OFR 61(2)-78

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Mining Engineering Section

COAL MINE ELECTRICAL SYSTEM EVALUATION
VOLUME II — TRANSIENT ANALYSIS

Prepared for
UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF MINES

by
Lloyd Morley
Jeffrey L. Kohler
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ANNUAL REPORT
on
Grant No. G0155003

May 15, 1977

OFR
78-61 (2)

EGE OF EARTH AND MINERAL SCIENCES
sity Park, Pennsylvania

REPORT DOCUMENTATION PAGE

1. Report No.	2.	3. Recipient's Accession No.
4. Title and Subtitle Coal Mine Electrical System Evaluation Volume II - Transients Analysis		5. Report Date May 15, 1977 6.
7. Author(s) Lloyd A. Morley, Jeffery L. Kohler, William R. Chubb		8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Mining Engineering The Pennsylvania State University University Park, PA 16802		10. Project/Task/Work Unit No. 11. Contract or Grant No. G0155003
12. Sponsoring Organization Name and Address Assistant Director -- Mining Bureau of Mines Department of the Interior Washington, D.C. 20241		13. Type of Report Annual 14.

15. Supplementary Notes

16. Abstract

This report details the continuation of mine power systems transient research under USBM Grant G0155003. The purpose of the work, which commenced under Grant G0133077, is the elimination of safety hazards created by transients, and the objective is to provide knowledge about transients existing in a-c and d-c coal mine power systems.

The report chapters cover theoretical background, instrumentation, and experimental investigations. The instrumentation discussion scans measurement problems and considerations plus the development of a low-cost peak-detector. Transient data from in-mine measurements are presented and include high-voltage distribution and d-c trolley systems. Extremely unique field exercises are described involving actual power equipment connected on the surface to duplicate typical underground coal mine system arrangements. Here, transients on high-voltage distribution resulting from vacuum circuit breaker operations could be observed under controlled conditions, and work centered around how surge capacitors effect transients. Using the in-mine and staged transient data, specific conclusions and recommendations are made with emphasis on high-voltage distribution.

17. Originator's Key Words	18. Availability Statement
Coal Mining, Electrical Systems, Transients, Surge Capacitors, Safety.	

19. U. S. Security Classif. of the Report	20. U. S. Security Classif. of This Page	21. No. of Pages	22. Price

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Coal Mine Electrical System Evaluation

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DISCLAIMER NOTICE

"The views and conclusions in this document are those of the authors and should not be interpreted as necessarily representing the official policies of the Interior Department's Bureau of Mines or the U.S. Government."

CERTIFICATION OF THE ABSENCE OF PATENTS AND INVENTIONS

This statement certifies that at the grant report date, no inventions have been developed from Grant G0155003. Consequently, no patents are pending.

Lloyd A. Morley, Project Director

FOREWORD

This report was prepared by The Pennsylvania State University, College of Earth and Mineral Sciences, Department of Mineral Engineering, University Park, Pennsylvania, under USBM Grant No. G0155003. The grant was initiated under the Coal Mine Health and Safety Research Program. It was administered under the technical direction of the Pittsburgh Mining and Safety Research Center with Mr. G. J. Conroy acting as the technical project officer. Mr. J. A. Herickes was the grant administrator for the Bureau of Mines.

This report is a summary of the work recently completed as part of this grant during the period 4 November, 1975 to 3 November, 1976. This report was submitted by the authors on 15 May, 1977.

This technical report has been reviewed and approved.

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SUMMARY

This report details the continuation of mine power system transient research under USBM Grant G0155033. The purpose of the work, which commenced under Grant G0133077, is the elimination of safety hazards created by transients, and the objective is to provide knowledge about transients existing in a-c and d-c coal mine power systems.

The report chapters cover theoretical background, instrumentation, and experimental investigations. The instrumentation discussion scans measurement problems and considerations plus the development of a low-cost peak-detector. Transient data from in-mine measurements are presented and include high-voltage distribution and d-c trolley systems. Extremely unique field exercises are described involving actual power equipment connected on the surface to duplicate typical underground coal mine system arrangements. Here, transients on high-voltage distribution resulting from vacuum circuit breaker operations could be observed under controlled conditions, and work centered around how surge capacitors effect transients. Using the in-mine and staged transient data, specific conclusions and recommendations are made with emphasis on high-voltage distribution.

Chapter I

INTRODUCTION

Transients are a fact of life on every power system. Careful design, within the technical and economic constraints of a system, will result in a reduction of transient-related component failures. However, there is much to be learned about such failures, as they can be rather elusive.

The underground coal mine power system is particularly vulnerable to transient-induced failures because its operation is extremely dynamic. As the mining activity advances, the electrical system is expanded, often on a weekly basis. Although this expansion is normally designed into the system, circumstances underground sometimes dictate modifications, which are often not completely known by the engineering personnel. Sometimes, these on-the-spot modifications are not pursuant to sound engineering principles.

A lack of knowledge about transients has resulted in power system requirements which are considered vague by many mine power engineers. Furthermore, in the process of maintaining the system, faulty components can be replaced with one of different specifications or even total incompatibility. These two factors also increase the vulnerability of the mine power system.

Statement of the Problem

Transient-related failures on the mine electrical system often include those in transformers, cables, couplers, and solid-state devices. The nature of these malfunctions suggests that they may be the end result of a gradual erosion of component integrity. This can create severe safety hazards from electrical shock as well as ignition of the gassy mine atmosphere.

Elimination of these hazards requires more knowledge about the transients existing in mine power systems including both a-c and d-c.

Scope of Work

As stated in Grant G0155003 scope of work, power measurement studies shall be performed with particular emphasis applied to those aspects which directly affect system durability and safety, including characteristics of transients due to switching and faults shall be measured utilizing equipment developed under Grant G0133077. From previous research experience, acquisition of this data necessitates an improvement of existing instrumentation. For practical significance, the investigation should note the present industry transient-suppression practices and provide recommendations on their efficacy.

At the request of the Technical Project Officer, additional work has been performed at no cost to the Bureau of Mines. The supplementary tasks cover the development of a low-cost transient detector and field measurements at a Midwestern coal mine where lightning-related transients present some unique problems. The later effort has been performed in conjunction with MESA personnel.

Report Format

The next report chapter highlights the theoretical aspects of transients as they relate to this research. The theoretical development is intended for those unfamiliar with transient phenomena and can be skipped by those readers with such knowledge. Next, Chapter III covers the field instrumentation and is divided into two major sections. The first discusses the peculiar aspects of in-mine transient measurement and provides answers

to problems often encountered during such experiments. The second section outlines the development of an inexpensive and portable transient detector which was initially used to detect lightning transients. The experimental investigations performed during this research are described in Chapter IV with the most representative field trips being discussed in detail. Conclusions and recommendations for further research are presented in the fifth chapter which is followed by a list of references.

Chapter II

THEORETICAL DEVELOPMENT

General

The term, "electrical transient," can mean different things to people of different interests. There are some common ideas however. As defined by Greenwood (1), "an electrical transient is the outward manifestation of a sudden change in circuit conditions, as when a switch opens or closes, or a fault occurs on a system." The circuit parameters of inductance and capacitance are, to some extent, found in any power system. When the system is changed, the quantities of current, voltage, magnetic flux, and so on, do not instantly assume new values. Rather, they go through a transition to reach the new steady-state condition (2). It is this transition period which gives rise to the transient voltages and currents.

Transient Sources

There are several discrete sources of transient overvoltages. Although there are slight differences in classifying these events, IEEE standards catalog seven types (3):

1. lightning,
2. switching surges,
3. static,
4. contact with an high-voltage system,
5. line-to-ground faults,
6. resonant conditions, and
7. restriking ground faults.

These are briefly discussed in light of mining applications in the following paragraphs.

Direct lightning strikes to power equipment will result in large transient overvoltages if the equipment is not adequately protected. Title 30, Code of Federal Regulations, Part 75, appears satisfactory for protecting underground mine power systems, but Part 77 may not adequately cover surface facilities[1,2]. Induced voltages from nearby strokes are believed to be a hazard in Mid-Western strip mines and are discussed in Chapter IV. The buildup of overvoltage on exposed surface lines may result in destructive transient overvoltages, but existing practice usually precludes damage. The main hazard is to personnel working on the lines and is commonly experienced in Western surface mines.

Due to existing protection methods, transients resulting from line-to-ground faults or contact with higher voltage lines are minor, although destruction from localized heating may be severe. However, if the protective circuitry malfunctions, as sometimes occurs in the harsh mining environment, the problem can become critical. The intense local heating at the fault site will cause the conductors to melt or even vaporize. As this happens, the potential gradient across the conductors is sometimes sufficient to strike an arc. The arc will extinguish and reignite, all things remaining equal, at each zero crossing of the voltage wave. The random fluctuation of arc resistance, as well as phenomena related to arc reignition, results in large transient overvoltages (4).

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1. "Mandatory Safety Standards, Underground Coal Mines," Title 30, Code of Federal Regulations, Part 75, December 31, 1972.

2. "Mandatory Safety Standards, Surface Coal Mines and Surface Work Areas of Underground Coal Mines," Title 30, Code of Federal Regulations, Part 77, May 22, 1971.

Resonant conditions can result in transients exceeding ten times the nominal line voltage (5,6). Since the power system contains inductance and capacitance which are normally much greater than system resistance, resonance can occur at the natural frequency of the system. Resonance may result from the presence of line frequency harmonics (harmonic overvoltage) or from the frequency components of other transients (dynamic overvoltage). Although this is probably not the most frequent form of transient voltages, the number of failures resulting from this mode are believed by some engineers to be significant (7). When transformers are involved, transient resonant conditions creating dynamic overvoltages have historically been given the term, "ferroresonance." However, considering circuit component values, the occurrence of these transients in mine power systems should be rare, if not practically non-existent.

Restriking ground faults, which are found primarily on reactor-grounded systems, can cause transients several times greater than the nominal line voltage. Since coal mine power systems are required to use a resistance ground, this type of transient generation is also rare, except when the protective circuitry malfunctions. Then, as previously mentioned, uncleared faults may cause transients.

Switching operations account for the majority of all transient phenomena. Furthermore, research data collected through this research indicate that the most destructive power system transients occur from this source. (This statement has been substantiated as true for other industrial applications, other than specifically mining, through conversations with prominent power engineers specializing in transients.) Although switching can be separated into several categories, there are only two

relevant to this discussion. They are transformer-switching and circuit-breaker operations.

Switching Transients

Transformer switching is simply divided into two primary categories: energizing and de-energizing the transformer. Energizing will cause a transient, of up to two times the nominal secondary voltage, to appear on the secondary side. This type of transient is harmless within the framework of present component design and construction practice. It is also a transient which is characteristic of the proper operation of the transformer. Hence, it is classified as a "normal" transient. There are various other sources of normal transients which are usually of no consequence.

"Abnormal" transients, however, are not the result of correct component operation or system design. Hence, they are of primary interest to this investigation because severe damage can follow their occurrence. De-energizing a transformer, as well as other examples to follow, primarily causes an abnormal transient overvoltage. If the transformer secondary is connected to a high-impedance load, transients in excess of 10 times line voltage may result (8).

The second type of switching transient involves the application of switchgear, especially vacuum circuit breakers. Fundamental discussions on switching and the resulting transients can be found in most basic electrical engineering texts, for example, references 9 and 10. A more theoretical analysis is given in reference 11.

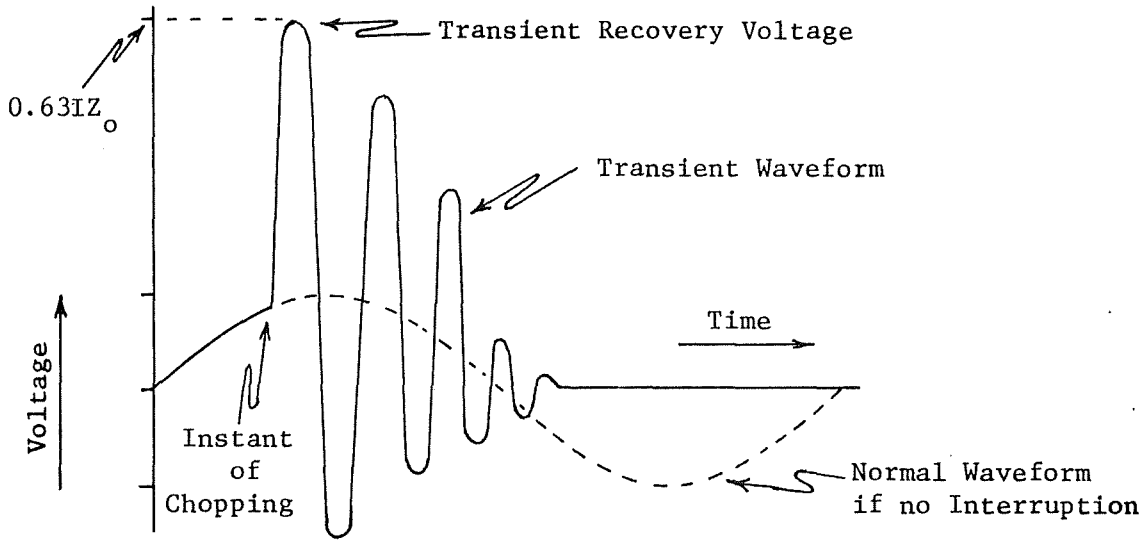
Switchgear has evolved from the hand-operated knife switch to the vacuum circuit breakers (VCB) of today which are capable of interrupting large fault currents in less than one cycle (60 Hz). Many of the more

recent advances in circuit-breaker technology have resulted from the use of vacuum as the dielectric between the contacts of the breaker.

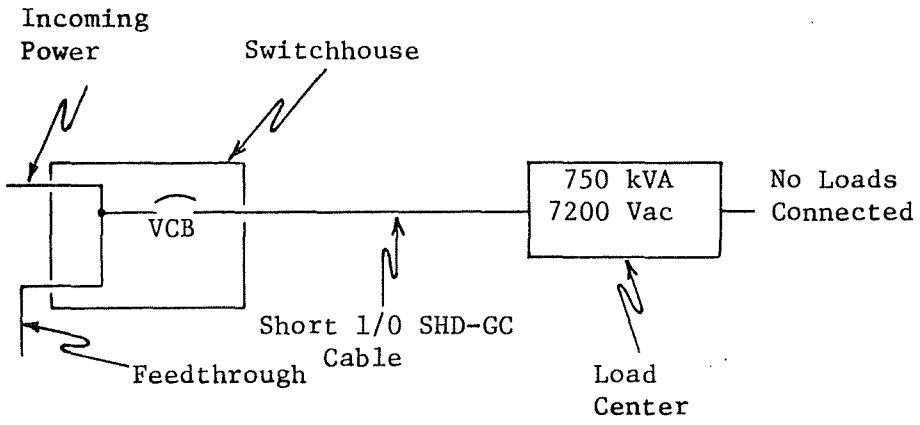
In addition to their ability to interrupt large currents at the first zero-current crossing, vacuum circuit breakers are relatively maintenance free and reliable. This coupled to small sizes has made them very attractive to the mining industry; their employment is now universal on high-voltage systems.

Chopping. The high efficiency of VCB's, which has in part led to their wide application, is ironically the characteristic which can cause severe transients. Such can occur when small currents, for example, transformer exciting current, are interrupted. In this case, the small current is forced to zero before the natural current zero, thereby trapping magnetic energy in the power system that is spontaneously released as a large voltage distribution (12). "Current chopping" is the name of this effect and is graphically illustrated in Figure 1a.

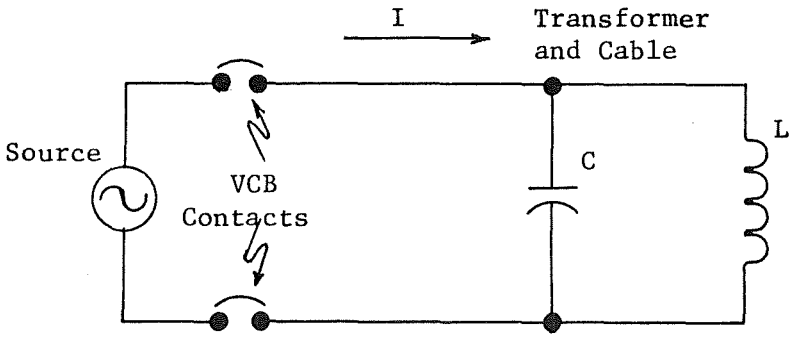
The level of current drop (di/dt), at the instant of chopping, is greatly influenced by the contact material, primarily the cathode (13). At this writing, most VCB contacts are of a copper-bismuth material, and it appears that copper is the large contributor to the chopping problem. Bismuthk in minor amounts, is employed to make the copper brittle, hence reduce its weld strength. Therefore, any welding of the contacts, during operation, can be easily broken by the breaker mechanism. The copper, however, does not generate enough vapor in the vacuum bottle on small currents to sustain arcing until the natural current zero. Consequently, small currents are usually chopped.



a. Graphic Example of a Chopping Voltage Transient.



b. A Segment of a Mine Power System.



c. Per Phase Equivalent Circuit for Figure 1b.

Figure 1. Chopping Voltage Transient Example and Possible Circuit.

This problem was explored with circuit-breaker manufacturers supplying the mining industry. At least one company is manufacturing VCB's with contact material (other than copper-bismuth) that reportedly minimizes chopping (14). Other manufacturers indicate an understanding of the problem and a willingness to find a solution. Although, it should be noted that one major producer of vacuum switchgear does not acknowledge any problem that exists by using copper-bismuth contacts.

It is beyond the scope of this report to derive the equations governing chopping transients; rather eloquent developments can be found in the literature (for example, reference 15). Without describing the origin, it is instructive to state the simplified equation which yields the transient voltage due to a current chop:

$$V_p = I(L/C)^{1/2} = IZ_o \qquad (1)$$

where,

V_p = peak transient voltage,

I = pre-chop current,

L = lumped inductance,

C = lumped capacitance, and

Z_o = system surge impedance.

This relationship does not account for resistance but, since resistance is usually very small for power systems, it can be ignored without grave consequence.

From equation 1, it is apparent that the peak transient voltage will be determined by the current flow at the time of chopping and the characteristic impedance of the circuit in question. Figures 1b and 1c portray

a typical mining application where chopping transients could present problems. Here, the current will be about 0.03 to 0.05 per-unit (a typical transformer magnetizing current). The transformer surge impedance is large so transients of up to 10 times nominal line voltage may be expected. However, the system exhibits losses, and modern dry-type transformers limit energy storage to about 40%. As a result, actual transients are usually limited to approximately 60% of that given in equation 1. Even so, transients of five to seven times line voltage can frequently occur.

If the cable length between the switchhouse and load center is increased, the cable capacitance will be proportionally increased. This will reduce the surge impedance and, therefore, the severity of the chopping transient. Too large of value for the cable capacitance can result in other transient phenomena such as prestrike.

Similar configurations to that described above can result in large chopping transients, for example, a cable-connected motor. Motor surge impedance and magnetizing current are smaller than for a transformer, thereby reducing the danger of large chopping transients.

Prestrike and Restrike. As stated earlier, mine power system capacitance can reduce the effects of chopping, however, large capacitance can cause severe transients upon energization. Pflantz (16) has shown that during initial energization of system capacitance, prestriking will occur across the VCB's contacts, prior to their closure. In these instances, overvoltages may reach substantial levels if the initial inrush current (that going into the circuit being energized) is momentarily stopped then followed by a subsequent prestrike

or contact closure. The magnitude is dependent on the ratio of capacitance, inductance, and resistance existing on both sides of the interrupter. However, three to seven times peak system voltage transients can happen, depending on the voltage existing on the capacitance prior to energizing. Furthermore, these voltage transients, transmitted through conductors or cables (in the form of traveling waves), may be amplified at power system discontinuities by reflection and refraction.

The high-voltage shielded cables abundant in underground coal mines can create such a capacitance problem. For example, the complex of feeder cables throughout the mine can reach thousands of feet and present a significantly large capacitance on the outby side of the switchhouse. The inby cable length, however, may only be a few tens or hundreds of feet. Therefore, a high ratio of outby-to-inby capacitance across the circuit breaker can exist, setting the stage for a probable prestrike-type transient. This capacitance ratio can be further enhanced by additional system capacitance beyond that of the cables (i.e., surge capacitors).

Breaker-contact opening to clear a fault can result in abnormal transients, if the arc reignites, known as restriking. This phenomenon is probably more of a problem on d-c than a-c systems. Restrike behaves similarly to prestrike in that large capacitance increases the probability of the event (18).

Transients in Direct-current Systems

The theory developed for a-c power systems is valid for the d-c case as long as it is remembered that the forced frequency is zero, hence the capacitive reactance is infinite. Therefore, cable or system capacitance is not important (for the topics discussed in this report).

The mining industry does not use vacuum circuit breakers to protect d-c systems and thus is immune to the chopping transients described in the previous section. However, the d-c system is subject to abnormal transients. Large amounts of energy can be stored in the system inductance, and any sudden current decrease will result in an overvoltage. The magnitude of this overvoltage is proportional to the product of circuit inductance and the time rate of current change (L di/dt).

Transient Induced Failures of Electrical Insulation

Deteriorating electrical insulation affects the entire mine power system and may jeopardize its safe operation. Whether the dielectric is in a transformer winding, motor winding, portable cable, or rectifier, it is a critical factor in the safe, economical, and reliable operation of any mine power system. Disturbances which threaten to compromise the integrity of the power system, must be eliminated at the source. This is why attention has been paid, in this research, to the causes of electrical transients and their elimination. Consequently, it may be helpful to examine the affect of abnormal voltages on dielectrics.

Each type of insulation or dielectric is designed for a safe maximum applied voltage and a transient overvoltage. The transient overvoltage rating is given in terms of BIL, the Basic Insulation Impulse Level. The most common BIL measurement is the 1.2x50 wave test, where the voltage impressed across the dielectric reaches its peak in 50 μs (18). Thus, a dielectric with a 95 kV BIL rating can safely withstand a 1.2x50 pulse of 95 kV. This wave test is considered more severe than the transients found in mine power systems.

The event of dielectric deterioration is determined in large part

by the rise time of the transient, as well as the peak magnitude. Of course, the greater the overvoltage pulse width (duration), the greater the probability for failure. These voltage anomalies break molecular bonds in the dielectric, which reduces its effectiveness. If the overvoltage contains sufficient energy, the dielectric can fail immediately; however, this is usually not the case. Rather, the insulation is progressively weakened until it finally fails.

If the weakened insulation is in a portable cable or splice, a considerable personnel safety hazard exists since the insulation "appears" to be functional, when in reality a lethal potential may exist on the cable surface. Although the deteriorating dielectric may not present a direct safety hazard, complete failure may do so from an explosion or arcing. In any case, a serious hazard exists for the equipment in terms of repair, replacement costs, and downtime.

The physical construction of equipment may increase its susceptibility to transient failure. For instance, motor and transformer windings often fail at the end of a coil due to the increased electrical gradient. When the dielectric has deteriorated to a critical point, a line-to-ground or line-to-line fault may occur. Corona may also occur thereby hastening the failure (19,20).

Transient Voltage Suppression

Elimination of transient voltage problems is best started with an excellent power system design applying time-tested principles (21). Additional overvoltage control can be obtained by using surge arresters, surge capacitors, or shielding.

Surge arresters, formerly called lightning arresters, clip the peak

of a voltage transient and divert the excess current to ground. Typically, they consist of two major parts: a spark gap and a valve section. The spark gap is designed to spark over, thus diverting the excess energy to ground at a given voltage level. The valve unit is designed to stop the current flow after the overvoltage is past. Although surge arresters are available for clipping as low as 50 V, they are generally used only on high-voltage systems in mining. Much surge arrester application information is available in the literature and from manufacturers (for example, references 21 and 22).

Surge capacitors limit the rate-of-rise of the transient voltage (as discussed earlier, the faster the pulse rise time, the greater the probability for damage). If a capacitor is connected into the circuit it will have to be charged by the transient before the overvoltage can be impressed upon system dielectric. The pulse rise time then will be largely determined by the capacitor charging rate. Surge capacitors can be located either at the power center or at equipment to be protected (or both). Currently, these devices are favored by the industry and widely used. However, data collected in this research indicates that they may aggravate prestrike transient problems.

Faraday shields have some application for protecting the low-side of a transformer against surge voltages. Transients can be coupled to the low-side through primary-to-secondary transformer capacities at per-unit voltage levels much higher than existing on the high-side (23). Grounded Faraday shields between the primary and secondary winding destroy the interwinding capacitance and, thereby, substantially reduce the transfer of surge conditions. However, such shields have been responsible for many transformer breakdowns as their presence

produces a dielectric-stress concentration at the edge of the shield (6). This tends to strain insulation locally and can result in destruction of the high-voltage winding. Even with the reported failures, several manufacturers appear to have solved the Faraday shield problem or the interwinding-capacitance problem through improved construction practices.

Summary

This chapter has attempted to define the electrical transient and its rammifactions on mine power system safety and integrity. The content has intended to build upon that previously reported (24,25). An electrical transient can be defined as the outward manifestation of a sudden change in circuit conditions. The magnitude and fast rise time of the overvoltage can cause damage to electrical components, particularly insulating materials. In addition to sound design practices, techniques are available to reduce the damage done by surge voltages, including surge arresters, capacitors, and Faraday shields.

Chapter III

INSTRUMENTATION

Background

Elimination of the safety hazard created by electrical transients requires a precise knowledge of their behavior on the mine power system. To obtain this information, it is required to instrument a mine's electrical system and record the pertinent characteristics of any transients. Since no organization has ever attempted to instrument something like this previously, it has been necessary to develop a suitable instrumentation package. Working with the technical project officer, Mr. G. J. Conroy, project personnel developed a package suitable for use in underground coal mines. The bulk of the work was completed in prior projects and was reported (24, 25). This equipment is summarized in the next paragraph to facilitate the discussion contained in this chapter.

With the exception of the transducers, all the equipment shown in the block diagram of Figure 2 is located inside a dolly-mounted metal enclosure having side access panels. The transducers, usually resistive voltage dividers, are temporarily attached to the electrical system. They reduce the nominal voltage level down to $\pm$ 0.12 V rms at their output where the signals are then fed, via coaxial cable, to the Biomation Transient Recorder. The transient recorder is the major component of the system. Basically, it is a two-channel digitizer with memory, appropriate trigger controls, and various output options. In use, a number of parameters must be specified on this instrument, including the trigger-voltage level and the time period for which

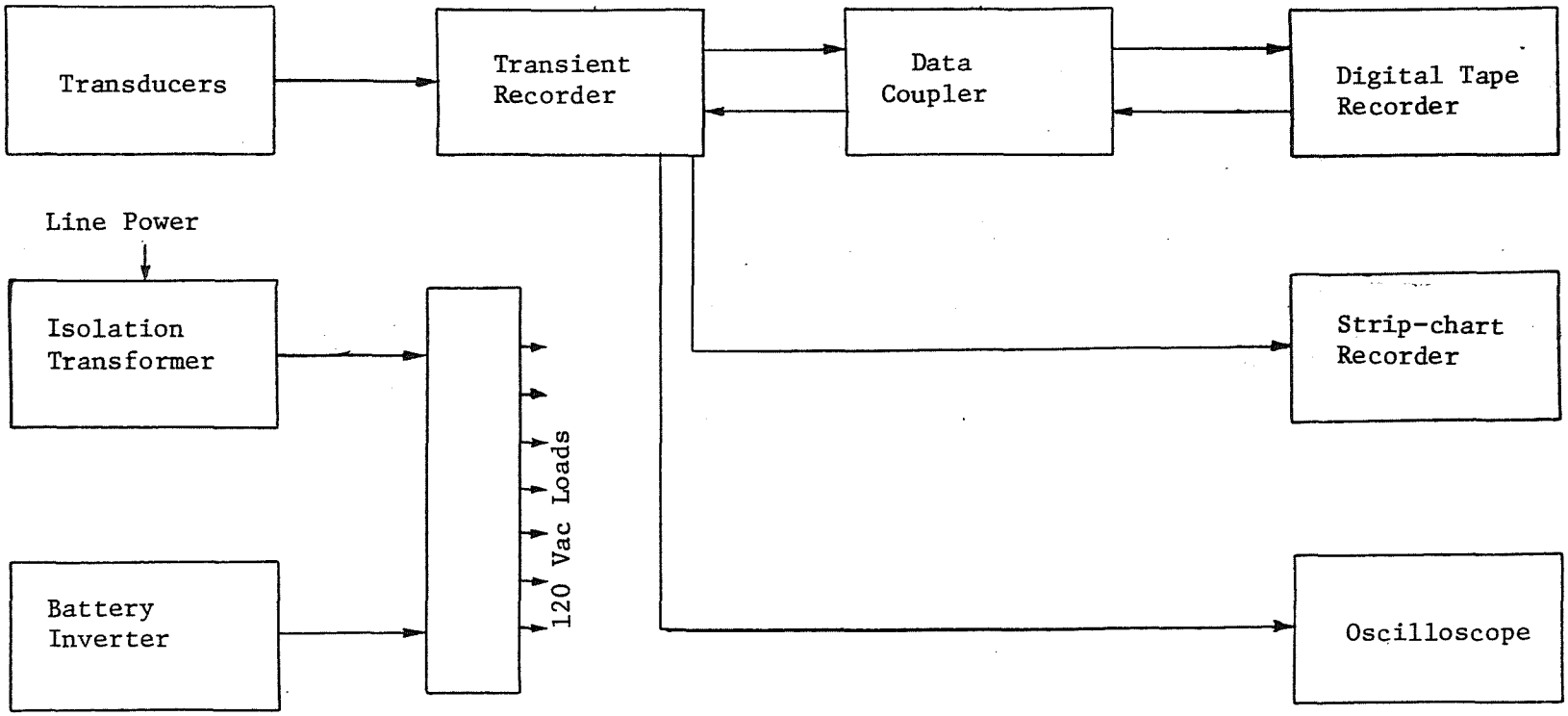


Figure 2. Block Diagram of Transient Recorder System.

information should be recorded prior to and after the transient. The recorded transient can then stored on a Kennedy incremental (digital) tape recorder, as well as a Brush strip-chart recorder. Simultaneously, the signal is displayed on an oscilloscope and, if the output of the transient is on manual control, the operator can prevent recording of the transient. Using this method, the operator can minimize data analysis by aborting false triggers and so forth.

Data Analysis

The data stored by the digital tape recorder can be analyzed on an IBM 360/370 computer. However, project personnel have developed software only to plot the transients on a Calcomp Plotter. From the plotted data, the pulse rise time, peak amplitude, and duration can be determined. Although the same information can be ascertained from the strip-chart recorder, the result is not as precise due to poorer resolution. The chart-recorder functions primarily as a hard-copy back-up in case of tape-recorder malfunction.

Field Use of the Transient Recording System

The mine use of any instrument system presents difficulties, particularly a sophisticated package like this transient-recording system, and much valuable experience has been gained by project personnel. Since it is anticipated that practicing mine power engineers will be making tests in their own mines, these experiences will be described in this section so others may avoid some common pitfalls. The main areas of discussion are the sophisticated nature of the equipment, the problem of multiple-ground paths, and the problems of constructing a high-voltage divider.

The Model 8100 Biomation transient recorder is a very good laboratory instrument, designed to provide a thorough quantitative knowledge of a transient. For this application, however, recent research has found it not suitable, first because it is intended as a laboratory instrument and second, it requires constant operator supervision to insure interpretable results. Despite the use of shock mounts and other protective features, the accuracy and reliability of the unit seemed to deteriorate with every field trip. Dust and moisture did not cause any problems.

There were some problems which resulted from intentional design features. Among these features were the 50 Ω input impedance, the triggering sensitivity, and the effect of a changing d-c offset signal on the direct-coupled input circuitry.

As will be explained in the voltage-divider section of this chapter, the 50 Ω input impedance created design problems in obtaining effective voltage dividers for operating with the high distribution voltages encountered in mines. An input impedance between 1.0 and 10 MΩ would have been more compatible with voltage dividers required for this application.

The trigger sensitivity of the transient recorder is adjustable and may be set to start the recording process on voltage level increased from a small percentage above the nominal line voltage to several times line voltage. There were many instances during data collection where it was desirable to trigger on levels of perhaps only 10% above the line level, such as during intentional vacuum circuit breaker tripping or closing. During such circumstances, there were cases where the "captured" transient was lost, due to retriggering by later and less important voltage rises. A circuit to prevent retriggering until manually commanded would have been helpful.

The signal level needed to trigger the recorder is the algebraic sum of the a-c peak and any d-c voltage which may be present. Therefore, if there were a sudden change in the d-c component, the trigger circuit would react. Conversely, if there were a sizeable d-c component of opposite polarity present, if would depress the expected transients and possibly no signal would be recorded. Either direct coupling or a-c coupling can be selected, but the a-c has a lower cut-off frequency of 1,500 Hz and is not desirable for this particular application. Consequently, data collection has been hampered by the presence of d-c offsets.

Among the design features, which were not due to intentional design (i.e. malfunctions), were crossover distortion, output level indecision, and a lack of isolation between the recorder and the source of equipment power.

Crossover distortion occurs as the signal goes through a zero crossing. It appears as a separation between the positive and negative portions of a signal or missing portions of the base line. It changes with time and with changes in temperature, and frequent adjustment is necessary to eliminate the distortion. The problem seemed to worsen as the unit aged.

Another problem which developed after about two years use was a condition that looked like the analog-to-digital converter could not decide which value to assign to a certain level. When a fixed voltage was applied to the input, the output would look similar to a squarewave of very low amplitude. This introduced a small error into the data, the value of which depends on how much dynamic range of the instrument is being used.

Multiple ground paths can introduce error into the data collected. The traces shown in Figure 3 are graphic illustrations of transients,

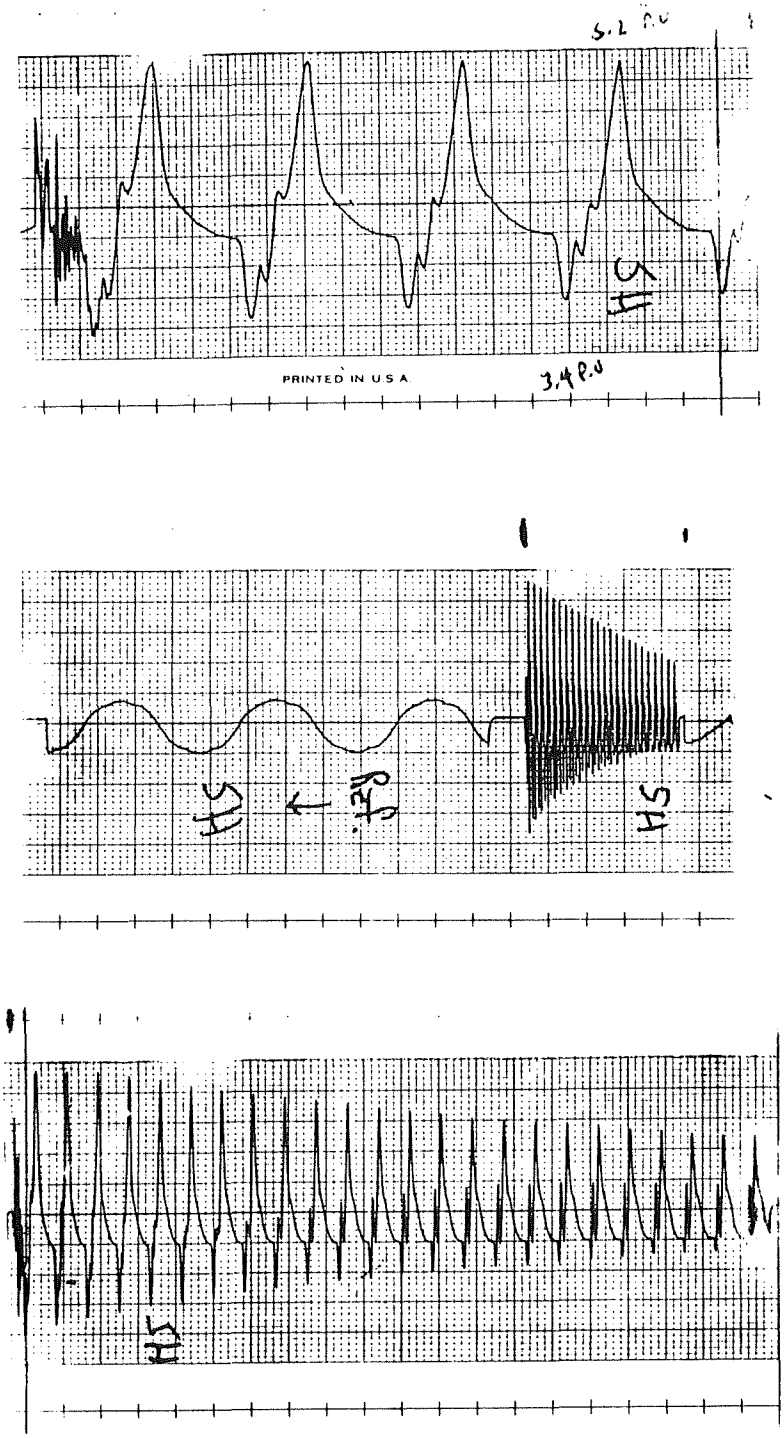


Figure 3. False Transient Recordings Created by Multiple Ground Paths.

which never occurred but resulted from voltages developed in multiple-ground circuits adding to the actual transient. Part of this multiple-ground circuit is created by a path back to the source which supplies power to the transient recorder. Isolation transformers and good line-filter practice in the instrument do reduce unwanted coupling. However, on an occasion where an engine-driven generator was available, a series of tests were run to compare aquired data. The results showed that the amplitudes of recorded transients were reduced by a factor of about two. Total elimination of ground-loop voltage from multiple paths may not be possible, but every effort should be made to keep them to a minimum. Thus, using an equipment power source which is entirely independent of the power system being measured is a good and sometimes mandatory goal.

Voltage Dividers

When the task of gathering data on mine power system voltage transients was started in Grant G0133077, little was known about the frequencies that would exist. Therefore, the initial voltage dividers (used to lower the instrumentation input voltages) were made up of high-quality film-type resistors of the proper resistance and line-to-neutral voltage ratings, mounted to prevent arcing and to provide protection to the operating personnel. Film types were used because they are non-inductive (or nearly so) and stable.

After the first few data gathering field trips, it became apparent that frequency components of several hundred kilohertz were common, and frequencies components of several megahertz were encountered. This required a closer look of any capacitive or inductive effects created by the physical arrangement of the voltage divider. Additionally,

the reactive component of the resistors had to be taken into account.

Attempts were made to actually measure the attenuation characteristics of the first voltage dividers. It was found that ordinary laboratory equipment was inadequate. The output of the signal generator was very small compared to the 13 kV lines encountered on field trips so the best oscilloscopes presently on the market were not sensitive enough to provide an adequate signal-to-noise ratio. However, as the frequency of the signal source was increased to several hundred kilohertz, it was readily apparent that capactiance shunting the high-value resistors (approximately one picofarad in parallel with 3 MΩ) was allowing the signal to be passed through the voltage divider with decreasing attenuation. This meant that any high-frequency components in a recorded transient would appear several times larger than the actual value.

Several different types of voltage dividers were investigated. One design used four resistors in series so the shunt capacitance from end-to-end on each resistor was put in series with the capacitance of the other resistors, thereby cutting the total shunting effect to about one-fourth of the original value. Figure 4 shows how the divider was constructed. This provided an adequate solution, but the divider was not totally frequency independent. Capacitive dividers were attempted, but the sensitivity of available instrumentation did not allow proper adjustment of values.

An interesting voltage divider for use on high voltages was found in the literature (24), and it consisted of a differentiator and integrator in series (26). When properly designed, the circuit is frequency insensitive over a selected bandwidth. The problem with this particular arrangement, however, is that an input capacitance must take the full voltage drop and must have rather precise capacitance. If time

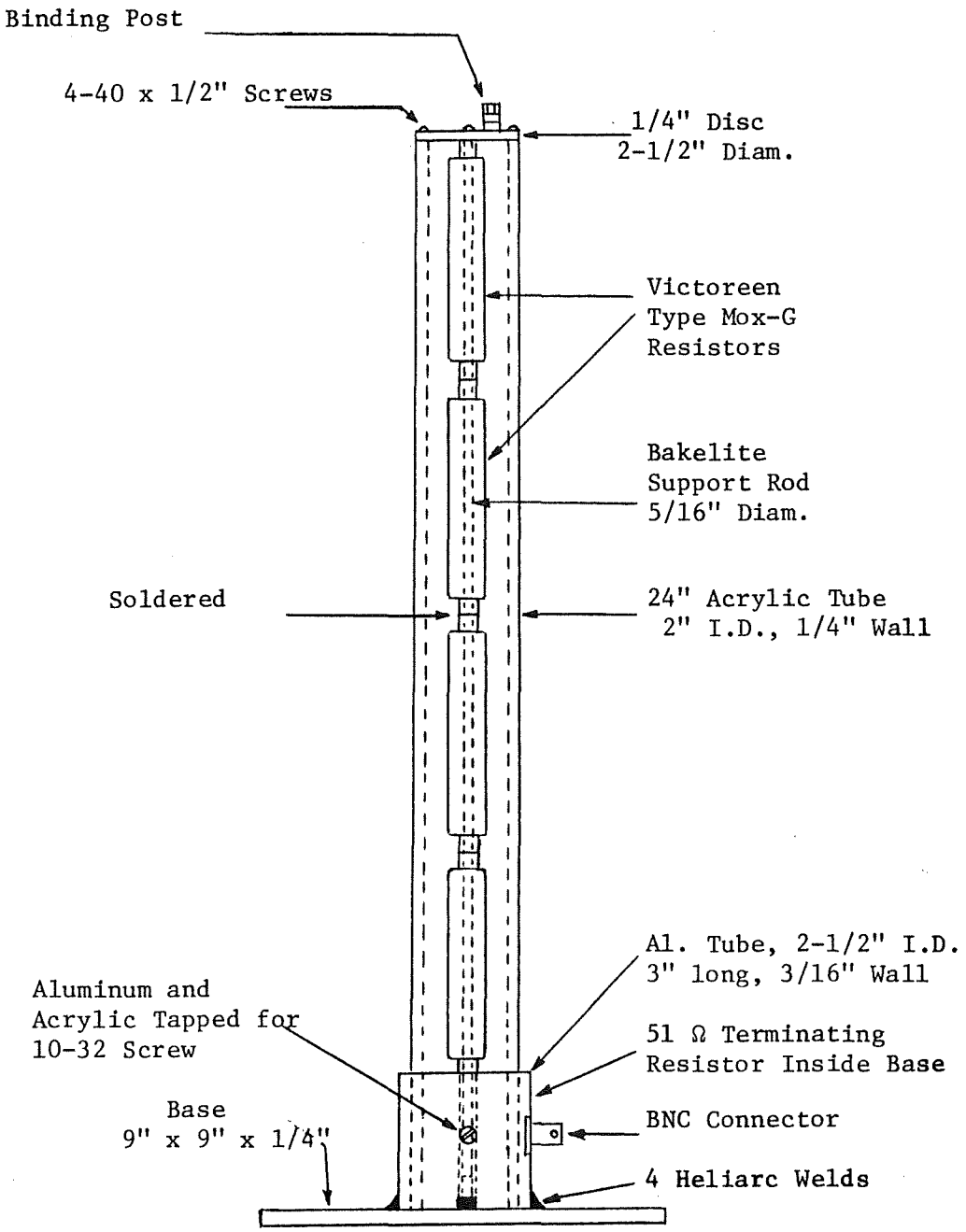


Figure 4. High Voltage Divider.

and funds had permitted, it might have been beneficial to fabricate the capacitor in the laboratory. Yet again, the problem of calibrating the divider without a very high-output signal source or a very sensitive indicator would still exist.

Literature was obtained from manufacturers of high-voltage dividers. Most used capacitors as the dividing elements but provided output voltages too high for the Biomation transient recorder. One manufactured unit had an operating frequency range of 40 to 70 Hz which was too restrictive. Another unit claimed a flat response to 10 MHz but required an instrument input of 10 MΩ for 100 Hz response at the low-frequency end. Both were designed to be used with the high input impedance of oscilloscopes and, therefore, are not directly useable with the 50 Ω input impedance of the transient recorder.

If future work should be done in this area, it is recommended that several attenuators of the second type mentioned be purchased and adapted for use with a transient recorder. This would of course still require a high-voltage variable-frequency supply for divider calibration.

Transient Peak Detectors

Introduction. Ground-check monitoring devices are used as a fail-safe device to disconnect the mine power system when integrity of the safety-ground circuit is lost. There have been several occurrences in surface coal mines where these protective devices were damaged. Many engineers have assumed the cause to be large voltages developed between the system (or station) ground and the safety (or mine) ground. Possible sources of the large transient voltages are lightning striking the utility's distribution network (either the incoming power lines or the

substation secondary circuits), lightning induced voltages on long trailing cables, and system switching transients. Whatever the origin, the problem manifests itself as damaged ground-check monitors.

In an effort to collect data to study these transients, project personnel developed a circuit that, because of the possible lightning problem source, has come to be called a "lightning detector."

Lightning Detector. This circuit is more correctly called a peak-detector circuit and, in this particular case, is composed of a 10,000:1 voltage divider, a precision detector, and an integrator. It is designed around a type 747 dual operation amplifier. The voltage divider is mounted on stand-off insulators fastened to the top of a plastic box containing the detector circuit, batteries, and so forth. A barrier strip provides a means of connecting a strip-chart recorder to the output. The circuit has been designed to be compatible with the Easterline-Angus model A601R strip-chart recorder (although other recorders can be used). Figure 5 is the detector circuit diagram, Figure 6 is its characteristic curve, and the Appendix provides construction details.

Theory of Operation. The voltage divider reduces the transient spike to a level compatible with capabilities of the operational amplifiers. Amplifier A1 acts as sample-and hold circuit; that is, it samples an incoming signal and holds that level until it receives a higher signal, is reset, or finds a discharge path. Because of the lightning-discharge application, the circuit designed to respond to positive spikes only. Diode D1 prevents amplifier A1 from being saturated if the input does become negative and provides feedback after a positive signal is detected. The feedback circuit for the detector is comprised of R5, R6, C1, and A2. The A2 circuit is also an integrator

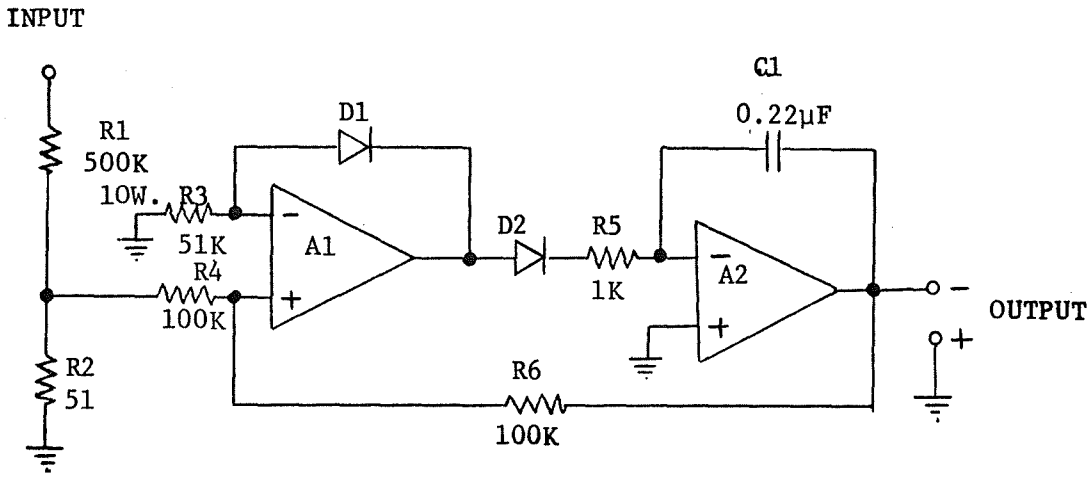


Figure 5. Peak Detector Circuit.

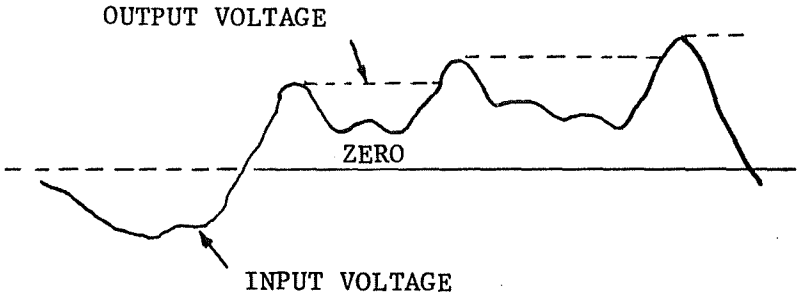


Figure 6. Peak Detector Characteristic.

circuit with C1 holding the charge. In the lightning detector application, C1 has time to discharge through A2 before another spike occurs. Diode D2 assures that C1 will charge in one direction only. A2 is connected as an inverter which results in a negative-going output, therefore, the positive terminal of the strip-chart recorder must be connected to the ground side of the output circuit.

Summary

This chapter has highlighted the present transient recording system and discussed the operational difficulties. It is hoped that the material presented here will help others avoid the many pitfalls of this type equipment. Although the sophisticated instrumentation provides the most detailed information, the peak-detector circuit should provide an adequate data base for mine power system design imporvements. Applications for this simple device, other than lightning transients, will be shown in the next chapter.

Chapter IV

EXPERIMENTAL PROGRAM

Introduction

The field program was designed to gather quantitative information about the nature of electrical transients. It consisted of several trips to underground coal mines and one strip coal mine operation. The instrumentation used to obtain this data was described in the last chapter. Only the most representative field trips will be described, and include three a-c and two d-c power systems in underground mining operations and one a-c system in a strip mine.

Realizing that severe transients do exist in underground coal mine distribution systems, an extensive series of measurements were made to clarify initial research findings, as described in previous reports (24, 25), and involved recording staged transients on unloaded and loaded systems by chopping (tripping the switchhouse) and prestrike (engaging the VCB).

Mine One

The effort commenced in-mine with the selected system segment shown in Figure 7. With no secondary loads, the VCB was closed and tripped several times. Therefore, the breaker would basically chop only the transformer exciting current during opening, while it would just look at inrush current upon closing. There was almost no abnormal transient activity during tripping, but many large transients were observed on closure, occurring practically everytime. An example of a typical event is given in Figure 8; the voltages shown are line-to-neutral.

Considering the large system capacitance (500 ft SHD-GC cable and 0.25 μF surge capacitors), the results for chopping were not surprising.

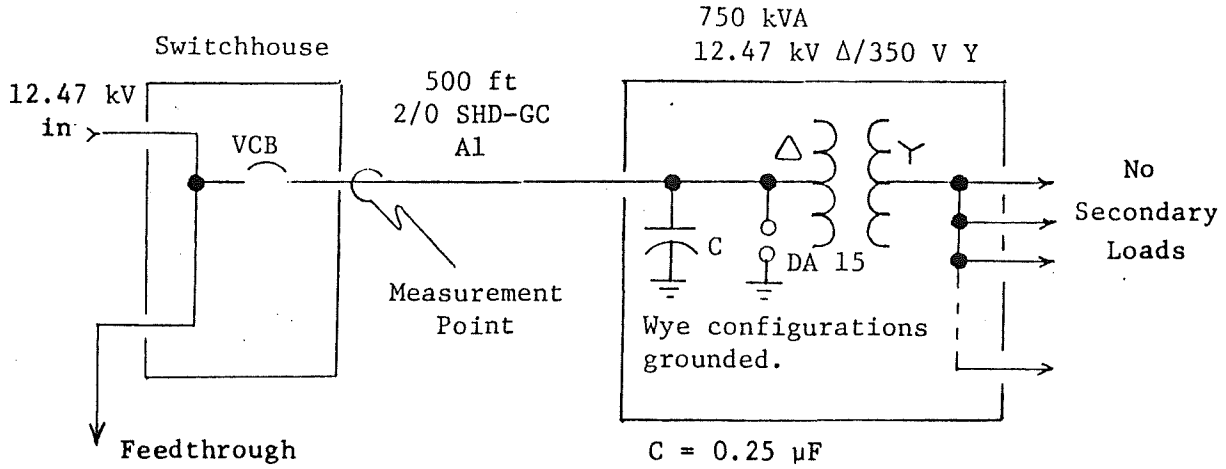


Figure 7. Simplified Sketch of 12.47 kV Power System Segment.

The high transient recovery voltages (8.0 per-unit voltage), upon closure, were rather unexpected but explainable by the aforementioned prestrike phenomena. If the breaker closure mechanism is slow during closure, there is a chance of an arc ignition in the vacuum bottle prior to contact. Referring to Figure 8, the first transient envelope could be such an event. As the inrush current waveform passed through zero, the arc was extinguished. Then, on the other side of current zero, a second pre-ignition happened. Finally, the small bursts after the second envelope could be contact bounce upon closure. The high oscillation frequencies are much greater than that dictated by natural system frequency but could be a result of transient wavefront reflections at system impedance discontinuities.

Therefore, the high overvoltages might have been created by a high outby-to-inby capacitance ratio as seen by the VCB and described by

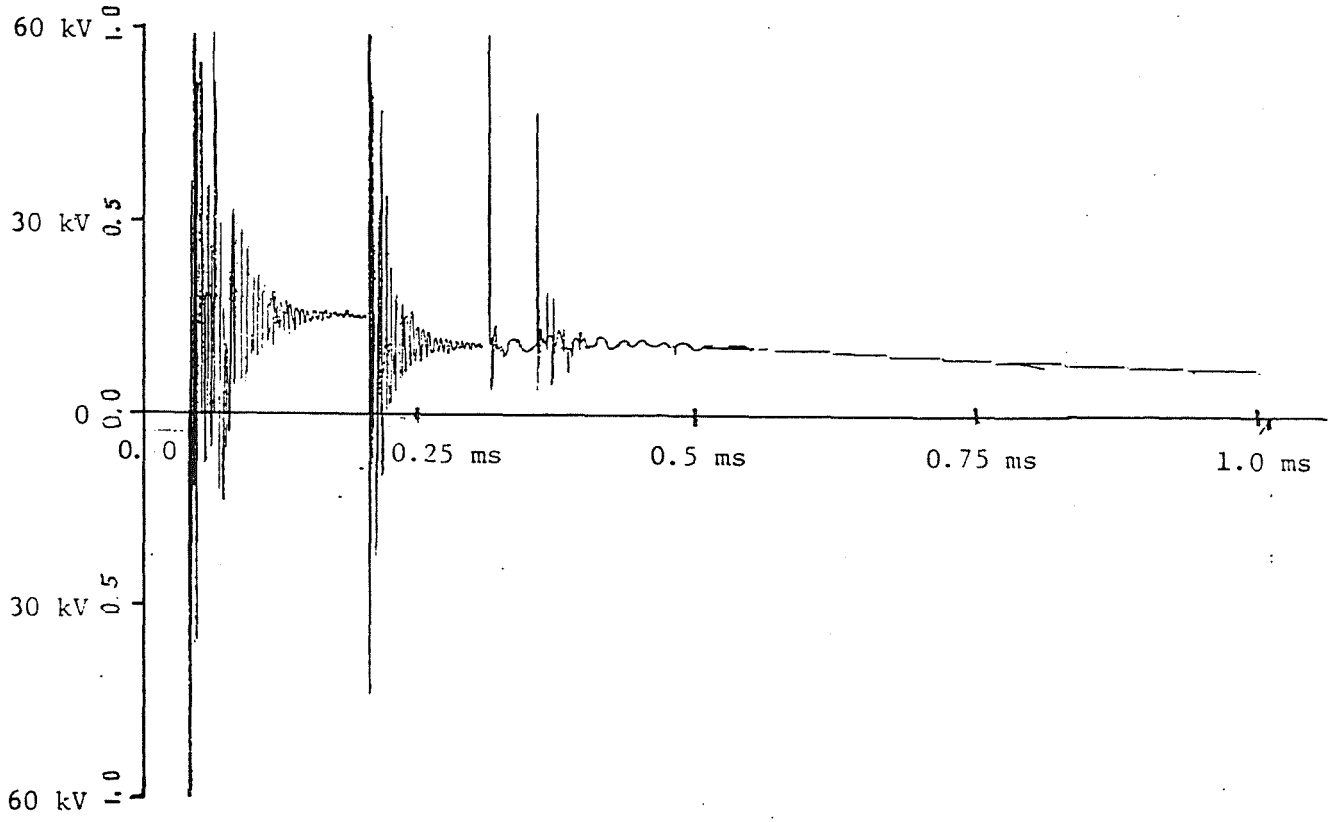


Figure 8. 12.47 kV Distribution Transient.

Pflantz (16). The peak voltages in Figure 8 do meet or exceed 60 kV (line-to-neutral, 8.3 pu nominal), but the surge arresters should have restricted the peaks to around 55 kV (for 15 kV distribution class arresters). The difference could be a result of measurement precision, but the arresters may have been inoperative.

Surge capacitors have long been recommended as a preventative for severe VCB chopping transients (see Chapter II). The mine visited, therefore, was employing them at the high-side of every distribution transformer. Such extensive use when added to cable capacitance might result in the prestrike transients. Furthermore, excessive system capacitance can definitely pose other problems in the coal mine's high-resistance grounding system. Most high-voltage distribution systems have 50 A ground-current limit or less. Yet, each time a 0.25 μF surge capacitor is added to the system, the capacitive ground charging current is increased by approximately 5 A (of course, dependent upon the voltage level). This charging current is around 0.2 A/1000 ft for typical high-voltage feeder cables. Therefore, with just 10 capacitors on the distribution system, charging currents exceed a 50 A limit. If a phase-to-neutral fault occurs in the complex, this capacitance can discharge, feeding the fault with capacitive ground current in excess of current limit. This could happen within the ground system, and there is a possibility that the ground resistor and its protective circuitry will not see it. As a result, surge capacitors might be adding more problems to the mine power system than they are protecting against.

To further verify the destructive quality of transients and to investigate their relationship with surge capacitors, two additional series of measurements (Mines Two and Three) were made. The overall

objective was to see if these capacitors were necessary to limit chopping voltage transients in a mine power system and what effect they have on prestrike events. The work was performed on the surface in order to gain control over system variables but, for comparison, actual 12.47 kV mine power equipment was employed to duplicate the circuit arrangement similar to Mine One.

Mine Two

The first trip for observation of staged transients under controlled conditions on the surface, was in central Pennsylvania. The direction of the measurements was to compare various combinations of system variables, primarily VCB and cable length effects. A 600 kVA, 12.47 kV Δ/Y load center, with either 60 ft of number 4/0 aluminum or 1,000 ft of number 2 copper SHD-GC feeder cable, and a vacuum circuit breaker comprised the system. The power source was a 5,000 kVA, 34.5 kV/12.47 kV substation transformer. Variations in system configuration during testing included:

1. the source power transformer loading:
    a. totally isolated from mine complex (minimum source capacitance), powering test set-up only, or
    b. tied to underground mine complex (maximum source capacitance of 6.6 μF per phase), carrying normal mine load and test set-up;
2. load center surge capacitors (0.25 μF per phase):
    a. normal wye grounded,
    b. wye ungrounded, or
    c. surge capacitors disconnected;
3. switchhouse to load center cable length:
    a. 60 ft or
    b. 1,000 ft; and

4. vacuum circuit breaker unit:

    a. copper-bismuth contacts,

    b. copper-chromium contacts.

The test site layout is presented in Figure 9. With each possible combination, ten trips and closures of the VCB's were made, and measurements taken at either the VCB's outgoing side or the high-side of the load center. The lightning arresters remained in the circuit and were verified as operational.

The results of these tests (line-to-neutral voltage, based on nominal) are summarized in Table 1, and it can be noted that some combinations of system arrangements are not shown. These resulted in recording no abnormal transients, as is also the case for some of the listed combinations. Comments about the implications of the data contained in Table 1 will be presented shortly.

Mine Three

Following the work at Mine Two, the second test site (again to observe staged transients on distribution systems) was located in West Virginia. Figure 10 is a one-line diagram of the test set-up which consisted of an 1,000 kVA 12.47 kV Δ/Y load center, 1,000 ft of number 2 SHD-GC feeder cable, and a switchhouse employing copper-chromium contact VCB's. The load center was located in a maintenance building. The power source was an overhead 12.47 kV power line from the mine's substation and was not modified during the tests.

The same three surge capacitor arrangements were used as previously described (i.e., grounded surge, ungrounded surge, and totally disconnected). However, two load center loading situations were used: either no loading or loading by a continuous miner and shuttle car causing 8 to 10 A of

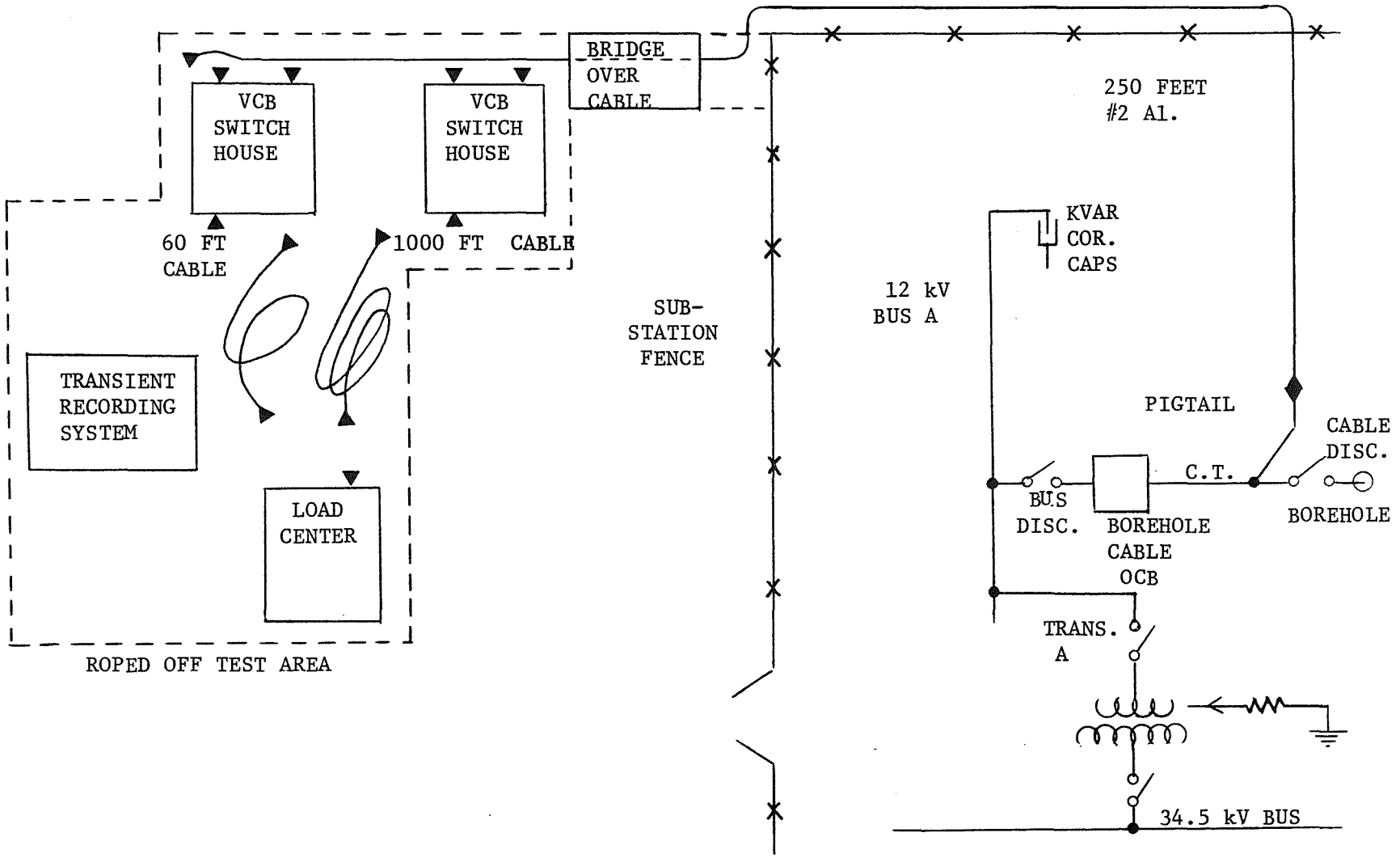


Figure 9. Layout of Test Site at Mine Two.

Table 1. Summary of Transient Data at Mine Two.

Test Series	Surge Capacitor Connection	Cable Length ft	Measure Point	Mine System	Prestrike (VCB Closure) Number >1.0 pu	Prestrike (VCB Closure) Max. Value	Chopping (VCB Tripped) Number >1.0 pu	Chopping (VCB Tripped) Max. Value
1	Disconnected	1000	VCB	Isolated	no abnormal values		no abnormal values	
2	Disconnected	1000	LC	Isolated	no abnormal values		no abnormal values	
3	Disconnected	60	LC	Isolated	1	2 pu	4	2 pu
4	Wye Grounded	60	LC	Connected	2	2.1 pu	no abnormal values	
5	Disconnected	60	LC	Connected	5	3 pu	5	4.5 pu
6(1)	Disconnected	60	LC	Connected	2	1.7 pu	10	5 pu
7	Wye Grounded	60	LC	Connected	10	4.7 pu	no abnormal values	
8(2)	Wye Grounded	60	LC	Connected	5	1.7 pu	no abnormal values	

(1) Series 6 was a repeat of 5 but used a different voltage divider.

(2) Series 8 was a repeat of 7 but used an engine driven generator for instrumentation power.

high-side current. Again, measurements were made at the switchhouse on one end of the 1,000 ft cable and at the load center on the other end. New voltage dividers were used to obtain (see Figure 4, Chapter III) the transient voltage data and were built shortly before this test. Twenty openings and closings of the switchhouse VCB were made to get a reasonable sample of resulting transients for each position and loading situation. Table 2 summarizes the results obtained; the values given are again line-to-neutral referenced to nominal.

The data contained in Tables 1 and 2 provide some interesting information. For the first controlled site (Mine Two), there was no significant difference between the two VCB types (copper-bismuth and copper-chromium). For both test sites the only abnormal transients existed in basically two combinations:

1. when surge capacitors were removed from the load center, thus allowing chopped currents to trap energy;
2. when the surge capacitors were installed, and the source feeding the switchhouse had significant capacitance.

All the configurations that had no abnormal events substantiated the findings of Mine One. Although the peak transient voltages were not as great, the prestrike activity also matched that found in the in-mine test.

These measurements throw suspicion on the use of surge capacitors on mine power distribution systems. Their effect of chopping-created transients is obvious but, when removed, the peak voltage levels are not extremely high. However, surge capacitors appear to create substantial prestrike transient voltages.

Table 2. Summary of Transient Results from Mine Three.

Test	Surge Capacitor Connection	System Loading	Prestrike Number >1.0 pu	Prestrike Max. Value	Chopping Number >1.0 pu	Chopping Max. Value
1	Wye Grounded	Unloaded	no abnormal		17	9.1 pu*
2	Wye Grounded	Unloaded	no abnormal		16	7.5 pu
3	Disconnected	Unloaded	3	3.7 pu	no abnormal	
4	Disconnected	Loaded	no abnormal		no abnormal	

* 9.1 pu occurred twice, next highest peaks (on other events) were 3.8 pu.

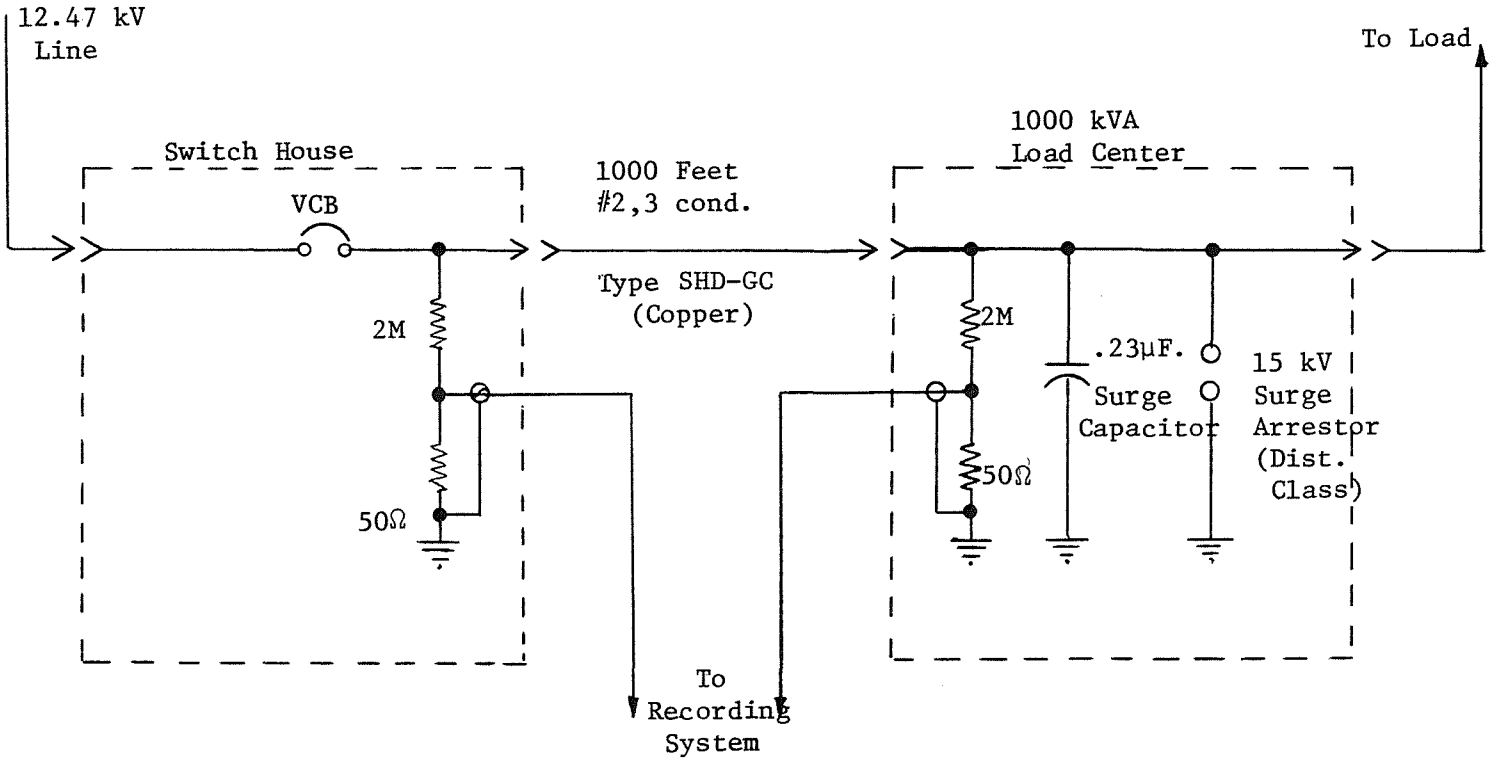


Figure 10. One Line Diagram of Second Test Site.

In the interest of obtaining simultaneous data at each end of the power transmission cable for compairson purposes an attempt was made to take advantage of the dual channel capability of the Biomation transient recorder. One voltage divider as shown in Figure 16 was placed at the switchhouse (load side of VCB) with another on the high-voltage side of the load center. The same phase line was used at each location. The transient signal was taken from the voltage divider by 50 Ω coax cable to the transient recorder, and the cable was terminated with 50 Ω loads at each end. The results of making such recordings were interesting and predictable. Common-mode voltage developed in the signal circuits, as a result of this multiple-ground loops, created the trace shown in Figure 11a. This trace came from the switchhouse end. Figure 11b shows the signal obtained at the load center end for the same transient. Disconnecting the load center voltage divider resulted in obtaining a normal transient as shown in Figure 11c. These measurements and figures clarify the importance of isolated equipment power sources and elimination of multiple-ground loops, as discussed in Chapter III.

Mine Four

In the Spring of 1976, Midwestern strip mine operators approached MESA about ground-check monitor failures which were thought to occur during electrical storms. The U.S. Bureau of Mines, as well as other groups, aided in searching for a solution to this problem. At the Technical Project Officer's request, Penn State's input was the development of an inexpensive peak detector and initial data procurement. The data collected on the peak detectors (placed by Penn State personnel) suggests some severe switching transients.

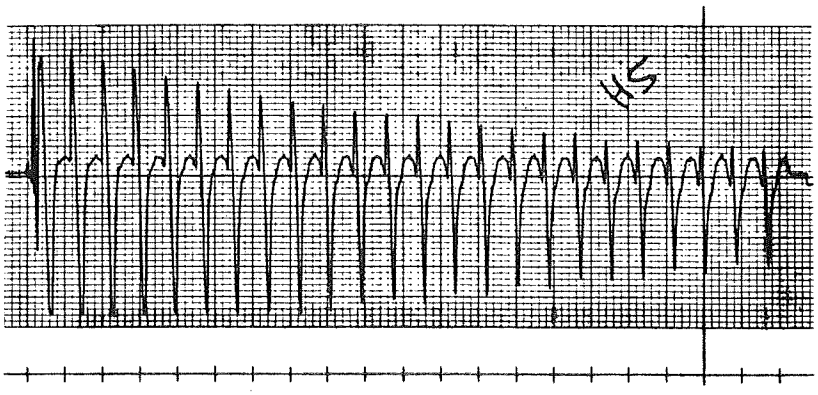


Figure 11a. Switchhouse Multiple Ground Path Transient

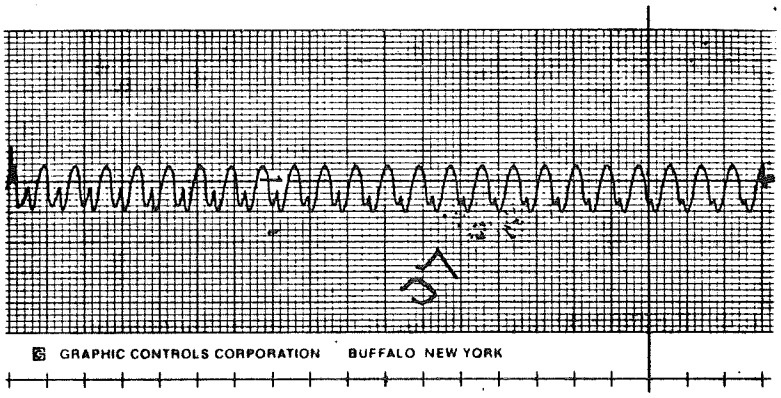


Figure 11b. Load Center Multiple Ground Path Transient

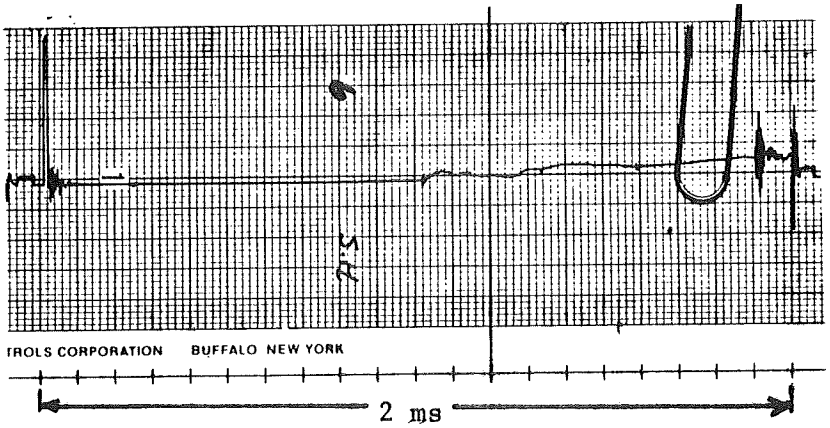


Figure 11c. Switchhouse "Normal" Transient

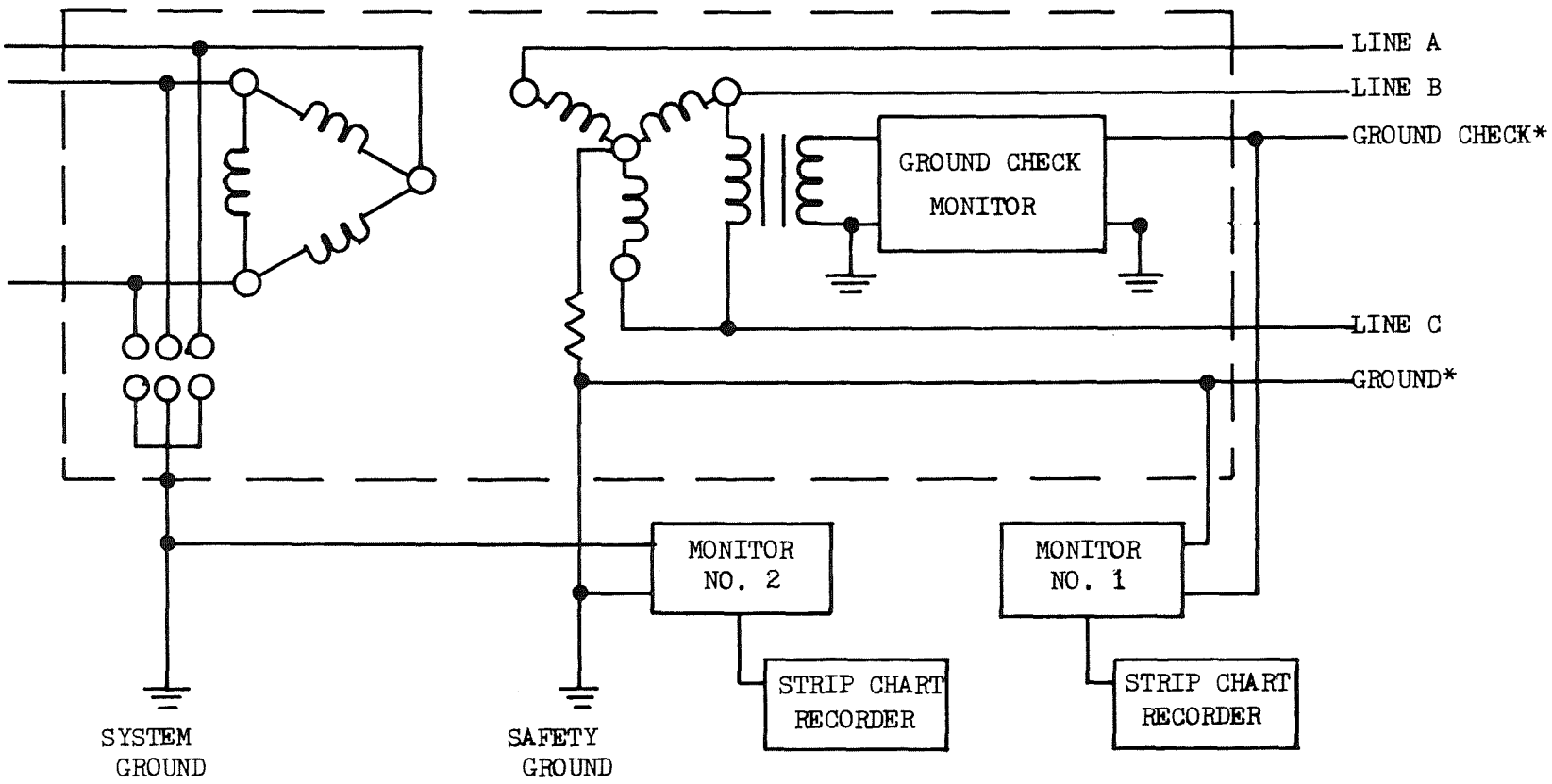
The instrumentation was installed at a pit substation. As shown in Figure 12, unit Number 1 was connected between the ground-check wire (high-side of the voltage divider) and the safety-ground wire (low-side of the voltage divider). Unit Number 2 was connected between the system ground (divider high-side) and the safety ground (divider low-side). This location was monitored for approximately four weeks, and Table 3 summarizes the transient activity for the first week.

As mentioned earlier, analysis of this data is beyond the scope of this research. There are a few observations which are warranted. Because of the detector circuitry and the method in which they are used, it is fairly safe to label the transients of June 22 and 28 as switching transients. The anomalies recorded on June 29 were probably due to lightning-induced voltages. In any case, these should serve as a further example of the high-voltage levels which can occur on a mine power system.

Mine Five

Mine Five was employed for the first project measurements of d-c trolley-line transients. The mine used drift-entry haulage so recordings were made both on the surface near the mine's preparation plant and underground. The transients produced were recorded using the transient recording system.

Figure 13 represents the layout of the surface test site. Data were collected on both sides of the circuit breaker and at the end of the trolley line about 2000 ft from the rectifier station. Attempts were made to record transients during manual opening and closing plus forced overcurrent interruptions of the circuit breaker. For the overcurrent trials, a 27-ton locomotive was positioned at the trolley line end, the brakes were set and the controller was then advanced until circuit breaker interruption occurred.



* Ground and Ground Check wires were joined on dragline frame.

Figure 12. Connection Diagram of the Peak Detectors at the Pit Substation

Table 3. Summary of First Week of Monitoring at Mine Four.

Monitor #1			Monitor #2		
Date	Time	Reading	Date	Time	Reading
June 22	20:13	9.5 kV	June 22	20:13	9.5 kV
June 28	7:38	2.5 kV	June 28	7:38	2.5 kV
June 29	20:45	7.0 kV	June 29	20:45	5.5 kV
June 29	20:55	3.0 kV	June 29	20:55	0.5 kV
June 29	20:58	2.0 kV	June 29	20:58	0.5 kV
June 29	21:01	5.0 kV	June 29	21:01	3.0 kV

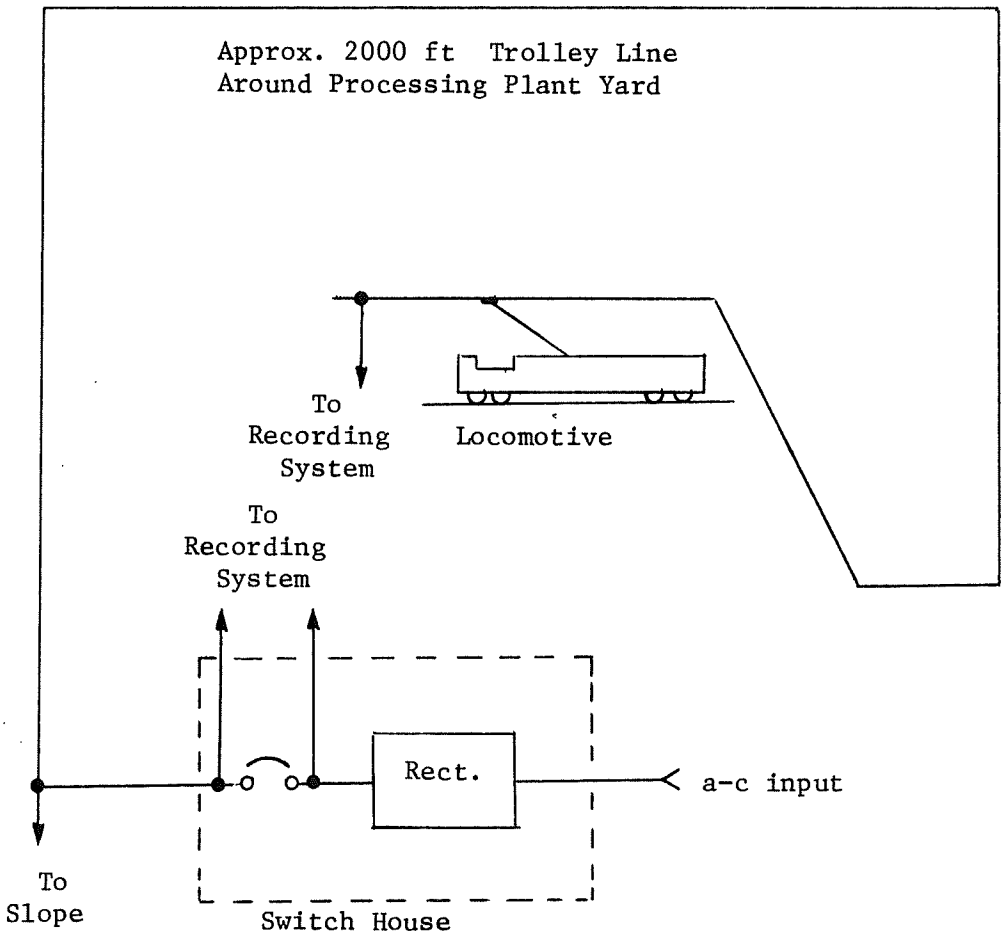


Figure 13. D-C Trolley Transient Test Site.

Of the approximately 23 traces recorded, only seven contained noise or transient spikes which exceeded the nominal line voltage by more than 20% (1.2 pu). The maximum spike was 1.47 pu and was recorded at the end of the trolley line (2000 ft from the circuit breaker) when the circuit breaker was closing.

The transient recording system was then placed underground near a marshalling station from which loaded mine cars started for the surface. This location was about 1000 ft from one rectifier and 4000 ft from another (i.e., inside a block). The objective was to record variations in trolley-line voltage as well as any transients created by a 27-ton locomotive as it started pulling a train of loaded cars. A recording was made while the locomotive was pushing nine loaded cars uphill in a direction away from the slope. There was only one small transient of about 1.14 pu when the locomotive was turned off. The duration of the recording was about 10 seconds, and the trace showed a considerable drop in line voltage to about 0.6 pu at the start of the push. System voltage fluctuated slightly and gradually increased as the inertia of the load was overcome so that, at the end of 10 seconds, it was up to 0.8 pu.

There was a mild decline in track elevation in the direction of the surface. Consequently, when the loaded train left, the pull was much smoother than the effort described above and this could be seen by the variations in the system voltage. There were no abnormal transients and only very smooth decreases in the voltage level as the motorman advanced the controller.

The results of this field trip substantially confused project personnel. By theory, the actions taken should have produced abnormal transients, yet none were recorded. By laboratory measurements, the

transient recording system operation was verified as correct just before the field exercise. Suspecting instrumentation failure (because of the field trip results), subsequent inspection of the transient recorder was made but, again, the unit was found operational.

Mine Six

The purpose of this last field effort was again to monitor d-c trolley-line transients. As the transient recording system was under suspect, a peak-detector circuit and a strip-chart recorder were employed as instrumentation back-up. As was discussed in Chapter III, the original application for this circuit was for lightning transients. The only modification necessary for trolley-system measurements was to reduce the voltage divider ratio to 1000:1. The simple change thus only involved selecting resistors to provide the correct input voltage to the first amplifier of the detector (see Appendix for construction details).

The test site was on a 2000 ft length of trolley wire connected between two 500 kW rectifiers (defining the haulage block). Both instruments were connected between the 300 V trolley line (divider high-side) and the track (divider low-side). A 60-ton locomotive was located at the center of the rectifier block, the brakes were locked, and full-load current was drawn. At full-load current (approximately 2000 A), the locomotive contactors were dropped. This procedure was repeated several times within the span of two hours.

As with the results of Mine Five, no abnormal transients were captured with the transient recording system. However, the situation was entirely different with the inexpensive peak-detector, and a copy of the strip-chart recording has been provided in Figure 14. The several large peaks, ranging from 2100 to 4300 V (7 to 14.3 pu nominal voltage), occurred

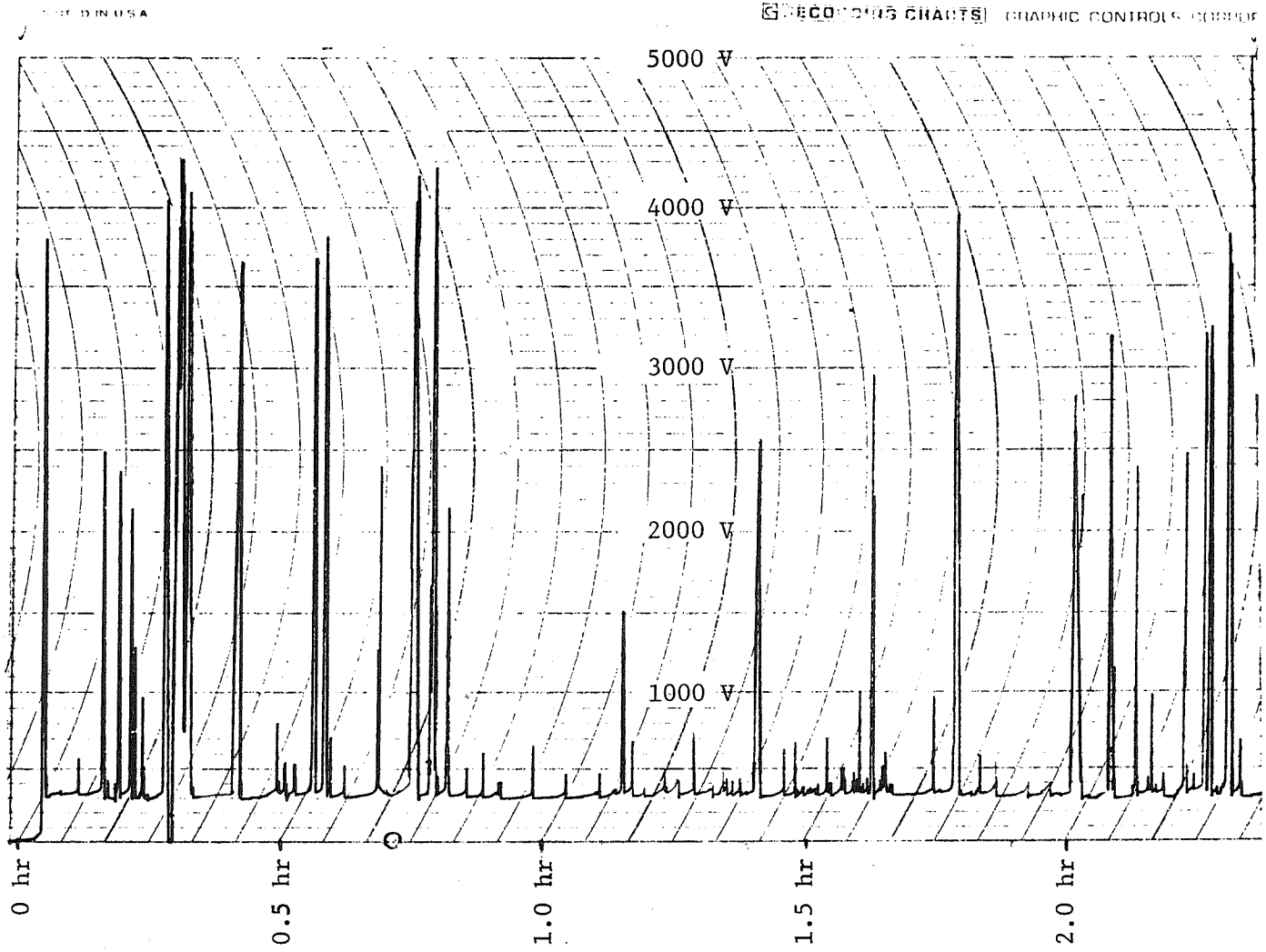


Figure 14. D-C Transients at Mine Six.

during the locomotive contactor dropping. The small spikes were caused by jeeps running on the adjacent rectifier block. It should be noted that the width of each peak in Figure 14 is a function of the peak magnitude and, therefore, must not be confused with the actual transient duration (which is unknown). Furthermore, the tracing is rectilinear, and the curves on the strip-chart paper should be ignored.

These results demonstrate the probability of enormous transient voltages existing on d-c trolley systems. The specific source here is obviously related to the trapped energy. Upon current termination (dropping the contactors), there exists a high rate of current change, developing a voltage across the system impedance by L di/dt (as was discussed in Chapter II). Perhaps this is one reason for component failures on d-c trolley systems, for example, illumination equipment inverter failures.

The problems, again encountered with the transient recording system, are traced to the Biomation instrument. After extensive laboratory investigations, it has been found that the unit's trigger circuits are temperature sensitive. Instrument operation in certain temperature ranges causes the trigger circuits to fail.

Summary

The information presented in the foregoing paragraphs has extended project knowledge about mine power system transients extensively. This is especially true about high-voltage distribution systems. The ramifications of this data will be discussed in the following chapter.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

The research performed during this grant period under G0155003 has led to some specific suggestions to minimize electrical transients. From the information presented earlier in this report, it should be obvious that minimization of transients will increase electrical safety and electrical component availability. Based on the research, the following observations are presented.

First, short cables should not be used between VCB switchhouses and transformers. Realizing that the capacitance of 1/0 to 4/0 SHD cables is approximately 0.1 μF/1000 ft, the minimum length should be around 500 ft. This can decrease possible peak transient voltages from chopping by around 60 percent for most mining applications (as compared with very short cable lengths). Additionally, it seems unwise to specify VCB's in the same enclosure as a power transformer without stringent precautions.

It appears now that extensive surge capacitor use, which adds significant capacitance to that inherent in mine power distribution, can cause excessive capacitive ground current during faulting and severe prestrike transients from VCB operation. They do, however, readily correct transient problems from VCB chopping. Therefore, these devices cannot be unilaterally removed without constraint. The worries are two-fold: surge arresters and basic insulation impulse levels (BIL).

Present standard transformer BIL's are 25 kV for 5000V insulation class distribution, 35 kV for 8000 V, and 50 kV for 15 kV. From theoretical and observed levels, these appear too low for mine power systems. In mines employing VCB's, it is suggested that any new transformers

purchased have 95 kV BIL. This is true for any of the common high-voltage distribution systems and appears a minimum protection level for units switched less than once per week.

Excessive overvoltage problems can be readily fixed with the proper application of distribution class surge arresters. Yet, it is mandatory that these be sized to the system's distribution voltage; the references cited in Chapter II provide the necessary sizing information. However, surge arresters alone cannot provide adequate transient protection.

Often, typical mine operations interrupt unloaded transformers from vacuum switchhouses no less than twice a week and up to once per day. Obviously, all totally unnecessary switching should be eliminated but, for this many operations, power engineers suggest that surge capacitors should be employed (27).

Considering the results presented in Chapter IV, extensive use of surge capacitors on underground coal mine power systems create an avenue for prestrike transients. Further, prestrike transients appear to be much more serious than chopping events (under normal system arrangements) and are dependent upon capacitive inrush current during contact closure. The magnitude of inrush current is controlled by the amount of capacitance inby the VCB. Therefore, the general use of surge capacitors could result in more severe transients than those they are installed to correct.

With 95 kV transformer BIL and distribution class surge arresters across each high-voltage load, there appears to be no reason why surge capacitors cannot be removed. The result should be adequate protection with a mine power system improvement both in transients and capacitive

charging currents. However, with lower insulation (BIL) levels, such removal cannot be recommended unless minimum cable lengths are maintained.

Because too many surge capacitors can be harmful, the number of these devices, when required, should not exceed more than one per vacuum switchhouse. As the best location to suppress switching transients is at the source, the capacitors should be installed in the switchhouse immediately inby the vacuum bottles. This recommendation is in opposition to other industry applications, where the best placement is at the load.

Since overvoltages are dependent upon vacuum breaker contact material, improved contacts would reduce switching transients. In this area, some VCB manufacturers are now using a copper-chromium alloy contact material instead of the common copper-bismuth. Measurements in this research so far are inconclusive, but the new contacts reportedly produce one-third less transient overvoltages from chopping or prestrike. This is an aspect of vacuum circuit breaker design that is sure to gain more attention in the near future and, as such, it would behoove the mine power engineer to make specific inquiries before purchasing new switchgear.

In-mine measurements of transients would be a worthwhile endeavor at any mine. The peak-detector described herein can be easily constructed to provide at least 10% precision. This would be adequate for locating transient sources and correcting them.

Recommendations for Future Research

It would be helpful to determine the transient energy level in every section of a mine. Such a complete data collection program would

be too time consuming utilizing the transient recording system. Furthermore, being a complex instrument intended for laboratory use, it is plagued with operation malfunctions when exposed to the underground coal mine environment. However, the peak-detector has the potential to achieve this program. Because it is portable and inexpensive, several units could be placed throughout the mine. The detector should be modified to give such features as the time of event, transient rise-time and duration, in addition to the peak amplitude.

A portable peak detector could also be used to gather transient data at machine terminals, something which is difficult to accomplish with the transient recording system.

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APPENDIX

PEAK-DETECTOR CONSTRUCTION

The construction of the peak-detector circuit, shown in Figure 5, is very straightforward. Table 4 is a complete parts list and bill of materials. To assist assembly, most small components are mounted on a printed-circuit. Figure 15 is a full-size positive of four printed boards (after etching, the board is cut to produce four separate circuits). Figure 16 provides the parts layout, where all components are mounted conventionally except for the feedback resistor R6. R6 is placed on the foil side of the board as shown (soldered to the leads extending through the board from C1 and R4). Figure 17 illustrates the external board connections and, finally, Figure 18 shows the hardware and component mounting on the plastic utility box, employed to house the peak-detector.

Table 4. Parts List for Peak-detector.

PARTS LIST

C1 - 0.22 μF, 50 V mylar capacitor

D1, D2 - 500 mA, 1000 PIV rectifier

IC1 - 747 dual operational amplifier

R1 - 5-100 kΩ, 2W, 5% resistors in series*

R2 - 51 Ω, 1/2W, 5% resistor

R3, R6 - 100 kΩ, 1/2W, 5% resistor

R4 - 51 kΩ, 1/2W, 5% resistor

R5 - 1 kΩ, 1/2W, 5% resistor

BILL OF MATERIALS

2 - 9 V batteries, Mallory MN1604 or equiv.

2 - 9 V battery clips with leads

1 - Plastic "D" size cell holder with terminals removed (holds 9 V batteries).

1 - DPST Slide switch

1 - 14-pin IC socket, solder pin

1 - Plastic utility box, 6-1/4 x 3-3/4 x 2 inches (Radio Shack No. 270-627).

2 - Cone-type ceramic stand-off insulators, 1-1/2 in. high x 1 in. base, with hardware

4-1/2 in. - Tygon plastic tubing, 3/8" I.D. (to hold R1)

1 - 2 terminal barrier strip, Jones type 140

1 - 5-way binding post (for external ground connection)

1 - Printed-circuit board (as per Figure 15)

4 - 3/4 in. spacers (for mounting printed-circuit)

Misc - screws, lockwashers, and nuts

*NOTE: R1, R2 voltage divider defines ratio for application.

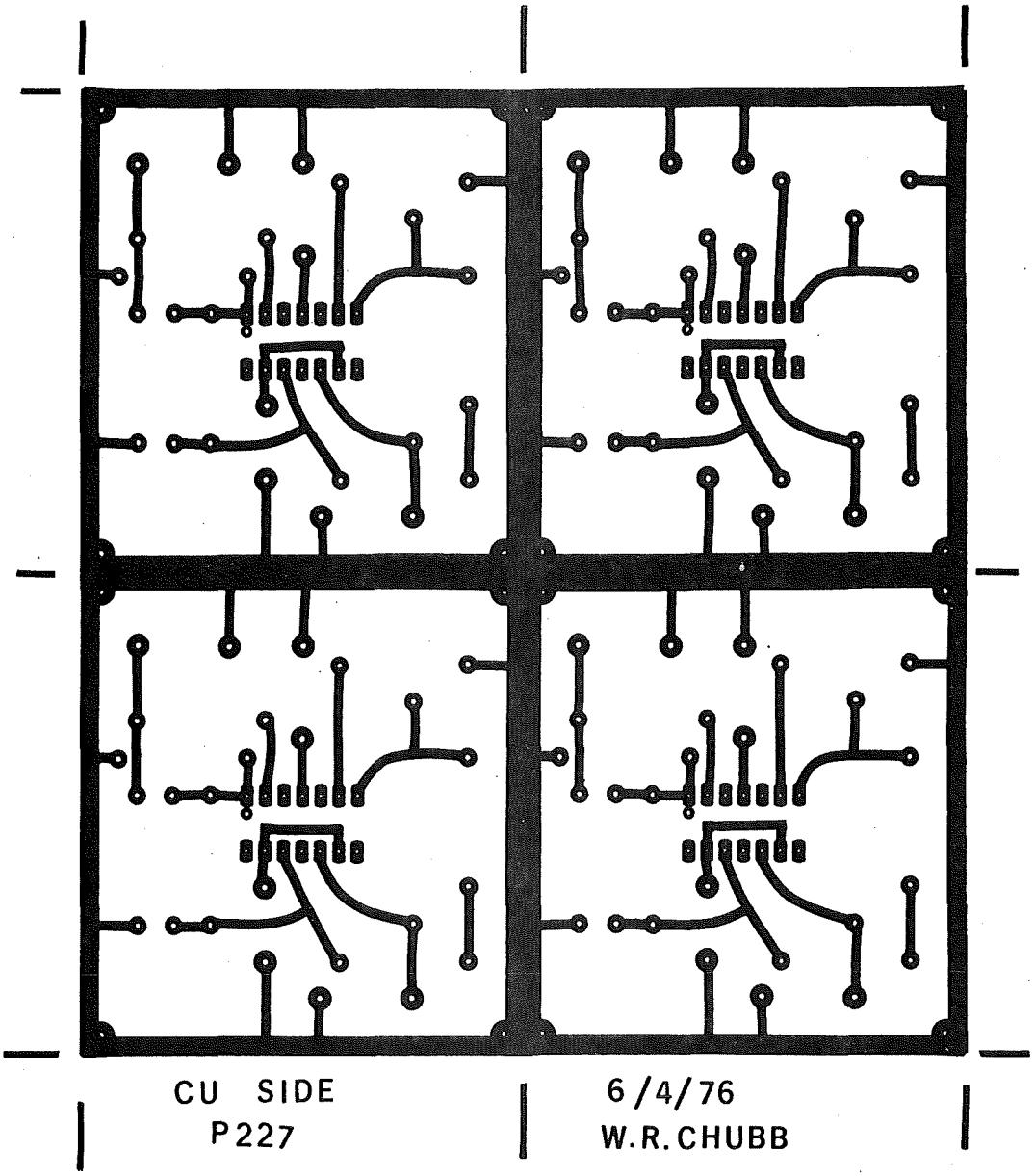
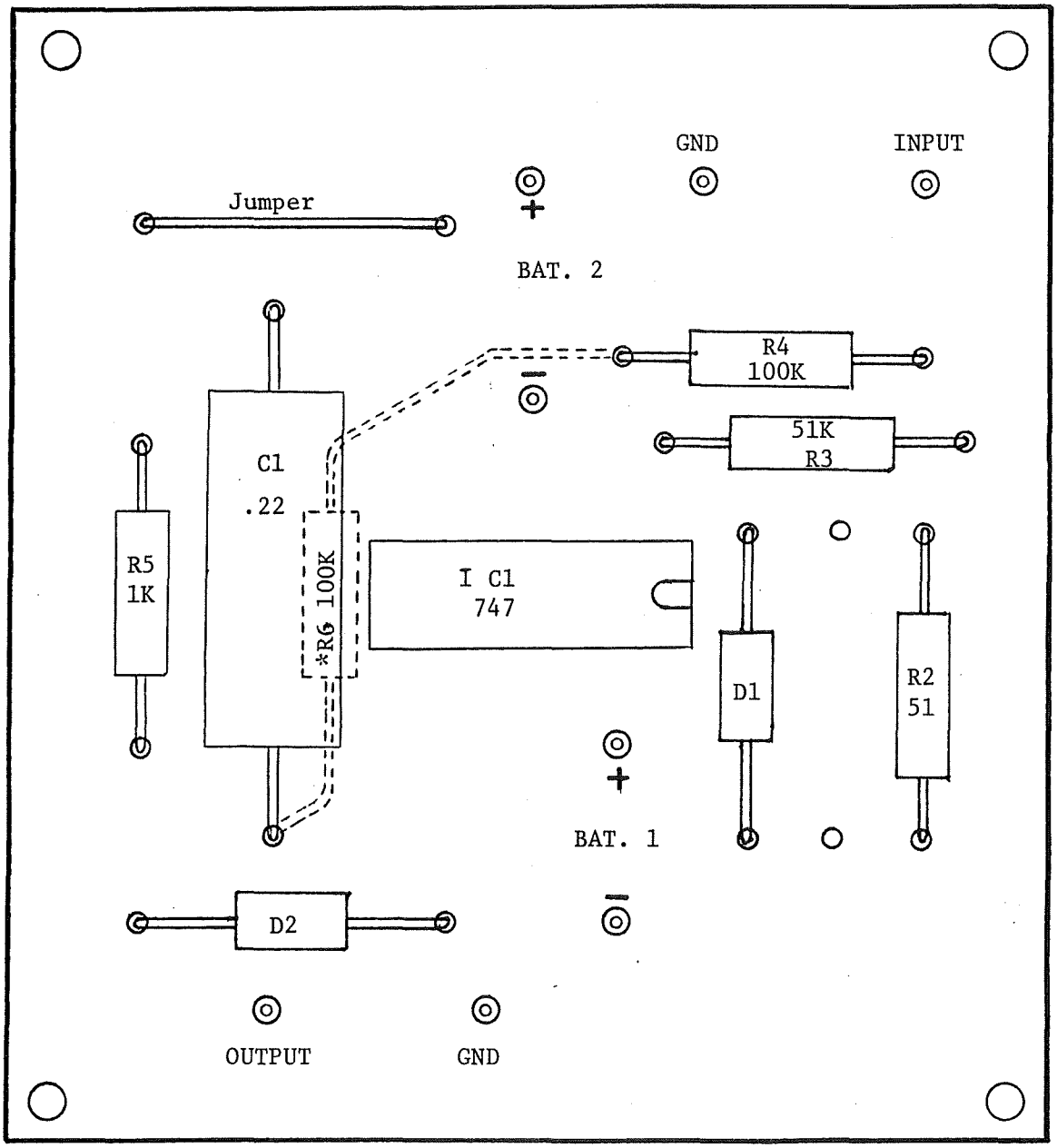


Figure 15. Positive for Four PC Boards.



* See note in text concerning mounting R6.

Figure 16. Printed-circuit Board Parts Layout.

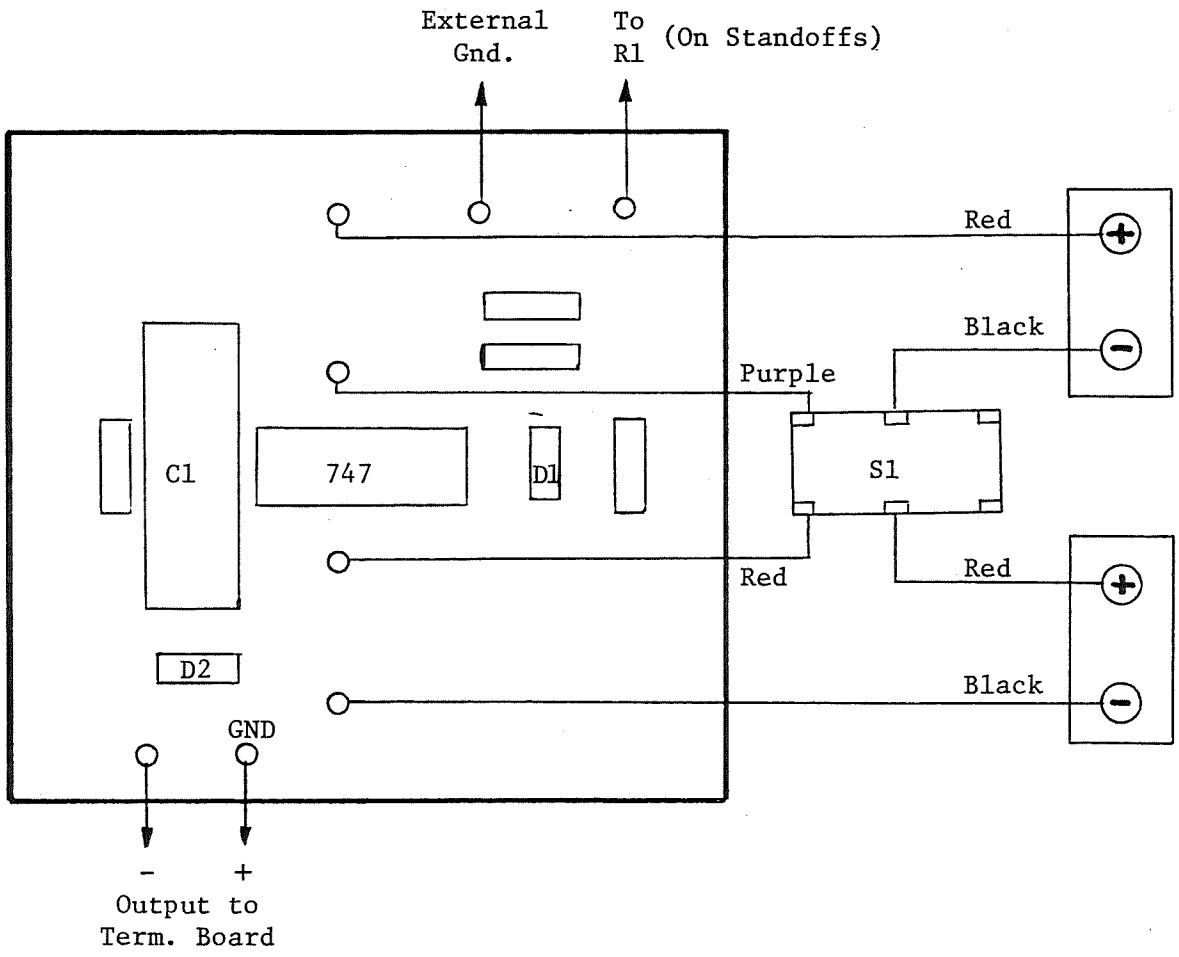


Figure 17. Printed-circuit Board External Connections.

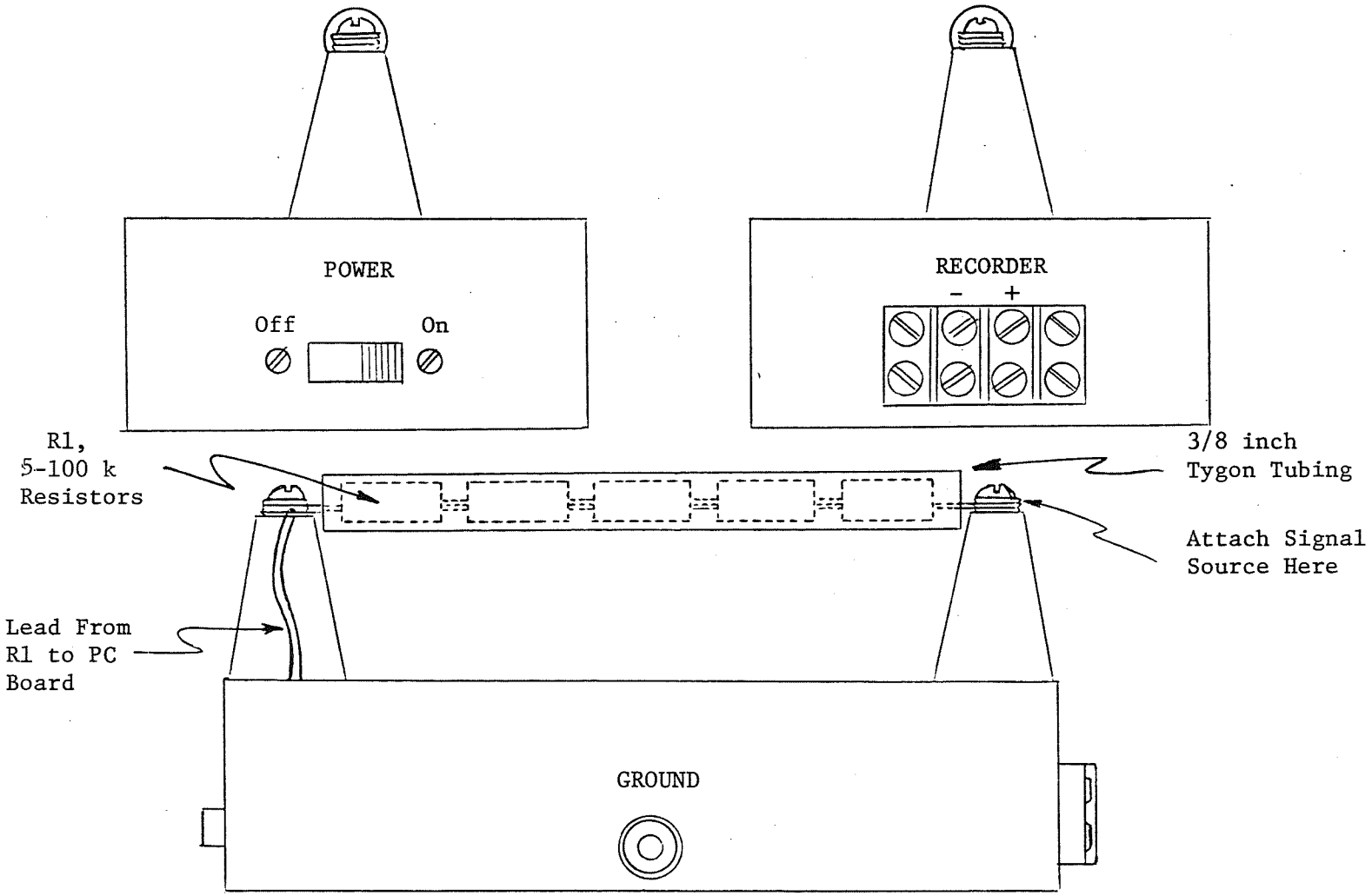


Figure 18. External Views of Peak-detector.