch interrupting ability just as the switch attempts to open the short-circuit.

It appears that the fused switch protection coordination is based on steady-state fault current and that upon blowing at least one fuse, fault magnitudes are considerably reduced to well within the switch rating. In the case of an arcing ground fault however, the fault current is transitory, imposing an unpredictable interrupting duty on the switch mechanism.

For this reason, the use of fused switches with inadequate load break ratings should be avoided.

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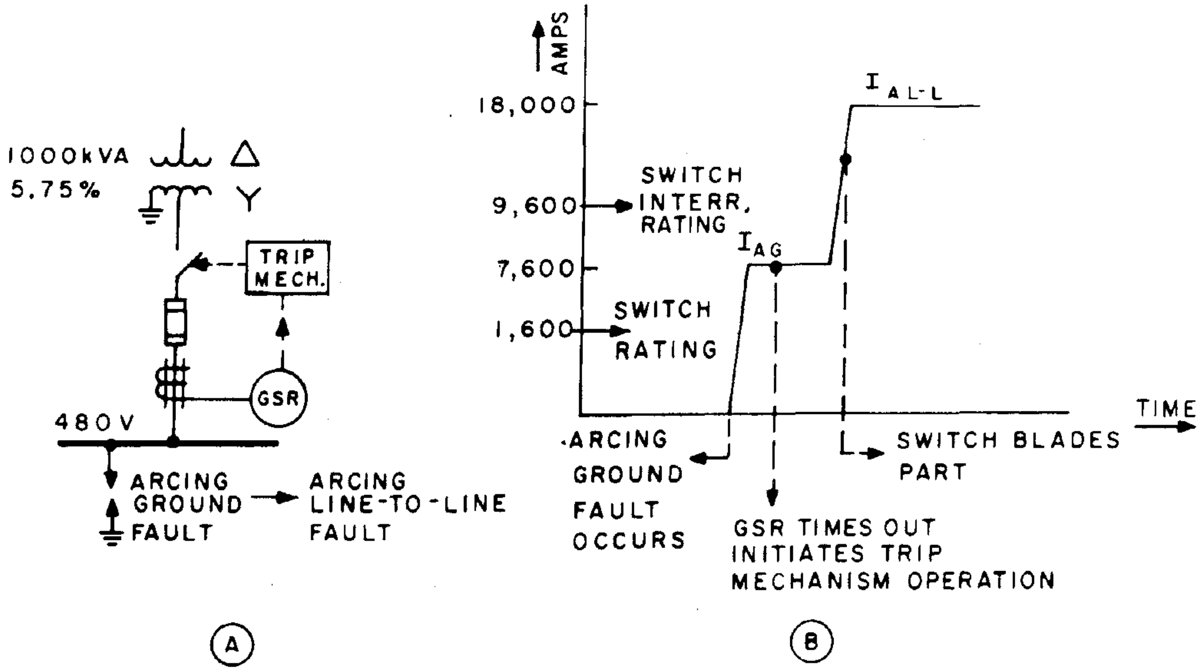



**Figure 8-9: The potential problem created by the operation of a fused switch in the presence of a dynamic arcing fault.**

**The limitation of fuses as a ground fault protector**

The inability of fuses to sense lower levels of arcing ground faults has been pointed out in the previous text. The following discussion will bring to light the fact that, even if a fuse properly senses a ground fault, the subsequent fuse blowing will not remove the ground fault.

To illustrate the problem, assume a balanced static 3-phase load (Fig. 8-10). A static load is defined as lamp or heating element load and is contrasted to a dynamic load, such as a motor.

In Fig. 8-10A, a 554 amp load is assumed, which consequently must have a .5 ohm impedance per phase on a 480 volt wye supply. If a ground fault occurs under the circumstances as indicated in Fig. 3-3 (P. 7), a 15,000 amp ground fault current will flow in the "a" phase transformer winding and circuit only. The 600 amp fuse in the "a" fuse can be expected to blow in less than 1 cycle (Fig. 8-10B).

To examine the subsequent developments, Fig. 8-10C represents the essential circuit elements. First of all, the "b" and "c" phase loadings are singe-phased, meaning that the line-to-line voltage (480 volts) is impressed on two .5 ohm loadings in series. As a result the current in the "b" and "c" phase conductors can be calculated to be:

$$I_b' = -I_c' = \frac{480}{.5 + .5} = \frac{480}{1} = 480 \text{ amp.}$$

Note that in the case of a *static* 3-phase load, the current in the unfaulted phases has *decreased* significantly (from 554 amp to 480 amp).

As a result of this current flow, the neutral point N is elevated above ground and forms the driving voltage for a continued ground fault current $I_g$. The magnitude of $I_g$ is thus a function of the load impedance. In other words the load magnitude has a controlling influence on the magnitude of the ground fault current, which continues to flow after the first fuse blows. More descriptively, the ground fault is being back-fed through the load once the first fuse blowing has caused the system to single-phase. A calculation of the magnitude of $I_g$ in Fig. 8-10C, made in the next paragraph, shows that, neglecting the transformer and ground return impedances, this current will be about 185 amp. The remaining 600 amp fuses will not sense the continuing ground fault, which sets the stage for subsequent burning. In the best of circumstances, it may burn into *another phase* conductor for the same circuit. The resulting phase-ground-phase fault should elevate fault currents sufficiently to cause the second fuse to blow. Even then the ground fault has not been removed. In other circumstances the burning caused by the flow of 185 amp ground fault current could involve a phase in *another circuit.* The variety and complexity of the possible escalated faults is only of academic interest. From a practical point of view, the consequences of

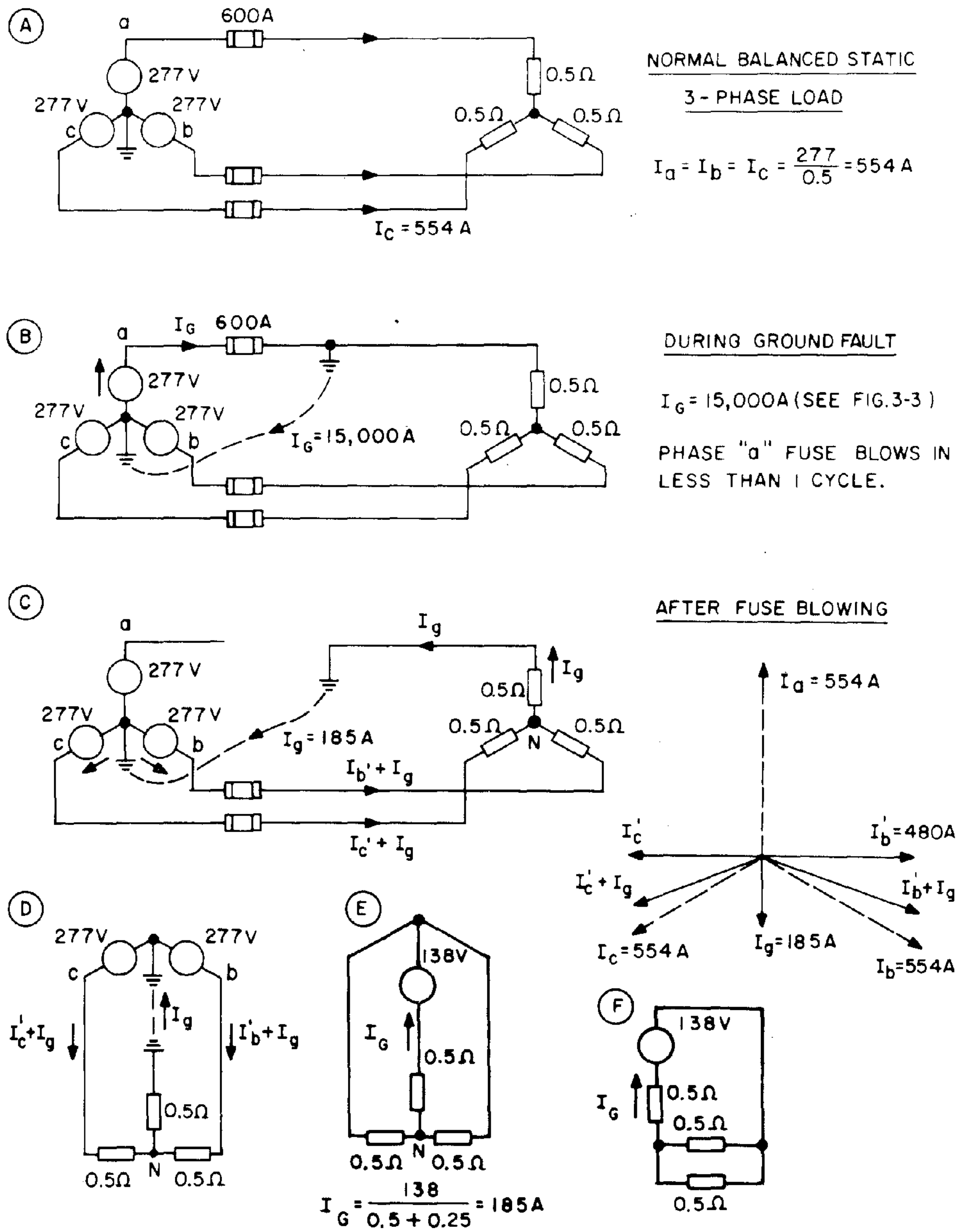



Figure 8-10: Sequence of events initiated by a ground fault which causes one fuse to blow.

the inadequacies of fuses to protect equipments against burning damage, whatever the chain of events, are serious.

The calculation of the continuing ground fault current shown in Figure 8-10C can be developed by the application of Thevenin's theorem. To establish the effective driving voltage, consider the ground fault to be an open circuit. With no fault current flowing, the open circuited load conductor would assume the same potential as the neutral point N, which is midway between the b and c phase conductors or 138 volts above ground. The effective impedance can be calculated by looking into the system from the fault point, which appears to be .5 ohm in series with a parallel pair of .5 ohm impedances or .5 + .25 = .75 ohm (Figure 8-10E and F). The ground fault current magnitude $I_G$ will thus be $\frac{138}{.75} = 185$ amps.

The assumption of a static load was introduced primarily to simplify the calculation of the ground fault current. More realistically, the load may be predominantly motors. Considering the complexity of the ground fault current calculations, it may suffice to indicate that the winding connected to the faulted phase (Fig. 8-11) is situated in the magnetic flux generated by the current in the "b" and "c" phases. As a result, a voltage will be induced in the "a" phase winding, which represents the driving voltage for the ground fault current $I'_g$. This generated voltage can force the motor neutral-to-ground voltage to 200 or 225 volts, which will exceed the equivalent maximum voltage for the static load condition of 138V (Fig. 8-10E). The resultant sustained ground fault currents under single-phasing conditions can therefore be considerably higher than the calculated value of 185A depending upon the motor loading connected to the transformer.

The previous discussion indicates the limitations of fuses in removing a ground fault from a power system. In addition, blowing one fuse creates a single-phasing condition which jeopardizes the 3-phase motor load on the system.

**The effect of single-phasing on 3-phase motors**

A ground fault on a solidly grounded system protected by fused switches is likely to blow only the fuse in the faulted phase. In this event, only single phase power can be transmitted past the point of the blown fuse. Single phase loads are not affected by the consequent single-phasing condition. Three phase loads however, in particular fully loaded 3-phase induction motors, could be in serious distress. The degree of distress depends to a great extent upon the location of the fuse in the system; that is a blown fuse in a

A. motor branch circuit
B. transformer main secondary circuit
C. transformer primary circuit

**A. Motor branch circuit single-phasing**

The least harmful single-phase condition is created by blowing the fuse in a fused combination starter (Fig. 8-12).

To better understand this phenomenon, it should be noted that the *load equipment* (compressor, pump, fan etc) *determines the horsepower loading* on the motor, regardless of the electrical conditions on which the motor is operating. Furthermore, the motor horsepower delivered to the load is approximately equal to the motor kva drawn from the power system. Because of the symmetry of the 3 windings, the texbook formula indicates that

Motor HP = motor kva $= V_aI_a + V_bI_b + V_cI_c$

where: $V_a$, $V_b$ and $V_c$ are the line-to-neutral voltages of phase a, b and c respectively. $I_a$, $I_b$ and $I_c$ are the currents in lines a, b, and c respectively.

During normal balanced conditions

$HP_B = 3\ V_aI_a = 3\ V_{L-N}I_L$

If as the result of a ground fault on phase b, the b fuse blows the motor no longer sees the voltage $V_b$. Instead only a single-phase voltage ($V_{ac}$) is impressed on the "a" and "c" winding (Fig. 8-12C).

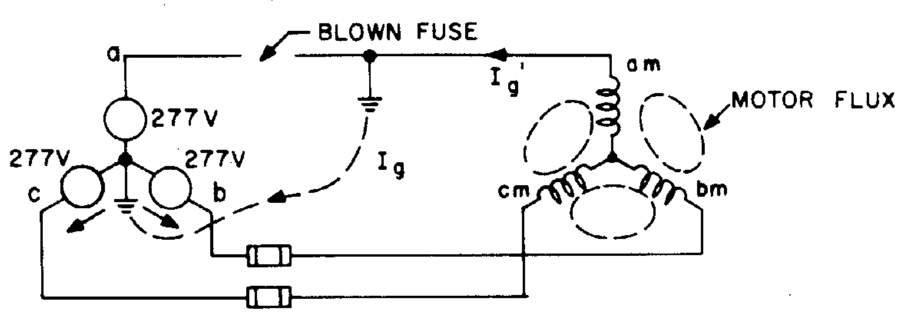
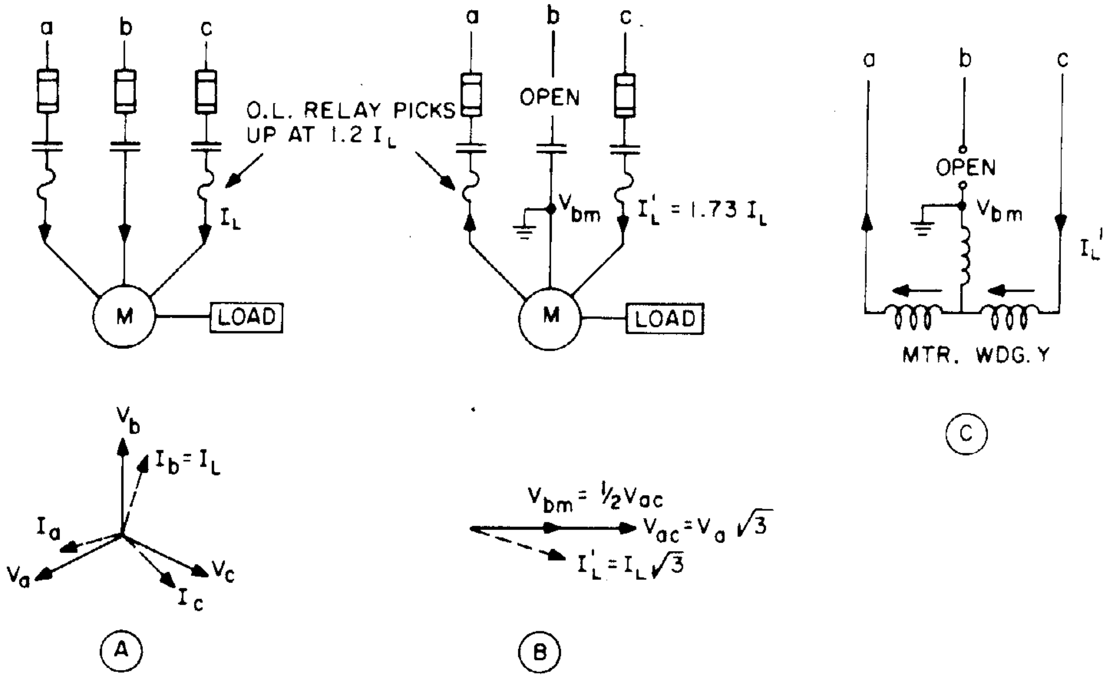



**Figure 8-11: Diagram showing that ground current can be induced by the stator flux in the faulted phase winding, raising $V_{am}$ to about 200 volts.**




Motor HP = Motor kVA = $V_aI_a + V_bI_b + V_cI_c$

For balanced conditions

$HP_b = 3V_aI_a$

$= V_{L\text{-}N}\ I_L$

For unbalanced conditions

$HP_u = (2)\ (\frac{1}{2}V_{ac})\ I_L'$

$= (2)\ (\frac{1}{2}V_a\sqrt{3})\ I_L'$

$= V'_{L\text{-}N}\ I_L'\sqrt{3}$

Mechanical load requires same HP

$HP_b = HP_u$

$3\ V_{L\text{-}N}I_L = V'_{L\text{-}N}I_L'\sqrt{3}$

Line-neutral voltage essentially the same before and after fuse blowing

$$3I_L = I_L'\sqrt{3} \rightarrow I_L' = \frac{3}{\sqrt{3}} = \sqrt{3} = 1.73$$

Consequences:

1. Overload relay senses single phasing and drops out contactor only if motor was fully loaded and after considerable time delay.
2. Two O.L. relays will suffice to protect the induction motor winding on this basis.
3. The ground fault will persist at considerable lower level due to voltage $V_{bm}$, which back feeds the ground fault.
4. Rotor winding or squirrel cage is subjected to injurious negative sequence heating.

**Figure 8-12: Diagrams showing the effect of motor single-phasing due to blowing a motor branch circuit fuse.**

Thus only two motor windings produce torque, which equals:

$$HP_U = (2)\ (\frac{1}{2}\ V_{ac})\ I_L' = (2)\ (\frac{1}{2}\ V_a\sqrt{3})\ I_L' = V_L'{}_{\text{-}N}I_L'\sqrt{3}$$

On the basis that the mechanical HP requirements have not changed, this can be expressed mathematically by the equation:

$HP_B = HP_U$

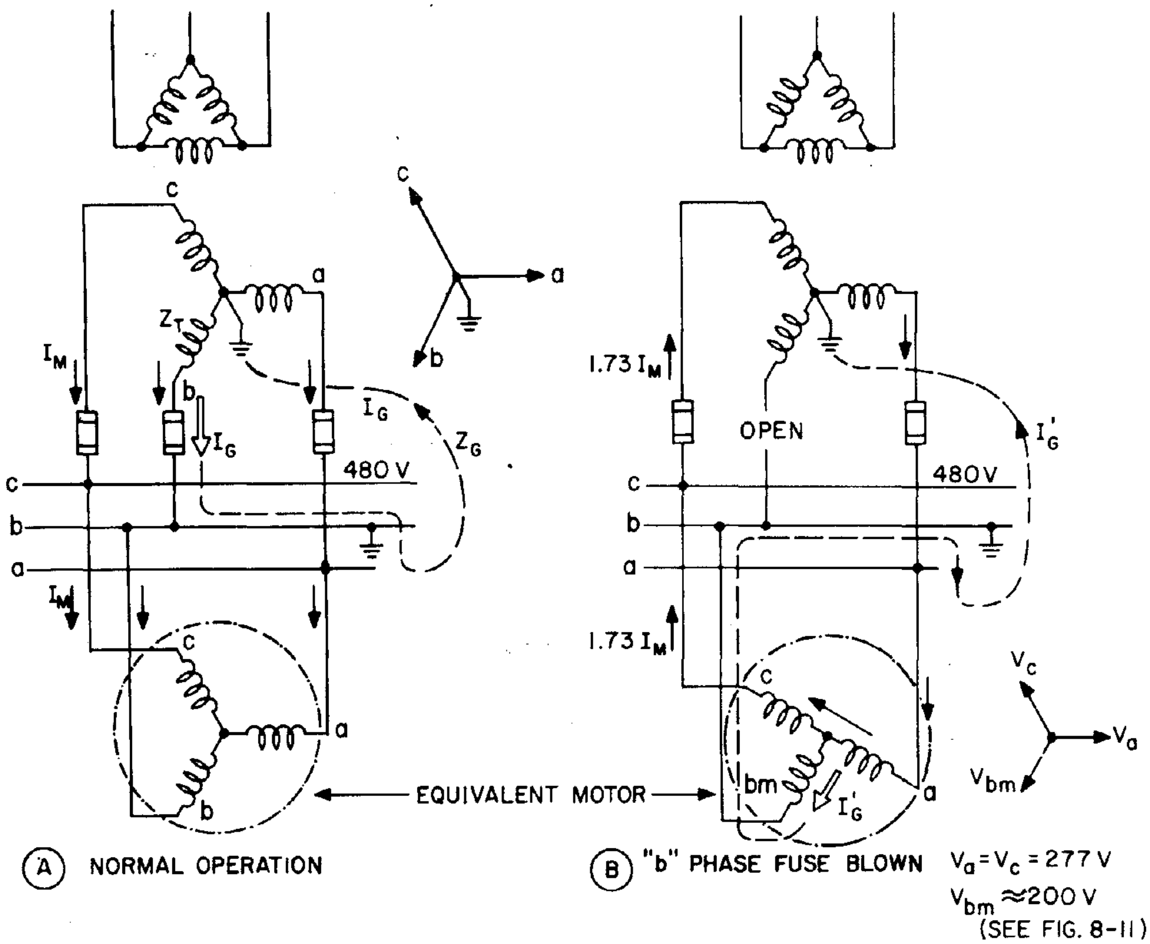
$$3\ V_{L\text{-}N}I_L = V_L'{}_{\text{-}N}I_L'\sqrt{3}$$

The line-to-neutral voltages before and after fuse blowing are essentially identical; thus

$3\ V_{L\text{-}N}I_L = V_{L\text{-}N}I_L'\sqrt{3}$

$$I_L' = \frac{3}{\sqrt{3}}I_L = I_L\sqrt{3} = 1.73I_L$$

Opening of the b phase appears to increase the line currents in the remaining phases by 73%. If more obscure effects of single-phasing on 3-phase induction motors are included; the phase current can run as high as 225%. But even at 173% of normal full load amps, however, the thermal overload relay, if properly selected to cause tripping at 115% of FLA, should pick-up and drop out the contactor after some time delay. In the meantime, however arc burning continues and ground fault current continues to flow.




$$I_G = \frac{V_b}{Z_T + Z_G}$$

$$I_G' = \frac{V_{bm}}{Z_T + Z_G + _{bm}}$$

For large motor equivalent, $Z_{bm}$ is small; $I_G'$ large.
For small motor equivalent, $Z_{bm}$ is large; $I_G'$ small.
Thus: $I_G'$ is function of motor load.

**Figure 8-13: Diagrams showing that groundfault on bus persists after blowing one incoming service fuse.**

Note that two overload relays are adequate to protect the motor winding against motor branch circuit single-phasing conditions. The rotor of the induction motor however may be in greater distress in that it is subjected to a so-called "negative sequence" flux which rapidly heats up the rotor[7]. This aspect is considered outside the scope of this discussion.

The motor winding configuration (delta or wye connection) has an important consideration, its effect does not materially influence the single-phase discussion.

It therefore appears that a running motor will continue to run for some time or even continuously in the case of unloaded motors when a branch circuit fuse blows. However, motors can not be started under these single-phase conditions.

Again referring to Fig. 8-12, it appears that the "b" phase lead is still grounded while it operates at a voltage above ground. This voltage results in a continued low level ground fault. In other words, a ground fault which caused a fuse to blow, is still very much a ground fault, back-fed through the motor windings.

**B. Transformer main secondary single-phasing.**

This resembles the motor branch circuit single-phasing condition except that the problem area is extended to include all motors. The motor shown in Fig. 8-13 is an equivalent motor, one which can be thought of as representing all small and large motors connected to the bus.

During the ground fault but prior to fuse blowing (Fig. 8-13A), assume that the ground fault is limited by the transformer and ground return impedances. This current is usually sufficiently large to blow a fuse after some or considerable time delay. Upon fuse blowing however, the "b" phase bus voltage is not zero and as a result the ground fault still exists (Fig. 8-13B), although considerably reduced in magnitude.

When only a small motor operates on the 480V bus, the motor impedance is high and thus the ground fault minimum. When the transformer is fully loaded with motors, the equivalent motor impedance is quite small and thus allows a relatively large ground fault current to flow.

Under these conditions the motor overload relays, if properly selected will in time drop out most contactors, thereby reducing the ground fault current before another transformer main secondary fuse blows. Note that eventually, the ground fault current is reduced to a level below the sensitivity of any available protective devices, allowing the ground fault to persist indefinitely. The probability exists, however, that the intermittent sparking at the ground fault location may result in a more severe fault or communication to other cable circuits.

A ground fault in a delta-wye connected transformer secondary winding or its connection to the fuse is of course not sensed by the main secondary fuses. If the fault develops in or close to the transformer terminal winding, sufficient ground fault current may flow to blow a primary fuse (Fig. 7-12, P. 26). But again the ground fault persists at lower levels (Fig. 7-13, P. 27). However, a ground fault in a winding close to the neutral is likely to be so small that properly selected and set *phase* overcurrent devices cannot sense its presence. It is for this purpose as well as to provide back-up ground fault protection that a ground fault relay and CT in the transformer neutral ground connection are recommended (Fig. 8-6). To do so in the presence of an extensive poorly planned system is to invite a complete system shutdown for many downstream minor ground fault conditions, which persist longer than anticipated.

**C. Transformer primary circuit single-phasing**

In the absence of a main secondary breaker or fuse, an arcing ground fault in the main bus structure can be extremely devastating in that only transformer primary protectors are available to detect such a ground fault. It will be shown that such protection may be inherently inadequate to prevent a catastrophic burn-out.

In Fig. 8-14, a ground fault is assumed on the "b" bus. The resultant ground current ($i_g$) in the low voltage "b" phase winding, causes a corresponding current ($I_G$) in the high voltage "b" phase winding. Observing that the primary delta current must be 58% of the corresponding secondary wye current to satisfy the transformer energy equations, it follows that $I_G = .58\ I_g$.

To determine the approximate magnitude, recall that in table 4-b (P. 11), the low voltage arcing ground fault current was estimated to be between 5.5 and 9.5 times the transformer current rating. Assuming a very light load on the transformer shown in Fig. 8-14, the primary current $I_G$ may vary between (.58) (5.5)=3.2 and (.58) (9.5)=5.5 times the transformer full load current.

It is appropriate to point out at this time, the difference in the nature of the primary $I_G$ and secondary $i_g$ currents. The low voltage $i_g$ current is truly a ground fault in that this current returns to the neutral of the low voltage winding through some ground return circuit. Observe that the primary $I_G$ current is not a ground current since it flows only in the phase conductors. As a result: *ground fault relays in the transformer primary supply circuit will not respond to low voltage ground fault currents*. Phase overcurrent relays in the transformer primary supply circuit, however, will sense the $I_G$ currents, but are not likely to operate at all or only after a considerable time delay, since they are set to pass relatively high steady-state load currents.

If the transformer primary protector is in fact a fuse, currents of these reduced magnitudes are not likely to blow a primary fuse or will do so only after a considerable time delay, measured in terms of a minute or longer. Of course, the fuse melting time will be measurably shortened when the transformer approaches full load conditions. In the meantime however, a low-voltage arcing fault causes considerable burning damage to equipments.

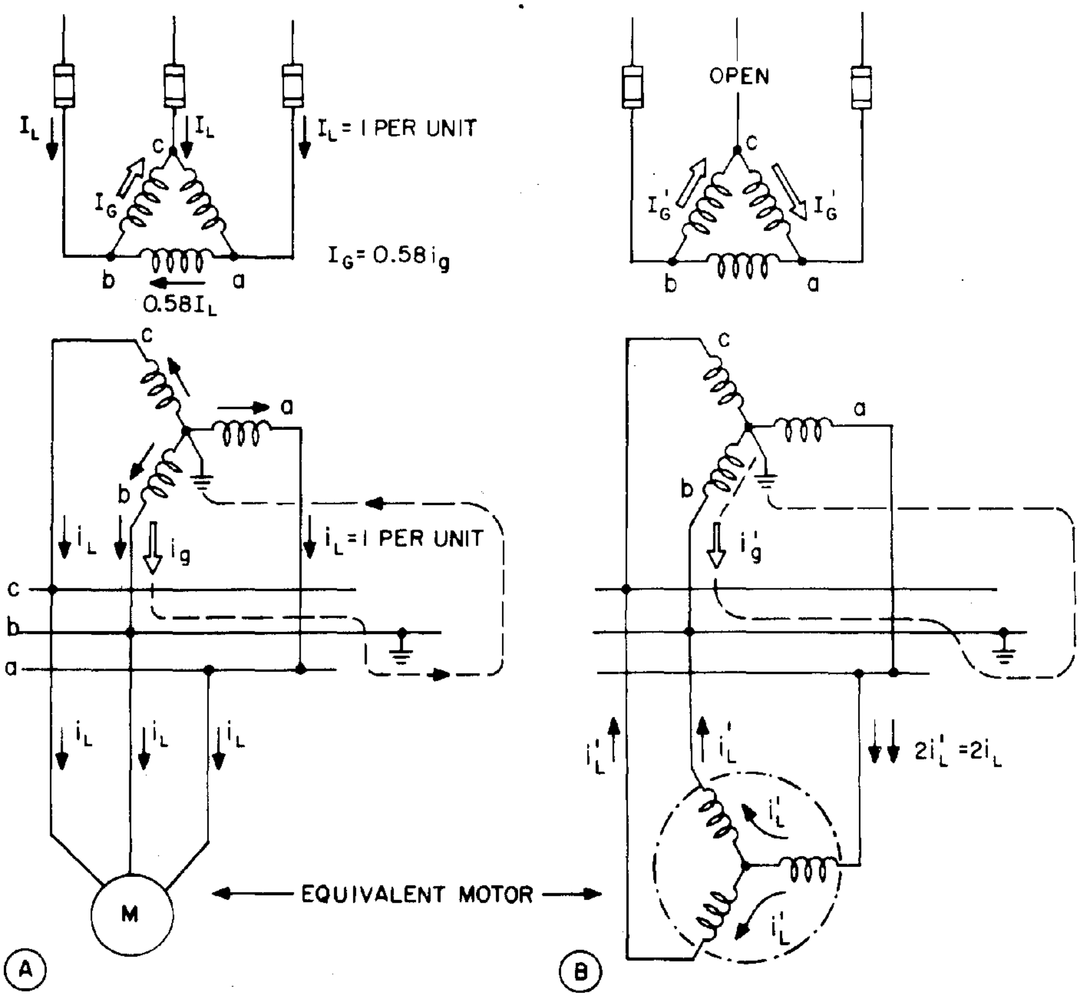
In the event a primary fuse does blow, (Fig. 8-14B), the problem is compounded since not only the ground fault persists at low current levels but the motor load is operated from a single-phased power supply. The primary $I_G'$ current is now forced to flow through the phase a-c winding which introduces an impedance with a magnitude dependent upon the normal load current. In the absence of load, a high (magnetizing) impedance is introduced, which reduces the $I_G'$ current to about 5% of $I_G$. A fully loaded transformer will introduce a low (leakage) impedance which reduces the $I_G'$ current to about 75% of $I_G$.

The single-phasing aspect forces a current distribution in the motor branch circuits in a 2-1-1 proportion (Fig. 8-14B). As a result only one phase will sense an overcurrent, which dictates the need for three overload relays.

In summary: *neither transformer primary fuses nor primary ground fault or phase relays in conjunction with breakers adequately protect a low voltage bus against arcing line-to-ground fault.*

### How to deal with double ended loadcenters

The implementation of ground fault protection as described above is generally applicable to radial low-voltage loadcenter unit substations. When applied to double ended loadcenters, specific problems may arise which should be recognized




$HP_b = 3\, e_{L\text{-}N}\, i_L$

$HP_u = 2\, i_L'\, e_{L\text{-}N} + (2)\, i_L' \frac{e_{L\text{-}N}}{2}$

$= 2\, i_L'\, e_{L\text{-}N} + i_L\, e_{L\text{-}N} = 3\, i_L'\, e_{L\text{-}N}$

Mechanical load requires same HP
$HP_b = HP_u \rightarrow 3\, e_{L\text{-}N}\, i_L = 3\, e_{L\text{-}N}\, i_L'$

$i_L = i_L'$

Consequences:

1. Three overload relays required to help assure that at least one will sense twice normal load current.
2. Rotor winding or squirrel cage is subjected to injurious negative sequence heating.
3. Ground fault will persist at low levels.

**Figure 8-14: Diagrams illustrating that ground fault persists after blowing one transformer primary fuse.**

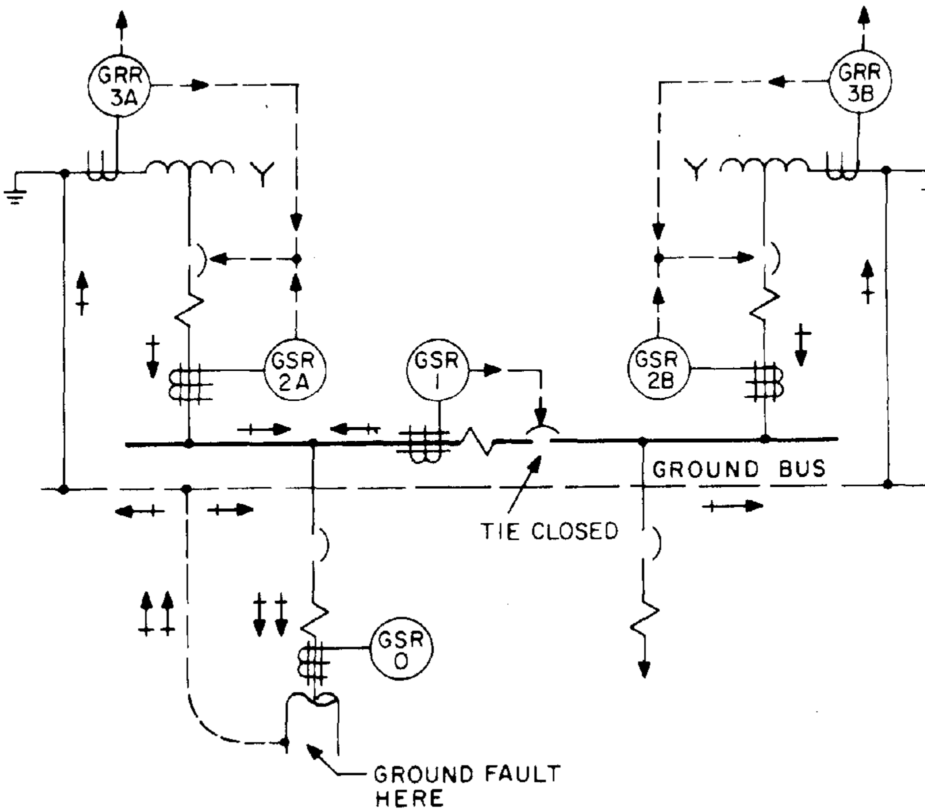



**Figure 8-15: Double ended 3-phase, 3-wire loadcenter, using direct-acting trips. Arrows show ground fault current flow.**

to help assure that all ground responsive devices operate selectively.

The _3-phase 3-wire_ double-ended loadcenters operating with normally open or closed tie breakers and serving balanced 3-phase loads offer no particular problems beyond the recognition that the tie breaker must also be equipped with compatible ground fault devices in the form of a GSR (Fig. 8-15) or a PSG (Fig. 8-16).

The alpha-numerical device identification not only specifies the ground detection mode (PSG, GSR, GRR) but also the desired selective sequence of operation. The numeral zero is usually reserved for instantaneous devices; the numeral one and subsequent numerals in ascending order identify increasing time delay steps.

Using Fig. 8-16 as an example, it is desirable to make PSG-1 operate as sensitive and as fast as possible as influenced by the downstream protectors. The PSG-2 device should be set to be selective with PSG-1. Both the PSG-3A and PSG-3B devices are usually set identically to be selective with PSG-2. The GRR-4 devices in the transformer neutrals are set to provide coordination with the PSG-3 trips and wired up as suggested in Fig. 8-6A. In case of a feeder ground fault, PSG-1 operates to trip the appropriate breaker. In case of a breaker failure or bus fault on bus A, PSG-2 operates to open the tie breaker (if closed), removing the ground fault from bus B. However, the fault is not removed until PSG-3A functions to open the main secondary breaker of bus A.

The _3-phase 4-wire_ double ended loadcenters serving unbalanced line-to-neutral loads require an insulated neutral bus and insulated cables to connect to the transformer neutrals. Figure 8-17 shows that the line-to-neutral load current is seen to come in and to go out of each set of PSG current transformers. In effect, the PSG devices are insensitive to unbalanced line-to-neutral load, which is vectorially shown in Fig. 7-13 (P. 27).

When a ground fault develops, as shown in Fig. 8-18, all PSG and GRR devices will sense a current flow, but only PSG-1 will respond due to selective coordination. Similarly, a fault on bus A will cause PSG-2 to operate first, which results in opening of

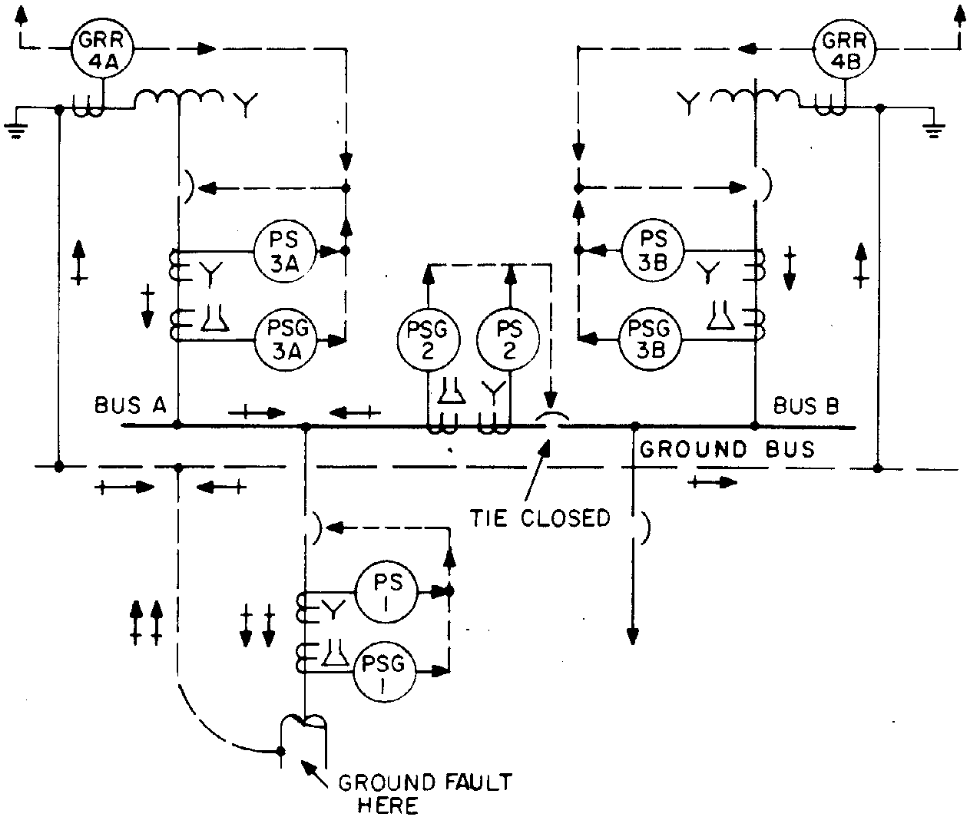



**Figure 8-16: Double ended 3-phase, 3-wire loadcenter using Power Sensor trips. Arrows show ground fault current flow.**

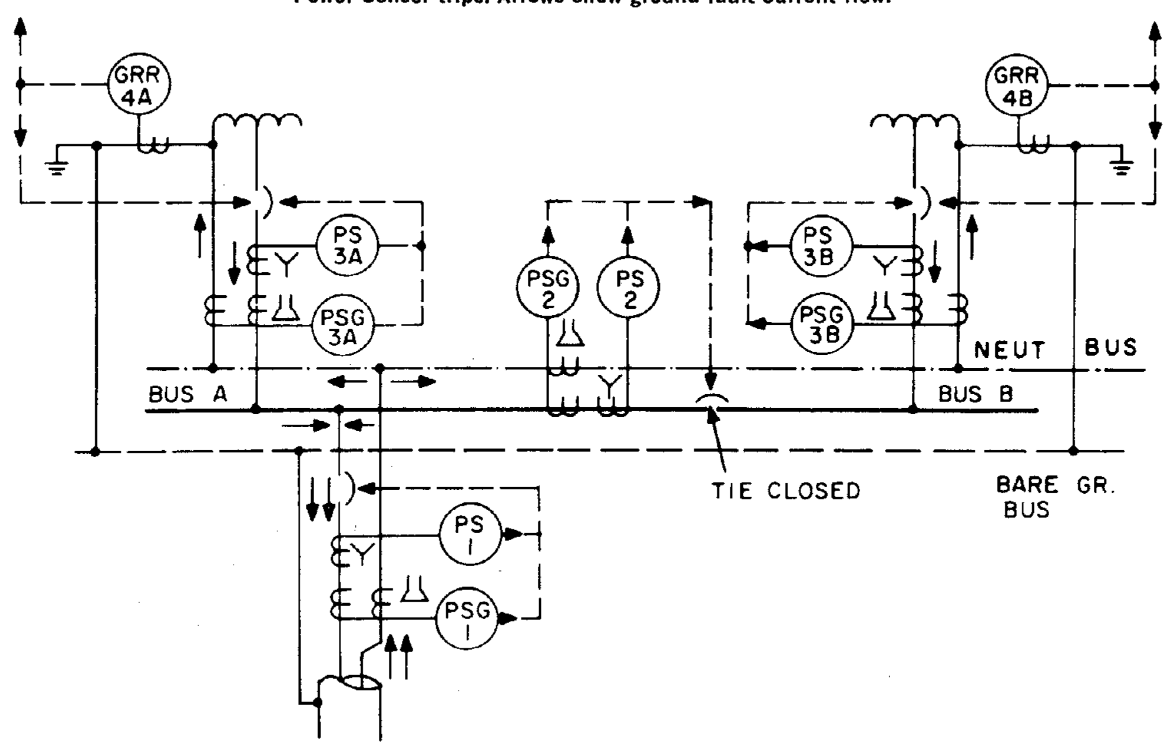



**Figure 8-17: Double ended 3-phase, 4-wire loadcenter. Arrows indicate unbalanced line-to-neutral load current.**

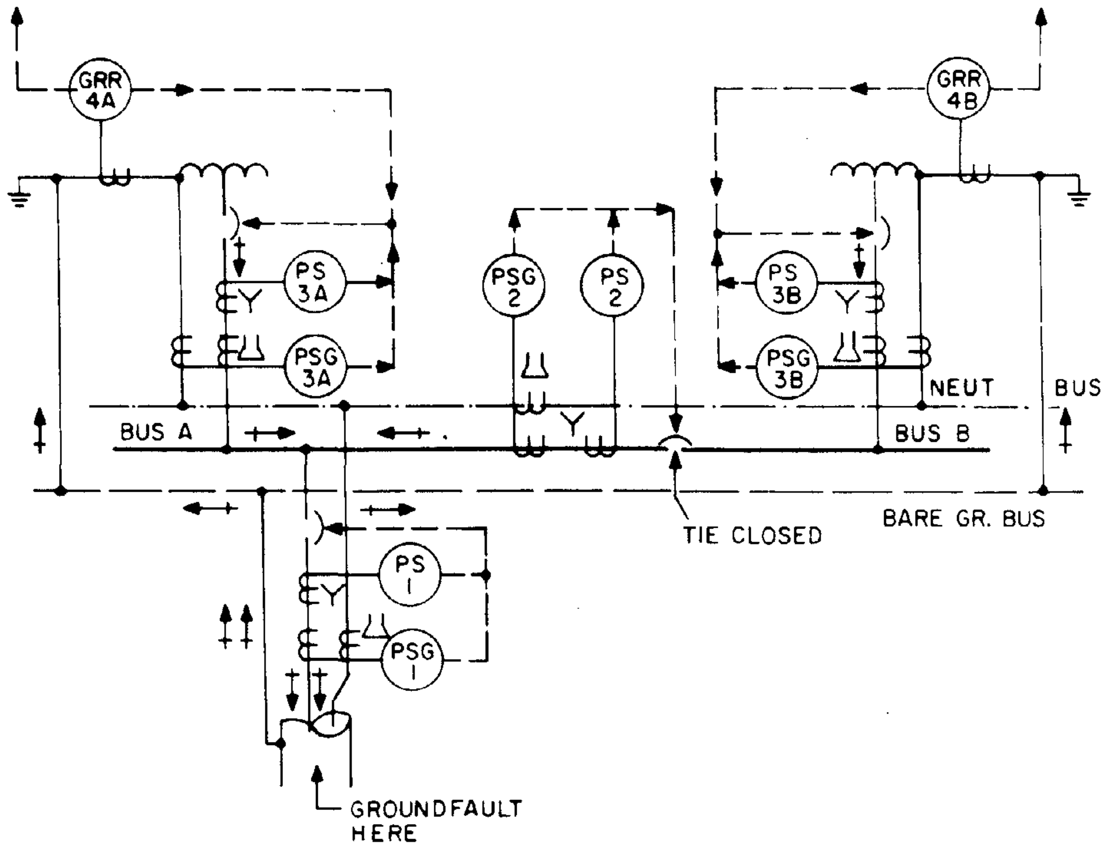



**Figure 8-18: Double ended 3-phase, 4-wire loadcenter. Arrows indicate ground fault current flow.**

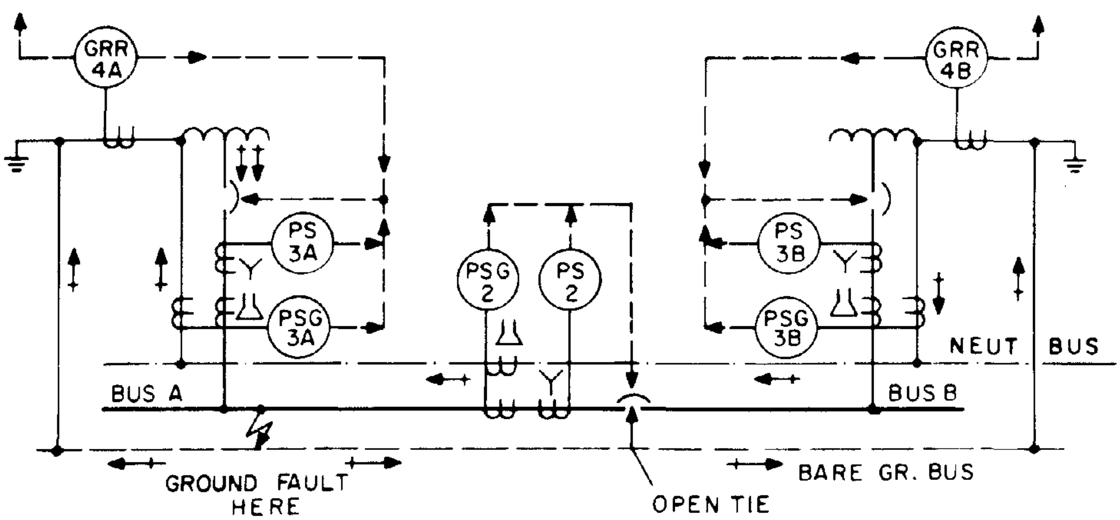



**Figure 8-19: Double ended 3-phase, 4-wire loadcenter with *open* tie breaker. Arrows indicate ground fault flow to which both PSG-3A and PSG-3B may simultaneously respond erroneously.**

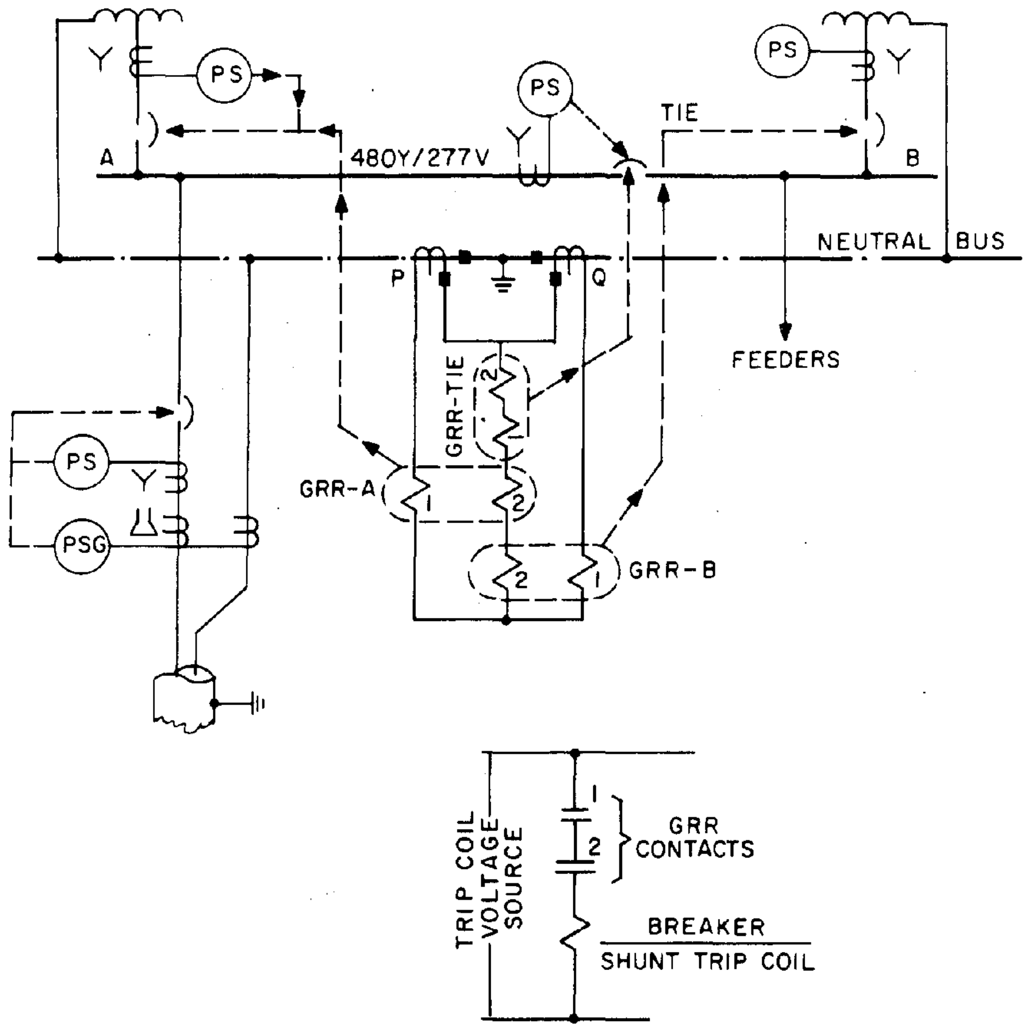



**Figure 8-20: Diagrams showing a method to provide ground fault protection on double-ended 3-phase, 4-wire substation with one common ground.**

the tie breaker. Separation of the 3 phase buses however proves to be inadequate to completely isolate the faulted A bus from the B bus. As shown in Fig. 8-19, the ground fault current splits between two loops; each one formed by the bare ground bus, the bare ground wire to the transformer neutral, the insulated neutral wire and the insulated neutral bus. Consequently, both PSG-3A and PSG-3B will sense approximately the same magnitude of current, creating a race between the two devices with the probable result of tripping both main secondary breakers. *This erroneous protective operation can also be anticipated on secondary selective systems, which are operated with normally open tie breakers, equipped with PSG or GSR protection.*

To remedy the problem, various protective schemes have been suggested. Most solutions rely on protective relays, because of their versatility. Without elaborating on competing protective schemes, only one such scheme will be discussed based on the one-line diagram shown in fig. 8-20. This scheme is applicable only to double ended loadcenters, *with one common ground.*

In essence, the A, B and Tie breakers are each controlled by an overcurrent relay which is designed with two current coils. Only if *both* contacts associated with the two current coils are closed will the corresponding breaker receive a trip signal. As a result, a form of "supervised tripping" is obtained, meaning two conditions must simultaneously exist to cause a breaker to trip. The GE type 12IAC55F1A overcurrent relay has been used extensively for such applications. Thus, three IAC55 relays will be required as indicated in fig. 8-20.

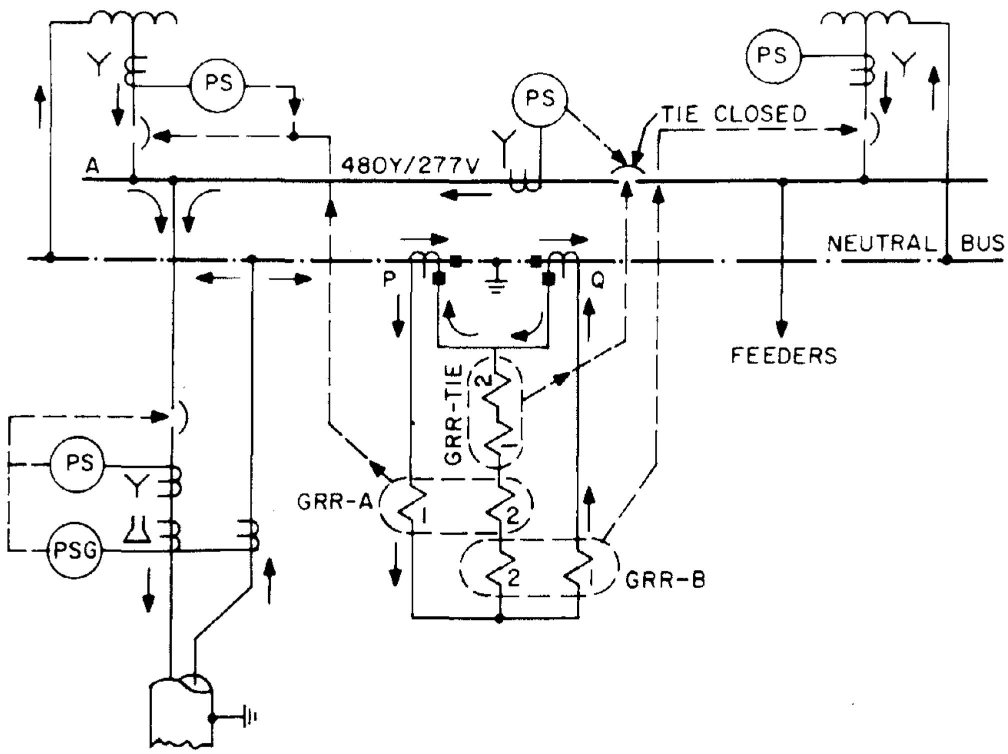



**Figure 8-21: Line-to-neutral load current flow with *closed* tie breaker for substation shown in Figure 8-20.**

Only two CT's, straddling the common ground are required. The CT primary current rating should equal or exceed the neutral bus rating.

Fig. 8-21 shows the distribution of normal line-neutral unbalanced load currents. With the Tie breaker closed, the neutral current will pass through both the P and Q current transformers. Observing the polarity markings, the secondary CT current will flow only through the number 1 coils of the GRR-A and B relays. These relays, which are usually set above the normal line-to-neutral current, should therefore not operate to close their number 1 contacts. Any transient unbalanced load however will close the number 1 contact but will not result in any breaker operation since the number 2 contacts are open due to the absence of current in the number 2 coils. (The PS function however will operate to cause the tie breaker to trip if the transient exceeds allowable limits). *Note that no secondary CT currents will flow when the tie breaker is open.*

When a line-to-ground fault develops with the tie breaker closed (Fig. 8-22) all current coils carry current. When the ground fault originates in a feeder circuit, the corresponding PSG will operate to trip the feeder breaker, allowing the GRR relays to reset. Failure to trip, or bus-faults, however, will cause the tie breaker GRR to time out first. The resultant opening of the tie breaker will not isolate the ground fault. (Fig. 8-23). Secondary CT currents continue to flow in both coils of relay GRR-A, which is set to be selective with the GRR-Tie relay. Not until GRR-A times out to trip breaker A will the assumed ground fault be removed from the system.

Note that only the faulted half of the double-ended substation was removed, allowing the B bus load to ride through the disturbance.

Depending upon the basic equipment layout and grounding modes, various protective schemes can be developed to suit specific objectives.

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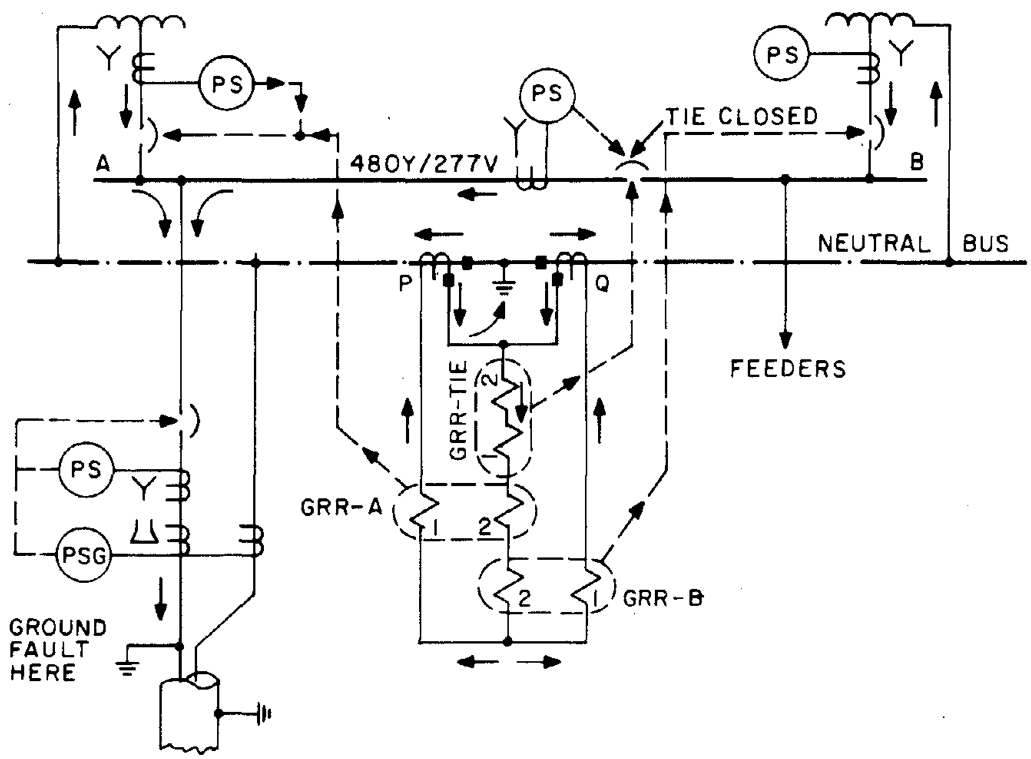


**Figure 8-22: Line-to-ground fault current distribution with *closed* tie breaker for substation shown in Figure 8-20.**

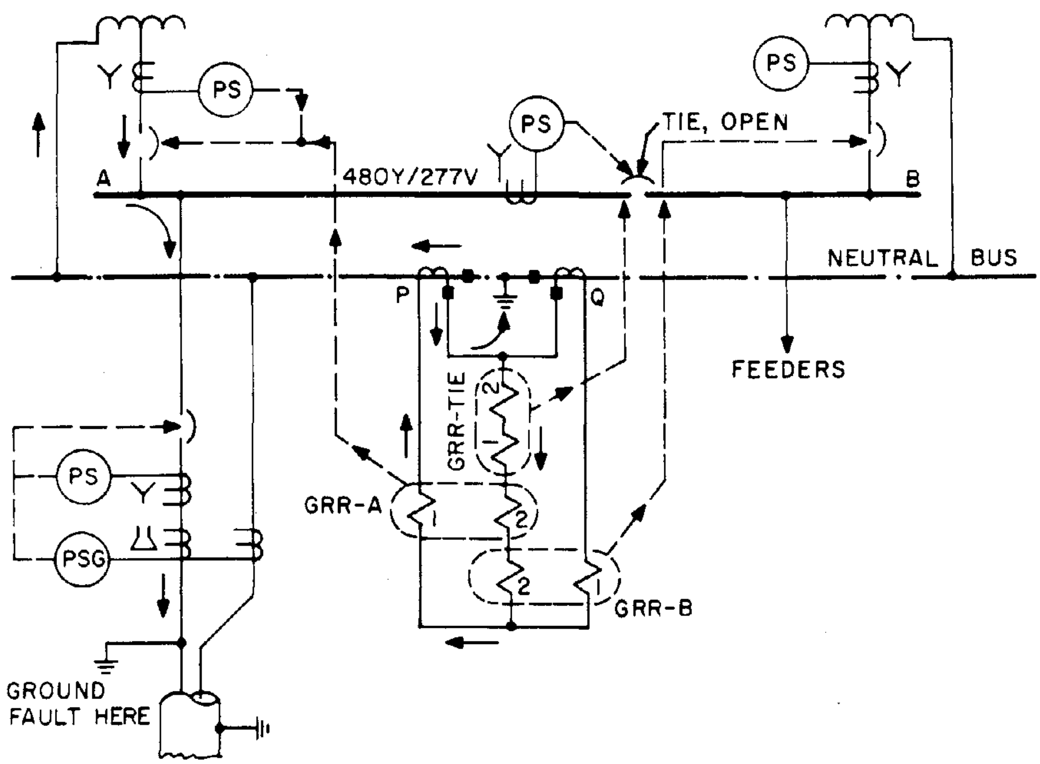


**Figure 8-23: Line-to-ground fault current distribution with *open* tie breaker for substation shown in Figure 8-20.**

## APPLICATION OF GROUND FAULT PROTECTION ON HIGH RESISTANCE GROUNDED SYSTEMS

The concept of high resistance grounding of transformer neutrals was introduced in chapter 5 as a compromise between suppression of transient line-to-neutral overvoltages and unexpected shut downs of critical circuits due to a ground fault in circuit conductors.

The ground resistor current magnitude in high resistance grounded systems should be limited to no less than the total capacitive charging current to ground. On this basis the ground fault on the general 480V system should be limited to about 1 to 2 amperes.

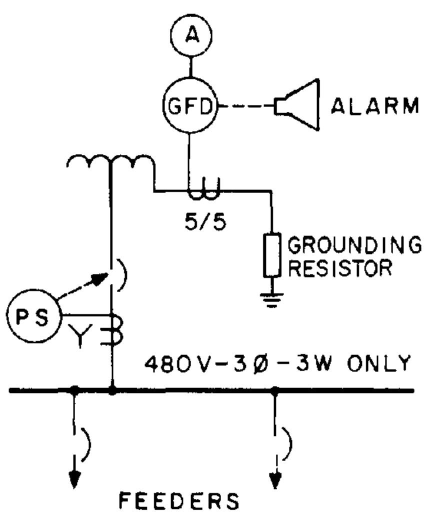


**Figure 8-24: One-line diagram showing principle of high-resistance grounding.**

Considering the extremely low level of fault current, no immediate separation of the faulted equipment is required. However immediate action to locate and orderly remove the faulted circuit is necessary to reduce the probability of the development of a second ground fault which results in a more serious double line-to-ground fault.

In its simplest form, the implementation of the high resistance grounding principle consists of a resistor with a rating of about 277 ohms and 1 ampere continuous current. (Fig. 8-24). The presence of ground fault is sensed by a time overcurrent relay and a 5/5 CT, which actuates an alarm. Until recently the actual location of the ground fault was usually accomplished by sequentially opening all feeder breakers. The loss of ground fault signal indicated the faulted feeder breaker. Repeating this

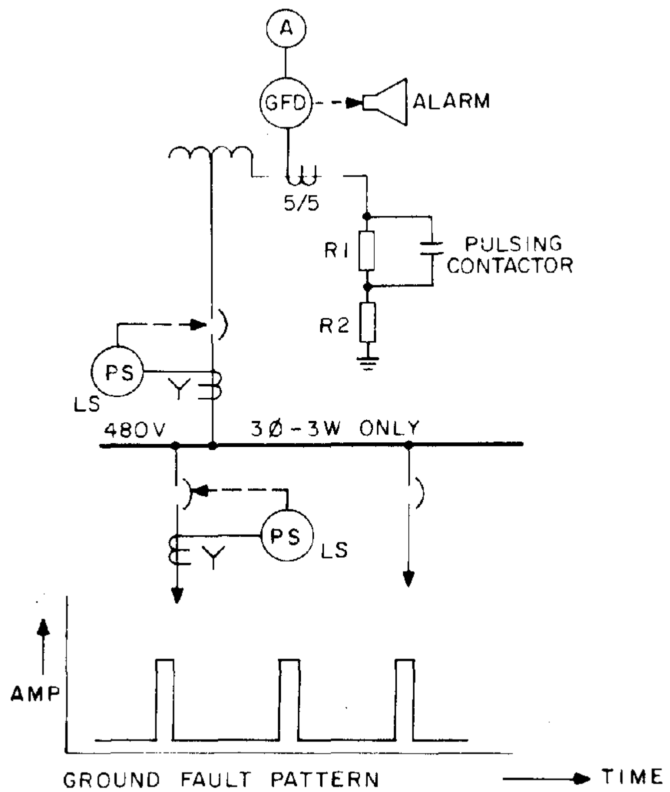


**Figure 8-25: Method to incorporate cyclic pulsing to facilitate ground fault locating in high-resistance grounded systems.**

process of elimination on all downstream circuit breakers ultimately identified the circuit containing the ground fault. This mode of fault locating, however, is not very practical in that all or most circuits may be subjected to an outage every time a ground fault must be located.

To remove this disadvantage, several methods have been developed which use a portable sensing device to trace the course of pulsing ground fault current which can be recognized clearly and unmistakably even in the presence of stray signals usually found in low-voltage distribution systems.

In one simple approach, a 60 Hz ground pulse is generated by cyclicly shorting a portion of the grounding resistor (Fig. 8-25). In this manner, a 2 to 1 or 3 to 1 pulse magnitude ratio can be picked up with a relatively simple sensor. This scheme has found growing acceptance because of its simplicity and proven reliability.

The high resistance grounding concept should not be relied upon to sense ground faults in all machine windings since the windng impedance may be sufficiently high to reduce fault currents to levels below alarm pick-up.

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# 9. CONCLUSION

Arcing ground fault burn downs can be effectively reduced by designing low-voltage systems with arcing ground protection in mind. This leads to the selection of smaller 3-phase circuit breakers with short-time or instantaneous trips set sufficiently low to sense minimum levels of arcing faults on a selective or coordinated basis.

If this appears impractical or insufficient, ground fault relays should be applied to provide low-level arcing ground fault protection.

The use of fused switches with inadequate load break ratings and equipped with shunt trips and ground fault relays should be discouraged.

| BIBLIOGRAPHIC DATA SHEET | 1. Report No. BuMines OFR 39-72 | 2. | 3. Recipient's Accession No. PB 213-741 |
|---|---|---|---|
| 4. Title and Subtitle<br>Evaluation and Feasibility Study of Isolated Electrical Distribution Systems in Underground Coal Mines | | | 5. Report Date<br>April 17, 1972<br>6. Performing Organization Code |
| 7. Author(s)<br>General Electric Company | | | 8. Performing Organization Rept. No. |
| 9. Performing Organization Name and Address<br>General Electric Company<br>Philadelphia, PA | | | 10. Project/Task/Work Unit No.<br>11. Contract/~~Grant~~ No.<br>H0111465 |
| 12. Sponsoring Agency Name and Address<br>Office of Assistant Director--Mining<br>Bureau of Mines<br>U.S. Department of the Interior<br>Washington, DC 20240 | | | 13. Type of Report & Period Covered<br>Final report<br>14. Sponsoring Agency Code |

15. Supplementary Notes

16. Abstract The objectives of the contract were: to evaluate the feasibility of isolated electrical distribution systems in underground coal mines and to design, specify, and evaluate such a distribution system. This ~~final~~ report presents a state-of-the-art literature survey on ungrounded and grounded power systems, a report on literature pertaining to human threshold limits of electric shock, an analysis of the performance requirements of isolated systems, and a section on the design and performance specifications for an isolated system. It was established that there is no ideal ungrounded system due to the effect of inherent distributed capacitance to ground which is present in all components of the system. The conclusion is that a completely ungrounded power system of 480 v. or more is no safer than any other system from a human shock standpoint; also, the ungrounded system has no advantage with respect to gas ignition hazards. The contractor indicates that the high resistance grounded power system has personnel safety advantages for underground mining application.

17. Key Words and Document Analysis. 17a. Descriptors

Circuit protection
Coal mines
Electric arcs
Electric faults
Electric grounding
Electric ignition
Electric insulation
Electric power distribution
Electric shock
Mine lighting
Power distribution lines
Underground mining

17b. Identifiers/Open-Ended Terms



17c. COSATI Field/Group 08I

| 18. Distribution Statement | 19. Security Class (This Report) | 21. No. of Pages |
|---|---|---|
| Release unlimited by NTIS. | UNCLASSIFIED | 219 |
| | 20. Security Class (This Page) UNCLASSIFIED | 22. Price |

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