A mining research contract report
DECEMBER 1982

ELECTRICAL-SHOCK PREVENTION

VOLUME I – PROTECTION OF MAINTENANCE PERSONNEL

Contract J0113009
The Pennsylvania State University

OFR
83-177 (1)

BUREAU OF MINES
UNITED STATES DEPARTMENT OF THE INTERIOR



DISCLAIMER NOTICE

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

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO.	2.	3. Recipient's Accession No.

4. Title and Subtitle
Electrical-Shock Prevention
Volume I - Protection of Maintenance Personnel

5. Report Date
December 8, 1982

6.

7. Author(s)
L. A. Morley, T. Novak, and F. C. Trutt

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
Department of Mineral Engineering and
Electrical Engineering
The Pennsylvania State University
University Park, PA 16802

10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.
(C) J0113009
(G)

12. Sponsoring Organization Name and Address
U.S. Department of Interior
Bureau of Mines
2401 E. Street, N.W., Washington, DC 20241

13. Type of Report & Period Covered
Final, April 1981
through Dec. 1982

14.

15. Supplementary Notes
Volume I of the four-volume final report for Bureau of Mines Contract J0113009, "Recommended Practices for Electrical-Shock Prevention."

16. Abstract (Limit: 200 words)
The overall objective of the subject contract was to investigate the application, economic, and safety considerations of electrical-shock prevention techniques applied to surface and underground mines. Volume I of the four-volume final report starts by summarizing all research performed, and synopses of the three other report volumes are included. The balance of this volume concerns one major task of the contract, the protection of maintenance personnel. After specifying the scope of work for the task, electrical shock is defined, and needed ground-fault relay characteristics to prevent ventricular fibrillation are established. This is followed by an analysis of alternating-current systems, a comparison of these systems with respect to body currents, and the advantages and disadvantages of the various ground-fault protection techniques. An analysis of direct-current systems for off-track vehicles is then covered. These analyses form the basis for the research recommendations which, along with suggestions for future research, conclude the report volume.

17. Document Analysis a. Descriptors
Circuit Protection, Electric Relays, Electric Shock, Grounding, Mine Safety, Power Lines.

b. Identifiers/Open-Ended Terms
Dead-Front Panels, Electrical Accidents, Electrical Guarding, Electrical Hazards, Ground-Fault Interrupters, Ground-Fault Relays, Lock Outs, Ventricular Fibrillation.

c. COSATI Field/Group Field 9, Group C, Electronic and Electrical Engineering

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
Release Unlimited	Unclassified	124
	20. Security Class (This Page) Unclassified	22. Price

(See ANSI-Z39.18)

FOREWORD

This report was prepared by The Pennsylvania State University, Departments of Mineral Engineering and Electrical Engineering, University Park, Pennsylvania, under Bureau of Mines Contract Number J0113009 administered under the technical direction of the Pittsburgh Research Center with Mr. D. Ambrose and Mr. M. Yenchek acting as technical project officers. Mr. Frank Naughton was the contracting officer for the Bureau of Mines. This report is a summary of the work recently completed as part of this contract during the period April 1, 1981 through December 8, 1982. This report was submitted by the authors in December 1982. This technical report has been reviewed and approved.

No inventions have been developed from Contract J0113009, and no patents are pending.

Project personnel are grateful to outside individuals and companies who provided valuable inputs through discussion.

This report contains test data obtained in the course of this investigation and is provided for the purpose of disseminating information that might help improve mine-power-system performance. No product endorsements or disapprovals are intended.

TABLE OF CONTENTS

		Page
List of Tables		6
List of Figures		7
Chapter		
I	EXECUTIVE SUMMARY	11
	General	11
	Background	11
	Accidents	12
	Initial Prevention Recommendations	14
	Phase II	16
	Summaries of Other Report Volumes	17
	Ground-Fault Interrupting Devices	17
	Indication versus Interruption	19
	Overhead-Line Contact Fatalities	20
II	PROTECTION OF MAINTENANCE PERSONNEL	23
	General	23
	Statement of the Problem	24
	Scope of Work	24
	Report Format	24
III	ELECTRICAL SHOCK	25
	Ventricular Fibrillation	25
	Dalziel's Prediction	25
	Body Resistance	28
	Osypka's and Biegelmier's Predictions	30
	Jacimovic's Prediction	30
	Relay Characteristics	32
IV	ALTERNATING-CURRENT GROUNDING SYSTEMS	34
	General	34
	Grounding-System Types	34
	Ungrounded Systems	34
	Solidly-Grounded Systems	35
	Low-Resistance-Grounded Systems	35
	High-Resistance-Grounded Systems	35
	Body-Current Analysis	36
	Approach	36
	Implementation	41
	Results	41
	Ground-Fault Protection	54
	Direct Relaying	54
	Potential Relaying	56
	Zero-Sequence Relaying	56
	Residual Relaying	56
	Summary	58

TABLE OF CONTENTS (Continued)

Chapter		Page
V	DIRECT-CURRENT SYSTEMS FOR OFF-TRACK VEHICLES	59
	General	59
	Typical Direct-Current Systems	59
	Diode-Grounded System	59
	Grounding Conductor	62
	Neutral-Shift System	62
	Differential Current	62
	Body-Current Analysis	66
	No Ground-Fault Current Limit	66
	Ground-Fault Current Limit	67
	Summary	70
VI	RECOMMENDATIONS FOR IMPROVED ELECTRICAL SAFETY	73
	General	73
	Physical Design Modification	73
	Dead-Front Trouble-Shooting Panels	73
	Dead-Front Circuit-Breaker and Fuse Mounting	76
	Interlock Disable Precautions	77
	Isolated Test Points Without Physical Barriers	77
	Protective Guards for Exposed Conductors	80
	Shielding of Control Transformers	83
	Lock-Out Features	83
	Cable Design	85
	Color-Coded Cables	85
	Shielded Trailing Cables	87
	Protective Gloves	87
	Component Arrangement	87
	Alternating Current	90
	Connection of Ground-Fault Relays	90
	Test Circuits	90
	Visual Indication of Ground Faults	90
	Tripping Targets	93
	Neutral-Grounding-Resistor Monitoring	93
	Direct-Current Ground-Fault Protection	93
	Ground-Check Monitors	94
	Test Circuits for Diode-Grounded Systems	94
	Application of the U.S. Bureau of Mines' GFI	96
	Example of a Power Center with Incorporated Safety Features	98
	Summary	105
	Ground-Fault-Relay Characteristics to Prevent Ventricular Fibrillation	105
	Alternative-Current Protection Relaying	105
	Direct-Current Protective Relaying	106
	Physical Design Modifications	106
	Lock-Out Features	107
	Cables	107
	Protective Apparel	107
	Component Arrangement	107
	Substation Considerations	107

TABLE OF CONTENTS (Continued)

	Page
Chapter	
VII CONCLUSIONS	109
Future Research and Development	109
REFERENCES	111
APPENDIX I - SHOCK-PREVENTION BIOGRAPHY	112
APPENDIX II - COST ESTIMATES FOR MAINTENANCE - PERSONNEL PROTECTION RECOMMENDATIONS	120

LIST OF TABLES

Table		Page
1	Electrical hazards resulting in fatalities in the mining industry	13
2	Job types and activities most frequently resulting in electrical accidents during 1977 through 1980	14
3	Initial listing of possible preventions against electrical shock	15
4	Ranges of physiological response for alternating current	33
5	Ventricular fibrillation from electrical shock	33
6	Estimated materials and labor for implementing recommendations for protection of maintenance personnel	121
7	Cost estimates for items in table 6 based on 1982 dollars	124

LIST OF FIGURES

Figure		Page
1	Dalziel's fibrillation curve	26
2	Shock hazard and equivalent circuits	29
3	Body resistance measured by Freiberger	29
4	Fibrillation curves	31
5	General power system representation	37
6	Positive-sequence network for the power system of Figure 5	38
7	Negative-sequence network for the power system of Figure 5	38
8	Zero-sequence network for the power system of Figure 5	38
9	Symmetrical component model for a single-line-to-reference fault on the power system of Figure 5	40
10	Line-to-line-to-reference fault	40
11	Symmetrical component model for a line-to-line-to-ground fault	42
12	Body current as a function of body resistance (0.1 to 100 k Ω), neutral-grounding resistance (0 to ∞ Ω), grounding-conductor resistance (1.6 Ω), and system voltage (480 V)	43
13	Body current as a function of body resistance (0.1 to 100 k Ω), neutral-grounding resistance (0 to ∞ Ω), grounding-conductor resistance (75 Ω), and system voltage (480 V)	44
14	Body current as a function of body resistance (0.1 to 100 k Ω), neutral-grounding resistance (0 to ∞ Ω), grounding conductor resistance (∞ Ω), and system voltage (480 V)	45
15	Body current as a function of body resistance (0.1 to 100 k Ω), neutral-grounding resistance (0 to ∞ Ω), grounding-conductor resistance (1.6 Ω), and system voltage (1040 V)	46

LIST OF FIGURES (Continued)

Figure		Page
16	Body current as a function of body resistance (0.1 to 100 k Ω), neutral-grounding resistance (0 to ∞ Ω), grounding-conductor resistance (1.6 Ω), and system voltage (1040 V)	47
17	Body current as a function of body resistance (0.1 to 100 k Ω), neutral-grounding resistance (0 to ∞ Ω), grounding-conductor resistance (75 Ω), and system voltage (1040 V)	48
18	Body current as a function of body resistance (0.1 to 100 k Ω), neutral-grounding resistance (0 to ∞ Ω), grounding-conductor resistance (1 Ω), and system voltage (13,800 V)	49
19	Body current as a function of body resistance (0.1 to 100 k Ω), neutral-grounding resistance (0 to ∞ Ω), grounding-conductor resistance (75 Ω), and system voltage (13,800 V)	50
20	Body current as a function of body resistance (0.1 to 100 k Ω), neutral-grounding resistance (0 to ∞ Ω), grounding-conductor resistance (∞ Ω), and system voltage (13,800 V)	51
21	Body current for a direct contact with one phase (600 V)	52
22	Body current for a direct contact with one phase (1040 V)	53
23	Neutral relaying applied to grounding-resistor current as back-up protection	55
24	Potential relaying	55
25	Zero-sequence relaying	57
26	Residual relaying	57
27	Diode-grounded system with possible faults indicated	60
28	Basic grounding-conductor system	63
29	Relayed grounding-conductor system	63
30	Neutral-shift system	64

LIST OF FIGURES (Continued)

Figure		Page
31	Current-balance direct-current ground-fault relaying using a saturable reactor	64
32	Current-balance direct-current ground-fault relaying using a saturable transformer	65
33	Equivalent circuit of a shock hazard for a basic-grounding-conductor or diode-grounded system	68
34	Body current as a function of body resistance of 300-V dc systems	68
35	Shock hazard and equivalent circuit for a differential-current system	69
36	Shock hazard and equivalent circuit for a neutral-shift system	71
37	Dead-front trouble-shooting panel	74
38	Dead-front panel in the open position	75
39	Mounting of circuit breakers	78
40	Fuse mountings	78
41	Explosion-proof enclosure with isolated test points	79
42	Shuttle-car schematic showing suggested test points for a dead-front panel	81
43	Guards on line starters	82
44	Shielded control transformers	82
45	Cable-mounted plug with hinged lockout	84
46	Cable-mounted plug with a pin drilled for lockout	84
47	Lock-out receptacle	86
48	Separate compartments of a power center	89
49	Zero-sequence relaying with jumper in relay case	91
50	Typical test circuit for zero-sequence relaying	92

LIST OF FIGURES (Continued)

Figure		Page
51	Ground-fault indicator	92
52	Diode-grounded system with ground-fault interrupter	95
53	Test circuit for reverse leakage current through the grounding diode	95
54	Circuit for testing the proper operation of the diode-grounded system	97
55	Circuit for testing the polarity diode	97
56	Discriminating ground-fault protection	99
57	Relay connection for Figure 56	99
58	Top view of a power center with incorporated safety features	100
59	Dead-front trouble-shooting panel	103
60	Portion of dead-front trouble-shooting panel	103
61	Modular construction for each outgoing machine circuit	104

CHAPTER I

EXECUTIVE SUMMARY

General

This chapter summarizes project work performed under U.S. Bureau of Mines Contract J0113009, "Recommended Practices for Electrical-Shock Prevention." The overall research objective was to investigate the application, safety, and economic consideration of techniques designed to protect against electrical shock, when applied to all surface and underground mines. The twenty-month contract was divided into two major phases. Phase-I effort was concerned with background information, and the purpose was to determine the most important factors with respect to electrical-shock hazards and the requirements for shock prevention. Phase I provided the foundation for Phase II, where selected concepts were evaluated thoroughly to uncover the effectiveness of each. The research goal was not only to find shock-prevention solutions that could be uncovered during the contract period of performance but also to recommend further research that would likely result in additional solutions.

The following paragraphs will first abstract the background material resulting from Phase I. Afterwards, the research objectives and tasks of Phase II are presented. The contract research has produced three other report volumes. Information about these documents concludes this Executive Summary. As can be seen in this final report, all goals of the contract have been attained.

Background

Three directions were used to assemble the necessary background material for the research: literature review, acquiring and analyzing data on mine electrical accidents, and personal interviews. The search involved not only mining but other industrial applications. The major goals of information gathering were to uncover unsafe practices, general hazards, and existing solutions in the mining industry, as well as any possibly adaptable schemes or countermeasures that were being used in other industries.

Extensive relevant information was gained by personal interviews with representatives of:

1. MSHA, Division of Coal Mine Safety, Arlington, VA;
2. MSHA, Division of Metal/Nonmetal Safety, Denver, CO;
3. MSHA, Technical Support, Pittsburgh, PA, and Denver, CO; and
4. West Virginia University, Department of Electrical Engineering (in reference to their Bureau of Mines Contracts J0308025, "Develop Grounding Practices in Metal/Nonmetal Mines," and J0100096, "Analysis of Coal Mine Electrical Accidents").

These contacts resulted in detailed descriptions of 78 underground-coal, 58 surface-coal, and 94 metal/nonmetal electrocutions, which occurred primarily between 1970 and 1980. The conversations with MSHA personnel also yielded extensive thoughts on hazards and preventive measures. West Virginia University research had already analyzed metal/nonmetal accidents, including

numerous non-fatals, and these results were made available. In addition to these sources, the 1,622 mine-electrical accident reports for the years 1978 through 1980 were obtained from MSHA, Health and Safety Analysis Center, Denver, CO.

The following companies and organizations also supplied information about the primary areas of concern; those noted with an asterisk involved personal interviews:

1. American Electric Power Service Corporation,
2. Brown Boveri Electric*;
3. Climax Molybdenum Company*;
4. Consolidation Coal Company*;
5. Dravo Corporation;
6. Ensign Division of Hubbell*;
7. Exxon Corporation*;
8. FMC Corporation;
9. General Electric Company;
10. Homestake Mining Company*;
11. IEEE Mining Industry Committee*;
12. Line Power Manufacturing Corporation*;
13. Michigan Technological University*;
14. Morrison-Knudsen Company*;
15. Open-Pit Mining Association;
16. Pemco Corporation*;
17. Redtrol, Incorporated*;
18. Shell Oil Corporation (Turris Coal);
19. Square-O Company*;
20. Systems Control*;
21. T. A. Gross and Associates*;
22. Utah International*;
23. Westinghouse Electric Company; and
24. White Pine Copper Company*.

Accidents. Perhaps the best practical approach to pin-point electrical-shock hazards is to look at causes of electrocutions. Table 1 is a summation of those from 1970 to present, as extracted from the information-gathering effort. Some specifics about the fatalities are very enlightening.

1. The handling-cable accidents (items 1, 6, and 7) involved mainly insulation damage and bad splices. The majority resulted from routine handling of unshielded cables. The asterisks on the metal/nonmetal fatalities denote a lack of information, but it seems that the causes would be similar. It is interesting that surface coal mining has had no fatalities here.

2. Most of the direct-contract incidents (items 4 and 5) involved trouble shooting, testing, and repairing. Some typical activities or negligences were:
    a. fuse changing,
    b. improper lock-out procedures,
    c. improper guarding,
    d. not using protective gear, and
    e. too high of control voltage (e.g., 480 V).

Table 1. Electrical hazards resulting in fatalities in the mining industry

	Hazard	Underground Coal	Surface Coal	Metal/ Nonmetal
1.	Handling Low-Voltage (unshielded) Cables	12	0	7*
2.	Improper Lock-Out for Splicing Low-Voltage Cables	9	0	2
3.	Contact with Trolley Conductor	8	-	2
4.	Direct Contact with Live Parts in Equipment, Low Voltage	18	3	16
5.	Direct Contact with Live Parts in Equipment, High Voltage	8	21	11
6.	Unshielded High-Voltage Splices	3	0	*
7.	Handling High-Voltage Cable	0	0	2
8.	Energized Frames on Grounding Conductor	20	15	25
9.	Indirect Contact with Overhead Lines	--	19	29
10.	Total Fatalities	78	58	94

* Lack of specific information on the cable accidents involved.

3. Energized-frame hazards were the number-one killer in the electrical area of mining, and the primary cause was open grounding conductors in conjunction with simultaneous line-to-ground faults. The majority of accidents occurred on three-phase and direct-current equipment, but seven fatalities were on single-phase 120-V systems. No fatalities occurred with fixed equipment or cat-mounted machines, and the main problem appeared with rubber-tired vehicles. Required ground-check monitoring was bridged out in some cases. A few fatals were connected to double line-to-ground faults on ungrounded delta systems.

4. Indirect contact with overhead lines was the number-one leader of electrocutions in surface mines. Most instances resulted from contact with equipment, such as truck beds, drills, and cranes. The majority of individuals involved knew they were near power lines.

To reinforce the hazards listed in Table 1 and discussed above, West Virginia University investigated numerous fatal and non-fatal accidents in metal/nonmetal mining, and their findings were basically the same. In the initial stages of Phase I in this contract, project personnel analyzed 1,622 electrical accidents that occurred in the entire mining industry for 1977 to 1980. Part of these results are given in Table 2 and relates the most frequent job types and activities of those injured. Again, this is a confirmation, but it also clearly shows that the electrician/maintenance individual has been the most frequently involved in recent occurrences. Conversations with mining-company, manufacturer, and academic personnel concur with the table listings.

Initial Prevention Recommendations. Certain preventions for electric shock became quite obvious when reviewing electrical accidents, and Phase-I work concluded with an initial listing of possible solutions as given in Table 3. It can be noted that training does not appear as a preventive measure in the list. The authors realize that adequate training of mine personnel is one of the better avenues to safety. Part 48 of Title 30 Code of Federal Regulations requires training, and enforcement is mandated. However, trained and qualified individuals continue to get involved with electrical accidents, and there are many instances of unqualified personnel being injured when performing electrical work that they are not supposed to do. It appears that training is ineffective in preventing these kinds of accidents. Two specific instances are cutting into an energized cable prior to making a splice or driving nails in a cable for a power take-off. Consequently, the majority of Table 3 is pointed at building more safety into the electrical systems of mines.

Table 2. Job types and activities most frequently resulting in electrical accidents during 1977 through 1980

Job Type	Number (Percent of Total)
Electrician	331 (20.8%)
Mechanic/Repairman	326 (20.5%)
Foreman	151 (9.5%)
Laborer	142 (8.9%)
All Others	545 (34.2%)
(28 missing observations)	
Electrical Maintenance and Repair	699 (44.1%)
Machine Maintenance and Repair	167 (10.5%)
Cable Handling	65 (4.1%)
Equipment Inspection	30 (1.2%)
All others	586 (36.9%)
(36 missing observations)	

Table 3. Initial listing of possible preventions against electrical shock

Hazard	Some Possible Preventions
1. Handling Unshielded Cable	a. Use protective equipment, such as gloves. b. All cables of shielded construction. c. Sensitive ground-fault detection and very low ground-fault-current limits.
2. Splicing Cables	a. Improved lock-out procedures. b. Use visual or audio warning device to verify de-energized cable, such as tic-tracer. c. Couplers with internal lockout. d. Color-coded jacketing on cables.
3. Trolley Conductors	a. Improved guarding practices.
4. Direct Contact with Live Parts within Equipment	a. Better construction and design practices. b. No work on energized circuits. c. Require voltage tests before starting work. d. Prevention of UVR "block ins." e. Dead-front construction. f. Trouble-shooting mode for equipment maintenance (only the control-circuitry energized). g. Trouble-shooting panels or barrier strips. h. Integral test instrumentation with switches to allow quick verification of critical circuit operation. i. Grounding of control circuits. j. Electrostatic shielding of control transformers. k. Use available protective gear, such as gloves, hot poles, etc. l. No high-voltage components in low-voltage compartments. m. Barriers between high-voltage and low-voltage compartments. n. Interlocks on all high-voltage access panels. o. Guarding of live parts. p. Targets on all protective devices.
5. Unshielded High-Voltage Splices	a. Good splicing practices. b. Training. c. Use visual or audio warning devices to find unshielded splices.

Table 3. (Continued)

Hazard	Some Possible Preventions
6. Energized Frames, Grounding Conductors, or Grounded Conductors	a. Adequate grounding conductors. b. Prevention of ground-check monitor lockouts. c. Sensitive ground-fault detection on three-phase, single-phase, and dc portable and mobile equipment.
7. Indirect Contact with	a. Better construction, design, and layout practices. b. Proximity warning devices.

Phase II

The main objective of Phase II was to evaluate theoretically and experimentally all of the initial findings of Phase I. To facilitate research, the program plan was broken into seven tasks.

1. Task 1 assembled the evaluation and test criteria used in other Phase-II tasks. After developing general criteria adaptable to any shock-prevention technique or device, it became obvious that sensitive ground-fault detection required the majority of testing effort in Phase II. Thus, most of the Task-1 effort was spent on these devices.

2. Task 2 evaluated the applicability and performance of a ground-fault indicating/interrupting device intended for dc systems that was supplied by the Bureau of Mines.

3. Task 3 researched the applicability and performance of very-high-resistance grounding systems as exemplified in the U.K. coal-mining industry.

4. Originally, Task 4 was to evaluate other protective devices selected in Phase I for performance and applicability to the U.S. mining industry. This was modified to only sensitive GFIs, with the balance of the devices shifted to Task 7.

5. Task-5 research was based on the problem of providing protective circuits where interruption could cause a personnel hazard greater than that created form an electrical failure. Also involved were those circuit portions where indication of failures would augment safety. The principal area of concern was Ward-Leonard systems on surface excavators.

6. Task 6 was to investigate designs and layouts of power systems that would eliminate overhead-line contact fatalities. The goal was to produce guidelines from which operators could make their surface electrical systems more safe.

7. Task 7 was the main thrust of Phase II, where the research goals were:
   - recommendations of design modifications to equipment to enhance electrical-shock prevention or protection;
   - recommendations of methods or procedures for performing maintenance on electrical circuits and equipment;
   - suggestions pertaining to performing maintenance safety;
   - recommendations of types of devices for mine-industry usage for shock prevention, including advantages and disadvantages in applicability, performance, and/or operation; and
   - recommendations of factors that should be considered in future investigations on shock prevention, particularly related to mobile mining machines.

The seven tasks of Phase II produced a large amount of results. When organizing this documentation near the end of the contract, it also became apparent that certain task results were more useful in one portion of the mining industry than in others, either by the hazard area that the task addressed or the recommendations that came from the research. Accordingly, final reporting was divided into four separate volumes.

1. This volume covers the Executive Summary and Phase II, Tasks 2 and 7, and reporting on the Phase-II research follows this chapter.

2. "Volume II - Ground-Fault-Interrupting Devices details the results of Phase II, Tasks 1, 3, and 4.

3. "Volume III - Indication versus Interruption" involves Phase II, Task 5.

4. "Volume IV - Overhead-Line Contact Fatalities" is the result of Phase II, Task 6.

Information about the contents in Volumes II, III, and IV follows and concludes this chapter.

Summaries of Other Report Volumes

Ground-Fault Interrupting Devices. Volume II of the Final Report concerns the application of sensitive ground-fault interrupters (GFIs) to ac utilization circuits in U.S. mines. The main concepts examined are shock prevention and methods for reducing nuisance tripping. The research involved a literature search, input from previous Bureau of Mines contracts, contacts with electrical manufacturers and mining personnel, and tests on several devices that showed promise. The following paragraphs summarized the contents of the report volume, including problems with sensitive-GFI application, tests, and conclusions.

Background. Present ground-fault protection devices used in mining are inadequate for shock prevention, and their primary function can be considered protection of equipment. Pickup levels and maximum ground-fault current limits are considerably in excess of the level that can kill a person, especially if a grounding conductor becomes open.

A sensitive GFI is a ground-fault relay that picks up with currents in the milliampere range and, ideally, any current leakage sufficient to electrocute a human should be detected and then interrupted. However, applying sensitive GFIs to mine electrical systems might have a drastic effect on productivity if not done properly. For instance, the added sensitivity to prevent electrocutions may cause unwanted nuisance tripping. Trip signals at this level may result from normal system operation that is falsely interpreted by the sensitive GFI as a ground fault.

Several methods for ac ground-fault detection exist, but zero-sequence relaying is the most adaptable for reduced trip levels without nuisance tripping. The widespread use of zero-sequence relaying plus its application by all sensitive GFI manufacturers supports this statement.

The prevention of electrocution from ground faults is not obtained merely by adjusting of conventional-relay trip setting. As the output current and voltage of a zero-sequence current transformer is proportional to the fault current (i.e., milliamperes), a conventional electromagnetic scheme would fail. First, the actuating quantities would be too small and, second, false signals would be interpreted as trip signals. A sensitive solid-state device with amplification is called for.

Scope of Work. The possible problems encountered with sensitive GFI application in mining were determined as:

- low secondary voltage to operate relays,
- external flux interference,
- common-mode interference,
- transient interference,
- harmonic interference, and
- capacitive charging-current interference.

Each problem was investigated, and its suggested solution was detailed.

Five devices for sensitive ground-fault detection on three-phase industrial systems were located and purchased. Twelve tests were devised to ascertain if any of the devices would be acceptable to the U.S. mining industry.

During the testing of the various devices, it was found that those manufacturers who designed their devices according to the report recommendations had more success. Those devices intended for use in other industries may be perfectly suited for their environment but were found generally unacceptable for U.S. mining systems. However, by designing sensitive GFIs with an eye to mining application, better success was achieved.

Conclusions. The ground-fault protection used in mining can be upgraded to help protect personnel from electrocution by following several suggestions

highlighted in this report volume. Results of testing on several sensitive GFIs indicate the existence of two GFIs that may be modified to perform adequately on U.S. mining systems. A recommended set of guidelines is included in the report and covers design, construction specifications, and performance tests. A GFI that conforms to these recommendations can be expected to operate safely and without nuisance tripping in the mine environment.

Indication versus Interruption. Volume III presents an investigation of indication-versus-interruption procedures used on motion-drive power equipment, with emphasis on surface excavators. Many of the problems encountered with these systems are not new to engineers but have been multiplied and complicated by new machine technology. This report volume will clarify these problems and utilize well-established methods to recommend a scientific and unified approach to protection in motion-drive equipment.

Background. Developed some years ago, the system of variable-voltage speed control for dc motors is usually referred to as the Ward-Leonard Control system. It has proven to be reliable and fairly efficient in providing the variable speed-torque characteristics required of surface excavators and hoisting systems. With an M-G set utilizing an ac motor to drive a dc generator, the Ward-Leonard system by control of the generator field provides the variable armature voltage to the dc motor. The power (armature) loop between the dc generator and motor is the basis for control of the load, and any interruption or variation of the power loop effects the control of the load on the dc motor. The protection within this system must be capable of limiting fault currents without losing control of the motor load.

To comprehend the conditions of the drive system, examination of the excavator duty cycle, expressed as speed (voltage) and torque (current), illustrates that each motion drive requires rotation in both directions (positive and negative speed) as well as torque in both directions (motoring and braking). The operation of the crowd (or drag) and hoist motions are similar in that both gravity and inertia are involved. For the swing motion, gravity has very little influence, and the load inertia is very high.

Coordination of protection must be provided from the ac motor to the dc generator and dc motor and their inherent field controls. Short circuits and overloads upstream from the machine can be controlled by conventional methods. These methods, however, must not interfere with the necessary control of the load. Short circuits and overcurrents within the motion drive system must be controlled by a protective system that can provide the necessary logic, including the ability to distinguish between fault currents that are dangerously high and those that are minor and allow the operator to shutdown the machine.

Scope of Work. To understand the unique problems encountered with the drive systems of excavators, the sources of fault current were investigated to help determine proper indicating and interrupting procedures. Fault calculations performed for the ac system using conventional methods and including the ac motor of the excavator were reviewed. The dc system faults were studied for the contribution of both the dc generator and motor. The effort also examined the dynamic process of the machine and determined the effects of available fault current and position of machine to allow for an orderly shutdown. The logic here is that the dc fault current sensed in the

power loop may be controlled by the operator through indication. However, if the fault current is of a dangerous level, the machine can be automatically shut down and brakes actuated.

Another important aspect studied is the monitoring of overloads in the motion-drive system for preventive maintenance. By monitoring the machine during the digging cycle, it can be determined what levels of current will be immediately or eventually damaging to the drive motors. For instance, installation of temperature detectors in the motor windings allows for observation of overcurrents and insulation breakdown. A potentially hazardous fault may then be eliminated by proper maintenance or removal of the motor for rewinding.

Conclusions. The control of large inertia loads on excavating machines requires competent electrical and mechanical braking systems. Reliable braking can only be maintained with the dc power loop uninterrupted. Extensive future research into the various fault conditions that can occur in this system is required so that a safe and non-hazardous method to treat these faults can be obtained.

Alternative methods of a coordinated protection scheme may be found through the examination of individual-component protection. Coordination of these protection schemes may require the utilization of the most recent technological equipment for monitoring and control of machines. In order to achieve responsive control of potential fault conditions and immediate interruption for emergency-stop situations, a reliable on-board monitoring system should be considered.

Other mining operations that employ similar motion-drive systems are the mine hoists used for hauling personnel and for production. Hoisting systems also involve large inertias that must be controlled at safe speeds and have adequate braking. However, examination of hoist duty cycles may result in a protection scheme that varies from those applied to excavators. In order to maintain a safe operation for transporting personnel or ore, a thorough investigation of hoist drive-system protection should also be considered.

Overhead-Line Contact Fatalities. Volume IV of the Final Report examines the problem of indirect worker contact of overhead high-voltage power lines by mining personnel. This refers to the contact of energized lines by workers through some intermediate conductor such as a metallic tool or a piece of high-reaching mobile equipment, thus the term "indirect contact." The shock hazard presented by such contact has been a major cause of electrical fatalities associated with mining operations.

The report volume is divided into three major areas. The first gives a general background of overhead lines, basic characteristics, and associated hazards, and describes presently used techniques and devices which attempt to alleviate the contact problem. The second area narrows the discussion to the mining industry by presenting a detailed analysis of 39 overhead-line contact accidents in mining since 1970. The last major section uses the information from the first two to formulate recommendations to prevent these accidents.

Background. Overhead high-voltage power lines typically consist of a number of bare conductors supported from wood, concrete, or steel structures.

Installations range from single-phase lines on wooden poles to major transmission lines running hundreds of miles on steel towers. Power levels and operating voltages vary depending on the size and purpose of the lines, but most modern distribution and transmission systems as well as most mining installation are referenced to earth. This can mean either a grounded conductor in single-phase systems or the grounding of a three-phase system neutral. These arrangements allow objects in ground contact, such as mobile equipment, to become paths for ground-fault current upon line contact. Depending on factors like ground-contact resistance, the frames of such equipment can become energized above adjacent ground potentials and endanger any workman simultaneously touching the equipment frame and ground.

Several prevention methods are available or already proposed, but utilities endorse safe practices and individual alertness with respect to overhead lines through safety programs and technical assistance, and federal regulations specify line-installation standards as well as minimum safe working distances. These are sound ideas but rely on the human factor for implementation. Proximity-warning devices present a similar situation; beyond inconsistent operation, they rely on workers for correct use of devices and a safe and timely response to alarm activation. Boom cages and insulating links, intended to maintain safe potentials upon contact, rely less on work-force effort but are inadequate due to insulator performance under dirty conditions. These characteristics indicate that the most effective safeguard against indirect line-contact electrocutions may be the elimination of the hazard through planning, design, and a more comprehensive effort with respect to safe work practices near overhead lines.

Scope of Work. Thirty-nine reports of investigation of fatal electrical accidents dealing with indirect overhead-line contacts in mining were analyzed. This group represented a nearly complete listing of indirect-contact fatalities in coal and metal/nonmetal mining since 1970. These detailed reports covered primarily mobile equipment contacts but also included several non-equipment electrocutions. The majority of the accident were distributed equally among truck, mobile drill rig, and crane contacts, and were organized as such for the analysis. Each report was studied and specific points noted, the data was then compiled and similarities and trends identified among accident circumstances and factors.

Upon completion of the analysis, a number of common factors became evident. Based on presently used techniques and the recognition of the problem areas exposed, recommendations were set forth that should substantially reduce indirect-contact electrocutions.

Methods of preventing indirect-contact electrocutions presented were organized with respect to the manner in which each avoided these fatalities. They were ordered according to their relative effectiveness, but the last group, concerned with safe work practices and personnel training, should be combined with any other methods implemented. The general categories into which the measures were divided are:

- elimination of overhead lines,
- limiting access to overhead lines,
- overhead-line modification,

- protective devices, and
- safe work practices and personnel training.

This organization creates some overlapping of applications but allows consideration of a specific line-hazard situation and progress through the possible solutions.

Conclusions. The recommended solutions range from the costly relocation of overhead lines to simple verbal warnings to machine operators. They cover a wide range of overhead-line hazard situations and represent varying degrees of effectiveness. From this listing, operators wishing to reduce overhead-line shock hazards at mining or mining-related facilities should be able to construct a program combining those techniques which are applicable to their circumstances. The implementation of such programs should reduce the number of indirect line-contact fatalities in the mining industry.

CHAPTER II

PROTECTION OF MAINTENANCE PERSONNEL

General

As indicated in the Executive Summary, statistics for both coal and metal/nonmetal mines show that maintenance personnel have the highest frequency of electrical accidents. These statistics might be expected since repairmen have the greatest exposure to electrical hazards. Yet, electrical-safety features have been directed primarily toward protecting the electrical wiring and components of machines from heat and fire damage. The machine operator and other workers should, of course, receive greater protection from electrically faulted circuits but, on the basis of the evidence, the greatest emphasis should be placed on the protection of maintenance personnel.

The harsh operating conditions that are common to most mining processes contribute greatly to electric-shock hazards. As mineral or rock is extracted, the electrically-driven machines must advance, followed by their sources of power. During these moves, both equipment and cables are frequently stressed beyond their design limitations by being dragged over rough surfaces and being impacted. And all those who work in a mine can attest that the gentle handling of equipment is not the rule, but the exception. The extreme abuse increases the amount of maintenance, which in turn increases the repairman's exposure to electric shock.

The environmental conditions of the mine also enhance the probability of electrical accidents. Wet conditions, which decrease the contact resistance between a person and infinite earth, are often encountered. Thus, a person becomes more susceptible to electrocution from contacting an energized conductor.

The seam height and roof conditions in underground mines, for example, place limitations on the maximum cross-sectional dimensions of entries. The size limitations of the entries, in turn, impose constraints on the size of equipment. As a result, space on mining equipment is limited, and electrical control panels tend to be crowded. Trouble-shooting energized components in these confined spaces increases the risk of electric shock and even electrocution.

Training and the qualification of electricians is an effective means of reducing electrical accidents, but even the best trained repairman remains susceptible to electric shock due to an inadvertent slip of the hand while trouble-shooting an energized panel. Maintenance personnel are often required to work under difficult conditions. If a breakdown results in the interference of normal production, which is frequently the case, the repairman will probably be rushed. The stability of the roof and rib might also be a concern. Cramped working conditions and the production foreman's frequent encouragement to complete the repairs can create confusion factors. With such circumstances, it is difficult to maintain attention on electrical safety, and a person often reacts prior to thinking. A simple mistake may result in a fatal accident.

Statement of the Problem

The high degree of electrical maintenance and the unusual set of working conditions will probably not change; nevertheless, the accident statistics can be improved. Electric-shock prevention can be afforded to maintenance personnel by:

(1) minimizing exposure to energized components, and

(2) providing sensitive, rapid-response protective relaying.

The first approach can be implemented by having manufacturers and, in some cases, the mine-maintenance department incorporate design modifications within equipment. These design modifications can be simple in concept and may prove to be beneficial such that their initial cost could be balanced by reduced maintenance costs and improved safety. The second approach deals with detection and elimination of electrical hazards through sensitive and selective protective relaying. This approach is only now becoming fully realizable with the entry into the mining field of rugged reliable solid-state devices.

Scope of Work

Three research steps are required to meet the contract requirements and provide solutions for the above problem. In order to minimize hazards, electric-shock requirements must first be analyzed. In other words, that which constitutes an electrical shock must be established, based on the duration of exposure as well as the magnitude and frequency of current. Secondly, present practices should be evaluated to determine the types of conditions that can result in potentially dangerous situations. Finally, recommendations must be established to aid in the prevention of electrical-shock hazards. These recommendations should serve as a starting point for initiating a safety philosophy that is directed toward the protection of maintenance personnel. Not all of the recommendations may be practical from the standpoint of retrofitting existing equipment, but they may provide valuable input for future designs.

Report Format

The following report chapters commence by defining electrical shock and establishing the needed ground-fault relay characteristics to prevent ventricular fibrillation. Using this background, Chapter IV presents an analysis of alternating-current systems, a comparison of these systems with respect to body currents, and the advantages and disadvantages of the various ground-fault relaying techniques. In a similar manner, an analysis of direct-current systems for off-track vehicles is presented in Chapter IV. All these analyses form the basis for the research recommendations in Chapter V. Volume I then concludes with Chapter VI, in which the research accomplishments are summarized and recommendations for future research are given.

CHAPTER III

ELECTRICAL SHOCK

Ventricular Fibrillation

Electrical shock occurs when an individual becomes some part of a path which permits electrical current to flow through the body. Ironically, large currents (greater than a few amperes) are less likely to cause immediate death than small currents (less than 1 A), provided the shock duration is not prolonged. The major risk with larger currents is internal heating and burning, whereas smaller currents disrupt the electrical impulses of the nervous system and can result in ventricular fibrillation. When fibrillation occurs, the pumping action of the heart ceases, the pulse disappears, and death usually occurs within minutes. Therefore, the protection against ventricular fibrillation should be the primary goal for defining the sensitivity of ground-fault relaying schemes.

Current through the chest cavity of the body is particularly critical for determining the probability of ventricular fibrillation. Chest penetration depends upon where the current enters and exists the body. One of the most dangerous situations is an entry at one hand and an exit at the other hand. The entrance and exit of these points result in a large current density through the chest cavity, thus enhancing the probability of ventricular fibrillation. Another dangerous situation is an entry at one hand and an exit at the opposite leg, since a large current density can still occur in the chest cavity. In fact, the human body acts as a uniform conductor with most of its resistance confined to the surface skin, thus any entry and exit points will result in some current flow through the chest.

Dalziel's Prediction

The threshold of lethal currents through the chest cavity are not adequately known nor easily determined since experimentation on humans is not possible. Therefore, approximations have been developed for safety standards in an attempt to deal with typical situations and average people. Dalziel approached this problem by performing shock experiments on animals with body weights similar to humans [1]. The statistical data was then fitted to an equation for predicting the minimum threshold value of fibrillation for a body weight on 110 lb:

$$I = \frac{116}{\sqrt{t}} \quad (8.3 \text{ ms} < t < 5\text{s}) \tag{1}$$

where:

I = minimum current (mA, 60 Hz) at which fibrillation occurs for a pathway through major extremities, and
t = duration (s) of the shock.

The equation is represented graphically by the solid curve of Figure 1. According to Dalziel, the area underneath and to the left of the solid curve is considered the "safe area" with respect to fibrillation.

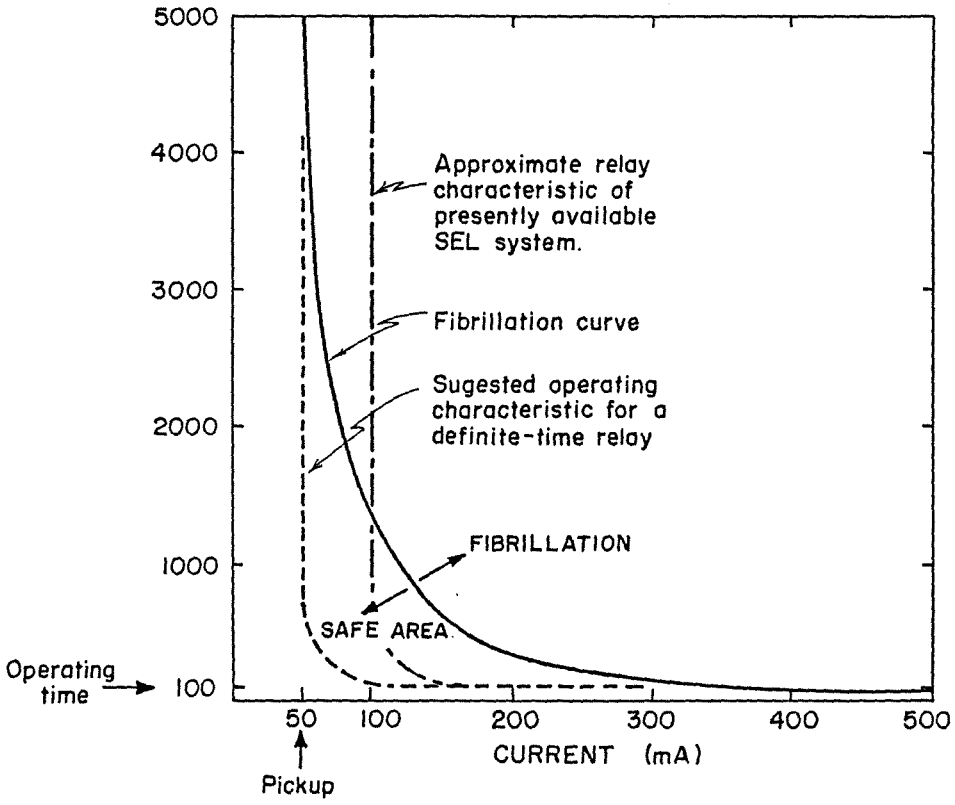


Figure 1. Dalziel's fibrillation curve.

Although it is impossible to eliminate fatal reactions to electrical shock for all cases, a reasonable degree of safety can be achieved by limiting the maximum ground-fault current to a low value (say 500 mA) and by matching the time-current characteristic of a ground-fault relay to Dalziel's fibrillation curve. A definite-time relay with an operating characteristic similar to the dashed line of Figure 1 would be required to meet the necessary sensitivity. The operating values are:

pick-up current: 50 mA
operating time: 100 ms

The pick-up current of 50 mA was selected since this value is generally considered the minimum threshold of fibrillation. The operating time of 100 ms is based on worst-case conditions which takes into account the maximum limit for system capacitance and the reaction time of a molded-case circuit breaker.

To justify the selection of the 100-ms operating time, consider the example presented in Figure 2a and its Thévenin equivalent circuit shown in Figure 2b. The system capacitance for each phase is lumped into a single capacitor connected between the phase conductor and ground. If the ground-fault current is limited to a maximum of 500 mA, as suggested earlier, the ohmic value of the neutral-grounding resistor would be:

$$R_G = \frac{V_{L-N}}{I_{F(max)}} = \frac{600/\sqrt{3}}{0.50} = 693\ \Omega. \qquad (2)$$

The worst-case condition due to system capacitance is specified by the definition of a high-resistance-grounded system: a system in which a high-value resistor is inserted in the neutral connection to ground to limit the resistor current under ground-fault conditions to value not less than the total system charging current. Therefore, the worst-case condition would result when the system charging current equals the resistor current during a ground fault. In other words, the reactance ($X_C/3$) due to system capacitance equals the resistance (R_G) of the neutral-grounding resistor. Assuming a standard body resistance (R_B) of 1000 Ω, the total equivalent impedance of Figure 2c would result. Thus, the maximum current through the body is approximately 250 mA. The reaction time of a molded-case circuit breaker is usually one to two cycles (16.7 ms - 33.3 ms). Therefore, if the relay picks up at 100 ms, a worst-case total clearing time of 133 ms would result. By referring back to Dalziel's equation, the minimum time of exposure can be predicted for this condition:

$$t = \left[\frac{116}{I}\right]^2 = \left[\frac{116}{250}\right]^2 = 215\ \text{ms}. \qquad (3)$$

Circuit interruption, therefore, occurs prior to reaching the minimum fibrillation level predicted by Dalziel.

The worst-case condition just described is an unrealistic situation. The system capacitance is primarily due to the distributed capacitance of the trailing cables and the low-voltage winding of the transformer. A typical capacitance for a trailing cable is 0.02 μF per 1000 ft, and a typical capacitance between the low-voltage winding and ground for a power-center transformer is 0.0042 μF [2]. For the worst-case condition, the system capacitance would be

$$3C = \frac{1}{\frac{X_c}{2\pi f(\frac{c}{3})}} = \frac{1}{2\pi(60)(693)} = 3.83\ \mu F \qquad (4)$$

$$= 1.28\ \mu F.$$

It is apparent that the probability of the worst-case situation occurring is extremely low. However, it serves a useful purpose by building a safety factor into the analysis and counteracts the possible error of overestimating the body resistance.

Body Resistance

The major weakness of the analysis lies in the selection of the ohmic value of the body resistance. A number of factors determines the resistance of the human body. The skin resistance is the dominant factor since its value is much greater than the combined value of internal body tissues. Using low-voltage sources, Dalziel measured body resistances ranging from 1135 Ω to 4430 Ω for humans grasping electrodes wetted with a salt-water solution. Osypka measured hand-to-hand resistances of 5000 Ω for dry conditions and 1300 Ω for wet conditions. He also measured hand-to-foot resistances of 3000 Ω for dry conditions and 1000 Ω for wet conditions [3]. All of Osypka's measurements were made with an 11-V source. Freiberger, using voltage sources ranging from 60 V to 240 V, performed resistance measurements on cadavers within 24 hours after death [3]. His results, as shown in Figure 3, indicates that body resistance decreases nonlinearly as the source voltage increases.

On the basis of past research, the selection of 1000 Ω as a typical resistance for a human body seems reasonable. However, the 1000-Ω value must be accepted with caution since skin resistance is highly variable. In fact, Keesey suggests the body resistance can be as low as 200 Ω if skin resistance is lowered by the presence of a small cut [3]. Bridges recently reported that the body exhibits a capacitive input impedance which results in a charging-current spike [3]. He indicates that the constant-current sources used in previous research may have yielded erroneous results since the body capacitance tends to integrate the applied waveform and to suppress the current spikes. However, in an attempt to approach the problem in a realistic sense and because of the lack of specific research data, a 1000-Ω body resistance will be considered acceptable.

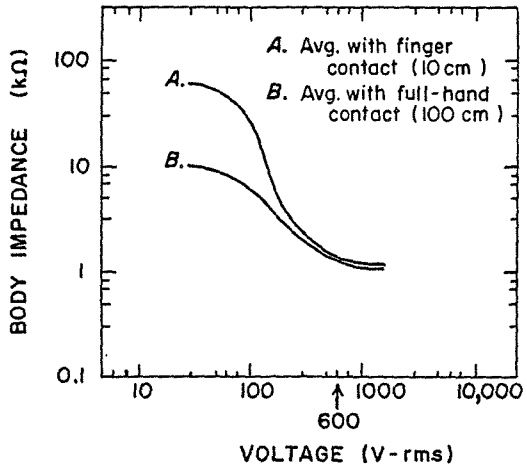


Figure 2. Shock hazard and equivalent circuits.

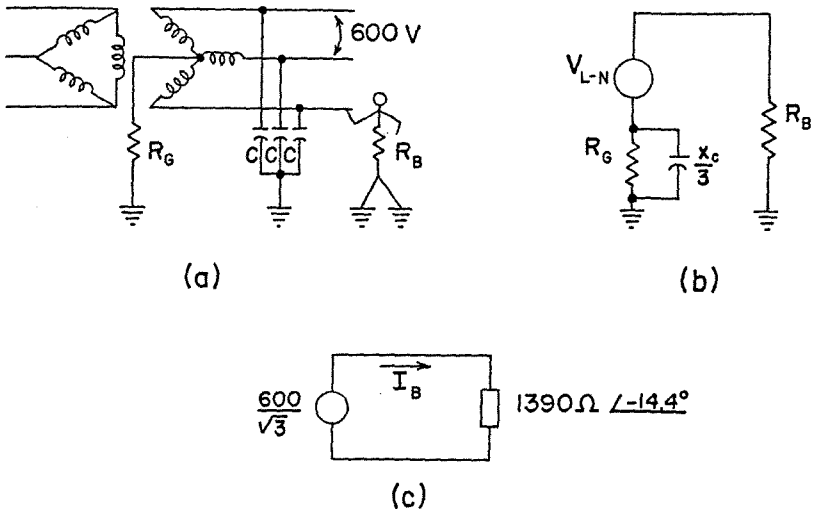


Figure 3. Body resistance measured by Freiberger.

Osypka's and Biegelmeir's Predictions

Dalziel's work is the most widely accepted research in the area of electrical shock; however, other researchers have also defined minimum fibrillation thresholds for 60-Hz currents. Figure 4 compares the fibrillation levels predicted by Dalziel, Osypka, and Biegelmeir (3). According to Dalziel, the fibrillation current is proportional to $1/\sqrt{t}$. Whereas, Osypka suggests that the minimum fibrillation level occurs at approximately 90 mA. Beyond 90 mA, the fibrillation current is proportional to 1/t. By comparing the two curves, it is apparent that Osypka's curve is less conservative than Dalziel's curve. Therefore, the relaying characteristic proposed earlier, which is illustrated in Figure 1, would also provide adequate protection on the basis of Osypka's fibrillation level. A third fibrillation-threshold prediction is suggested by Biegelmeir [3]. Actually, his interpretation is based on two distinct thresholds. The first threshold of 50 mA occurs if the duration of the shock is greater than one heart period (typically 12.5 ms), while the second threshold of 500 mA occurs if the duration is less than one heart period (the duration of the second threshold is so small that it cannot be illustrated with the scale used in Figure 4). On the basis of Biegelmeir's prediction, any body current greater than 50 mA would require a total circuit-clearing time less than 12.4 ms. However, a clearing time of such a small duration is not possible since the reaction time of a molded-case breaker ranges from 17 ms to 33 ms.

Jacimovic's Prediction

A fourth fibrillation prediction has been established by Jacimovic [4], which is given by

$$I = \frac{35}{t^{0.56}} \tag{5}$$

where I and t are again in milliamperes and seconds, respectively. He concludes that this equation represents maximum non-fibrillation current in the time range of 0.1 to 5 s for 99.5% population independent of weight and sex. Jacimovic feels that the number of experiments has been too small to make a definitive conclusion about the correlation between maximum non-fibrillation current and body weight. However, for the sake of comparison, he applied his equation to a body weight of 110 lb and a time interval from 0.08 s to 5 s, and obtained the following equation:

$$I = \frac{122}{t^{0.56}} \tag{6}$$

with the current and time units as before. This equation very closely matches Dalziel's prediction. (A comprehensive bibliography of research publications related to electrical shock has been prepared by Jacimovic and is presented in Appendix I.)

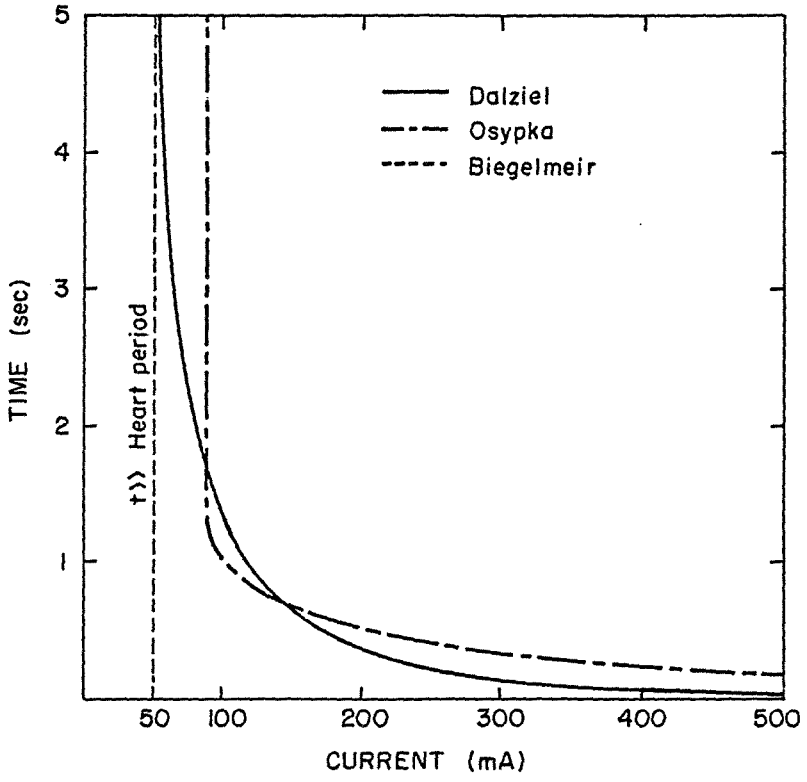


Figure 4. Fibrillation curves.

Relay Characteristics

From a practical standpoint, Dalziel's fibrillation curve appears to be the most realistic goal for defining the sensitivity of a ground-fault protection scheme. Table 4 summarizes the physiological responses to alternating-current flow for a duration of one second, according to Dalziel [5]. With a 50-mA pickup at 100 ms, pain and discomfort would be experienced, but the number of fatalities in the mining industry should be greatly reduced.

Ventricular fibrillation can also be caused by direct current, but related research has not been nearly as comprehensive when compared with alternating currents. However, Dalziel indicates that the fibrillation level of direct currents is significantly higher than the threshold of alternating currents, as presented in Table 5 [1,6]. Therefore, the following operating values of a definite-time relay for direct-current ground-fault protection are suggested:

pick-up current:	300 to 400 mA
operating time:	0.1 s

On the basis of Dalziel's predictions, a ground-fault relaying scheme with these operating values would achieve a reasonable degree of safety. Supportive information related to the selected values will be presented in Chapter V.

Table 4. Ranges of physiological response for alternating current.

Current Intensity, mA (one-second contact)	Physiological Effect
1	Threshold of perception.
5	Maximum harmless current.
10-20	Let-go currents.
50	Pain, fainting, exhaustion, but heart and respiration continue.
100-300	Ventricular fibrillation but respiration continues.
6000	Sustained myocardial contraction followed by normal heart rhythm then temporary respiratory paralysis. Burns if current density is high.

Table 5. Ventricular fibrillation from electrical shock.

Shock Duration, s	Direct Current, A	60-Hz Current, A
	Possible Death	
0.03	1.3	1.0
3.0	0.5	0.1
	Certain Death	
0.03	3.6	2.75
3.0	1.38	0.275

CHAPTER IV

ALTERNATING-CURRENT GROUNDING SYSTEMS

General

The fundamental design of mine-power systems is relatively standard for the coal industry. The standardization can primarily be attributed to strict federal regulations. However, a standardization of practices does not exist with metal/nonmetal mines. Federal regulations which apply to these mines are loosely defined and often ambiguous. In fact, a report funded by the U.S. Bureau of Mines suggests [7]:

> A Federally-approved manual or guidelines should be prepared which clarifies the Code of Regulations, Title 30, Sections 55.12, 56.12, and 57.12. The manual/guidelines should be issued to all metal/nonmetal mine inspectors and mine/mill operators.

The ambiguity of the regulations creates difficulty in the enforcement of proper safety practices by Mine Safety and Health Administration (MSHA) inspectors, while the liberal wording of the regulations has resulted in a wide variety of electrical practices [8].

Many electrical practices of the coal industry are directly applicable to the metal/nonmetal industry. It is not economically feasible to suggest that metal/nonmetal power systems be modified to adhere to coal-industry standards; however, significant safety benefits could be realized in future designs. The applicable practices are too numerous and lengthy for discussion here, but reference 9 provides an extensive information source for the safe design of mine power systems.

The following discussions deal with the grounding systems commonly used in the mining industry. Coal mines are required by federal regulations to use high-resistance grounding for all circuits powering mobile equipment. However, a variety of systems, which includes high-and low-resistance grounded, ungrounded, and solidly grounded, can be found in metal/nonmetal mines. The advantages and disadvantages, related to personnel safety, follows.

Grounding-System Types

Ungrounded Systems. With the ungrounded system, there is no intentional connection to ground. The term "ungrounded" is somewhat misleading because the system is actually coupled to ground through the inherent capacitance of transformer windings, cables, and motor windings. Thus, the term "ungrounded" often creates a false sense of security, since there is no visible return path for a line-to-ground fault. In fact, some repairmen, who are unaware of the distributed-capacitance phenomenon, will work on uninsulated energized components while feeling totally safe.

The major advantage of the ungrounded system is its ability to avoid immediate interruption of service when a single ground fault occurs. (This same advantage can be found with high-resistance grounding, without the disadvantages of the ungrounded system.) However, this advantage, in some

instances, can be considered a major disadvantage since no automatic tripping for the first fault occurs, provided a second line-to-ground fault does not occur before the first is removed. The faulty circuit, therefore, continues to operate. The ungrounded system is also vulnerable to insulation failure and increased shock hazards from transient and steadystate overvoltage conditions.

The use of the ungrounded system with ground-fault indicators requires excellent maintenance program to provide service reliability and continuity equivalent to that found in solidly-and resistance-grounded systems [10].

Solidly-Grounded Systems. The neutral point of the solidly-grounded system is connected to ground with no intentional impedance. The main advantages of the system are overvoltage control, immediate fault isolation, and protection against arcing-fault burndown. The major disadvantages are severe flash hazards and very high line-to-ground fault currents.

Low-Resistance-Grounded Systems. Low-resistance grounding is established by inserting a resistor between the system neutral and ground. The resistance is such that ground-fault currents are limited from 50 to 500 A, but commonly about 400 A. Transients are controlled because of the ground connection, and ample fault current is available for actuating protective relays. The flash hazard is not as serious as in the solidly-grounded system, but a current flow of 400 A can still cause considerable damage [9].

High-Resistance-Grounded Systems. As stated earlier, the high-resistance grounding is required by law in coal-mining applications on portable or mobile equipment. For low- and medium-voltage systems (1000 V or less), the neutral grounding resistor is required to limit the maximum ground-fault current to 25 A. (Most modern systems limit the ground-fault current to 15 A). For high-voltage systems (greater than 1000 V), the voltage drop in the grounding circuit, external to the resistor, must be 100 V or less under ground-fault conditions. With this system, sensitive relaying must detect faults of a few amperes. The low-level fault current practically eliminates arcing and flashover dangers, and the ground connection also serves to limit the amplitude of overvoltages. However, loads cannot be connected between line and neutral, since the grounding conductor must not carry any load current [9].

The high-resistance-grounded system can also be applied where immediate service interruption on the first ground fault is to be avoided. The system can prevent a disorderly shutdown of equipment which may result in severe financial losses, or a hazard to personnel or equipment. Unlike the ungrounded system, high-resistance grounding also provides some control of transient overvoltages [10].

The flexibility and safety benefits afforded by high-resistance grounding make it the best selection for most mining applications. As more sensitive ground-fault relays are developed, the system can also be easily retrofitted for improved personnel protection.

Body-Current Analysis

Approach. A symmetrical-component approach was selected for the analysis of alternating-current mine-power systems. Using this procedure, ground faults may be simulated by the appropriate symmetrical-component model, and potential body currents as a function of body impedance and the power-system parameters may be calculated.

In order to achieve a general procedure, the three-phase power-system diagram shown in Figure 5 was constructed. This system was configured to contain all parameters which might be of interest to an ac analysis. Any impedances which are not to be considered in a particular situation may be replaced by either an open or a short circuit.

To analyze the system of Figure 5 using the symmetrical-component procedure, the positive-, negative-, and zero-sequence networks must first be constructed. These networks are shown in Figures 6, 7, and 8, respectively.

The sequence networks may than be simplified as follows. For the positive sequence,

$$E_T = \frac{Z_c Z_1 (E/\sqrt{3})}{Z_t (Z_c + Z_1) + Z_c Z_1} \tag{7}$$

$$Z_1 = \frac{Z_t Z_c Z_1}{Z_c Z_1 + Z_t Z_1 + Z_t Z_c} \tag{8}$$

where:

E_T = Thévenin equivalent positive-sequence voltage (V)

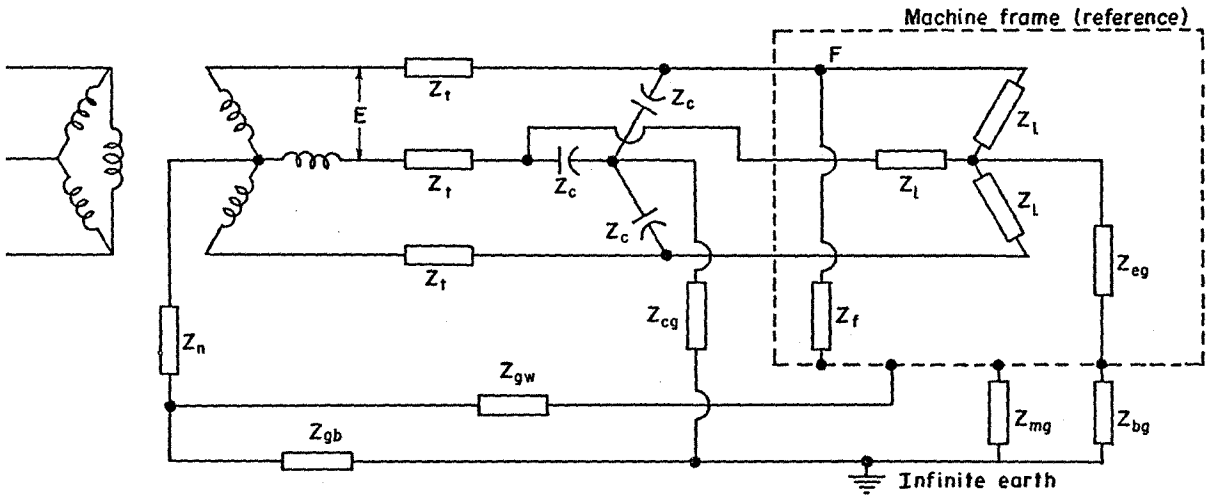
Z_1 = Thévenin equivalent positive-sequence impedance (Ω).

For the negative sequence,

$$Z_2 = \frac{Z_t Z_c Z_1}{Z_c Z_1 + Z_t Z_1 + Z_t Z_c} \tag{9}$$

where:

Z_2 = equivalent negative-sequence impedance (Ω).



Z_t = system line plus transformer impedances

Z_g = system impedance to neutral (capacitance)

Z_{cg} = system neutral impedance to infinite earth

Z_n = neutral-grounding impedance

Z_{gw} = grounding-conductor impedance

E = line-to-line nominal secondary system voltage

Z_{gb} = safety ground-bed impedance

Z_f = fault impedance (single-line fault)

Z_{mg} = machine impedance to infinite earth

Z_{bg} = body impedance to infinite earth

Z_l = system load impedance to neutral

Z_{eg} = load impedance from neutral to reference

Figure 5. General power system representation.

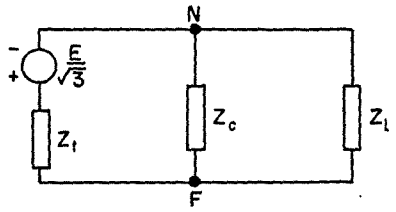


Figure 6. Positive-sequence network for the power system of Figure 5.

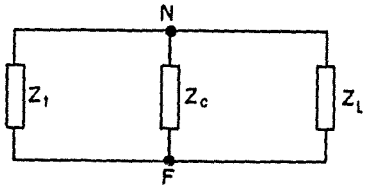


Figure 7. Negative-sequence network for the power system of Figure 5.

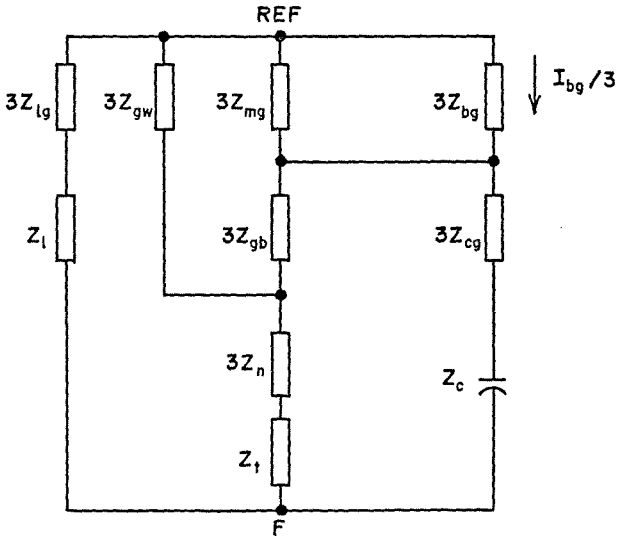


Figure 8. Zero-sequence network for the power system of Figure 5.

Then, for the zero sequence,

$$Z_o = \frac{(Z_1 + 3Z_{1g})\, Z'_o}{Z'_o + Z_1 + 3Z_{1g}} \tag{10}$$

$$Z'_o = \frac{Z_t + 3Z_n)(Z_c + 3Z_{cg})}{Z_t + 3Z_n + Z_c + 3Z_{cg} + 3Z_{gb}} + \frac{Z''_o\, Z'''_o}{Z''_o + Z'''_o} \tag{11}$$

$$Z''_o = 3\,\frac{Z_{bg}\, Z_{mg}}{Z_{bg} + Z_{mg}} + \frac{3Z_{gb}(Z_c + 3Z_{cg})}{3Z_{gb} + Z_c + 3Z_{cg} + Z_t + 3Z_n} \tag{12}$$

$$Z'''_o = 3Z_{gw} + \frac{3Z_{gb}\,(Z_t + 3Z_n)}{3Z_{gb} + Z_c + 3Z_{cg} + Z_t + 3Z_n} \tag{13}$$

where:

Z_o = equivalent zero-sequence impedance (Ω).

The summetrical-component model for a single-line-to-reference fault with an impedance Z_f (see Figure 5) is then as shown in Figure 9. Using this model, the single-line-to-reference fault current (I_f) may be calculated as:

$$I_f = \frac{3E_T}{Z_1 + Z_2 + Z_v + 3Z_f} = 3I_o. \tag{14}$$

The rms body current (I_{bg}, see Figure 8) is then given by:

$$I_{bg} = \frac{3I'_{bg}\, Z_{mg}}{Z_{mg} + Z_{bg}} \tag{15}$$

$$I'_{bg} = \frac{I''_{bg}\, Z'''_o}{Z''_o + Z'''_o} \tag{16}$$

$$I''_{bg} = \frac{Z'_o\, I_o}{Z_o}. \tag{17}$$

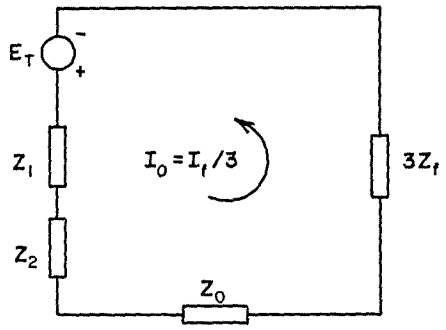


Figure 9. Symmetrical component model for a single-line-to-reference fault on the power system of Figure 5.

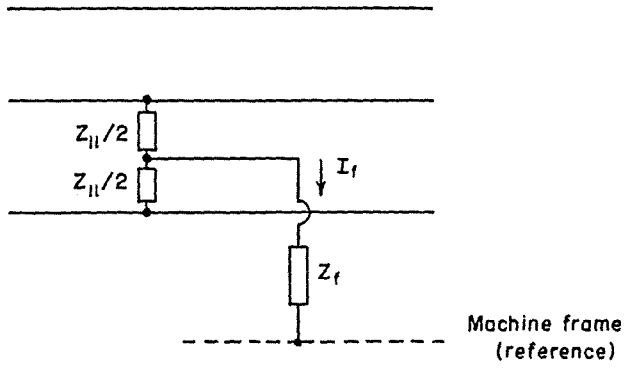


Figure 10. Line-to-line-to-reference fault.

Similar procedures may be used to compute the body current when a fault occurs which involves two lines and the reference as shown in Figure 10. In this case, Z_{11} is the fault impedance between the lines and Z_f is the fault impedance to reference.

The symmetrical-component model for this situation is as shown in Figure 11. Here is the fault current (I_f) is given by:

$$I_f = \frac{3(Z_2 + Z_{11}/2)}{Z_2 + Z_o + Z_{11} + 3Z_f} \qquad I'_f = 3\, I_1 \tag{18}$$

$$I'_f = \frac{E_T}{Z_1 + \frac{Z_{11}}{2} + \frac{(Z_2 + Z_{11}/2)(Z_o + Z_{11}/2 + 3Z_f)}{Z_2 + Z_o + Z_{11} + 3Z_f}} . \tag{19}$$

The body current may then be computed in a manner similar to that for a single-line-to-ground fault.

Implementation. To implement this ac system analysis, a digital computer program was written in FORTRAN IV. This program allows for input of arbitrary power-system parameters and provides output showing body current as a function of the body-to-infinite-earth resistance (real part of Z_{bg}). Provisions are included for variation of a third parameter (i.e., Z_n, Z_{gw}, E, Z_{gb}, etc.) so graphs may be drawn showing the influence of this variable. The present program is set up for a single-line-to-ground fault analysis but could be extended to double line-to-ground fault situations.

Examples of computations using the digital computer program are shown in Figures 12 through 22. These log-log graphs show variations of potential body current (abscissa) as a function of body resistance (ordinate), neutral grounding resistance (third parameter), grounding-conductor resistance, and system line voltage. An estimate of shunt capacitance is included so that the analysis of ungrounded cases is also possible. These estimates of shunt capacitance are derived from 500 feet of 4/0 2-kV SHD cable at utilization voltage levels and 10,000 feet (20 circuits at 500 ft each) of 4/0 cableat distribution voltage levels. Additional variables which may be investigated include the safety ground-bed impedance, the system impedance, surge and power-factor correction capacitance, load impedance, and fault impedance. These impedances are assumed to be zero (or infinite for shunt connection) in this demonstration analysis.

Results. Results shown in Figures 12 through 22 indicate the expected dependencies of shock currents upon the parameters investigated. Thus, increasing the neutral grounding resistance, increased body resistance, decreased grounding-conductor resistance, and decreased line voltage all contribute to the lowering of the potential body current. It should be noted, however, that the elimination of system grounding does not reduce the shock currents to zero (i.e., Figure 14) because of the inherent presence of shunt capacitance to ground.

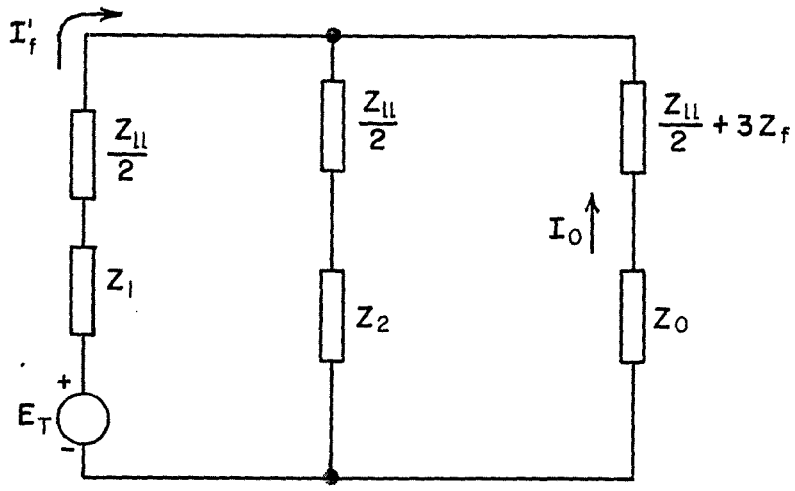


Figure 11. Symmetrical component model for a line-to-line-to-ground fault.

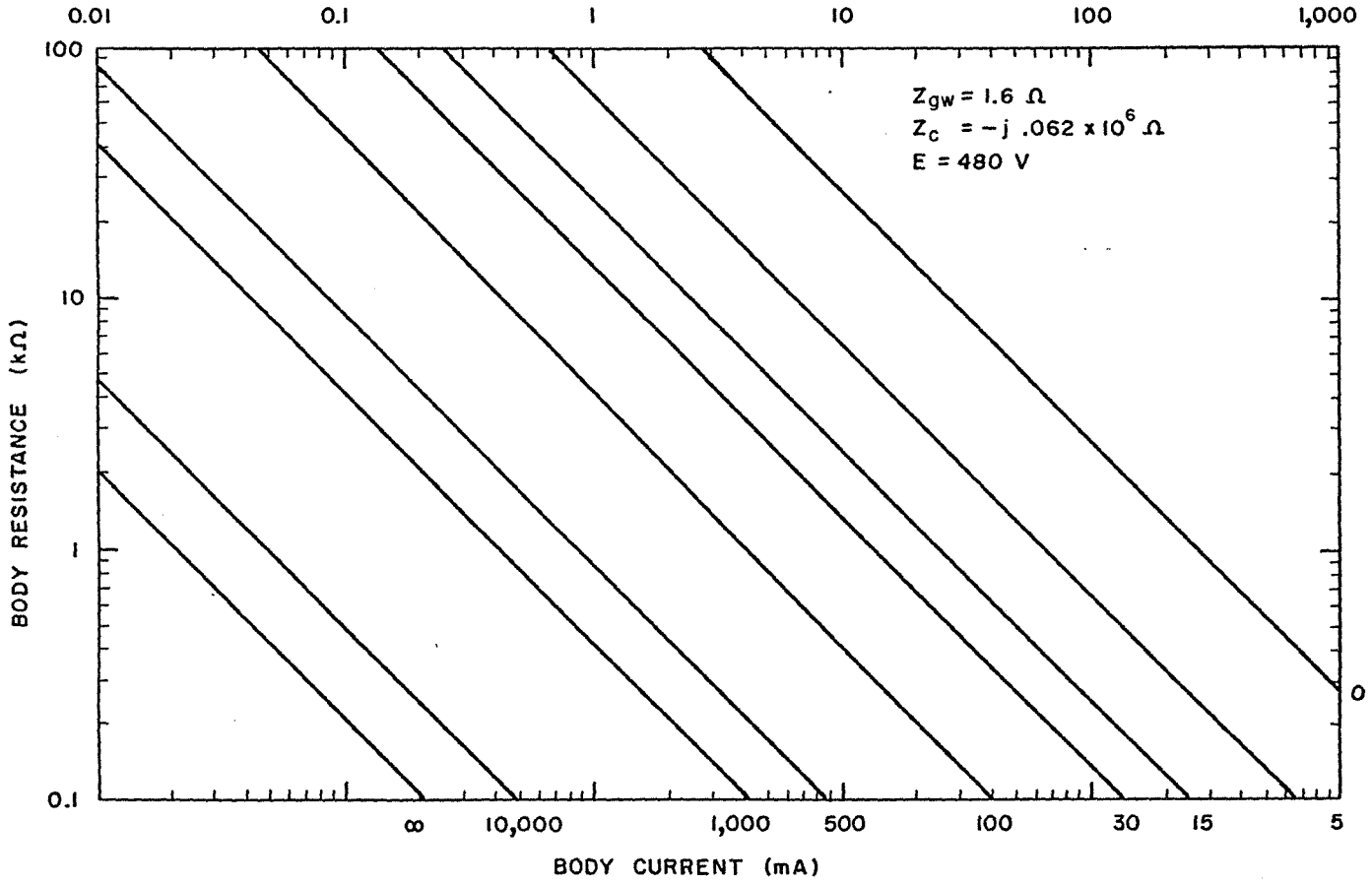


Figure 12. Body current as a function of body resistance (0.1 to 100 kΩ), neutral-grounding resistance (0 to ∞ Ω), grounding-conductor resistance (1.6 Ω), and system voltage (480 V).

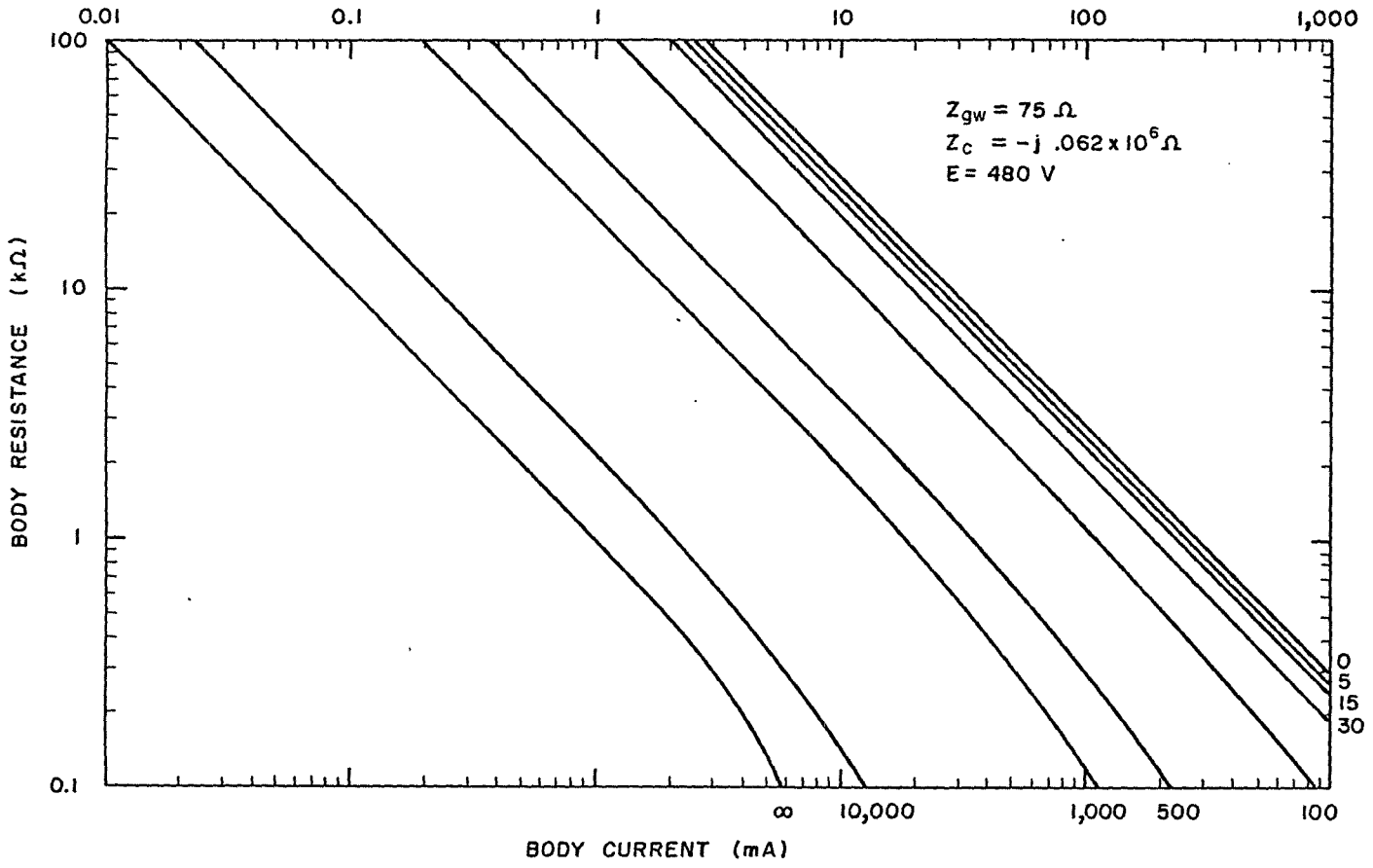


Figure 13. Body current as a function of body resistance (0.1 to 100 k Ω), neutral-grounding resistance (0 to ∞ Ω), grounding-conductor resistance (75 Ω), and system voltage (480 V).

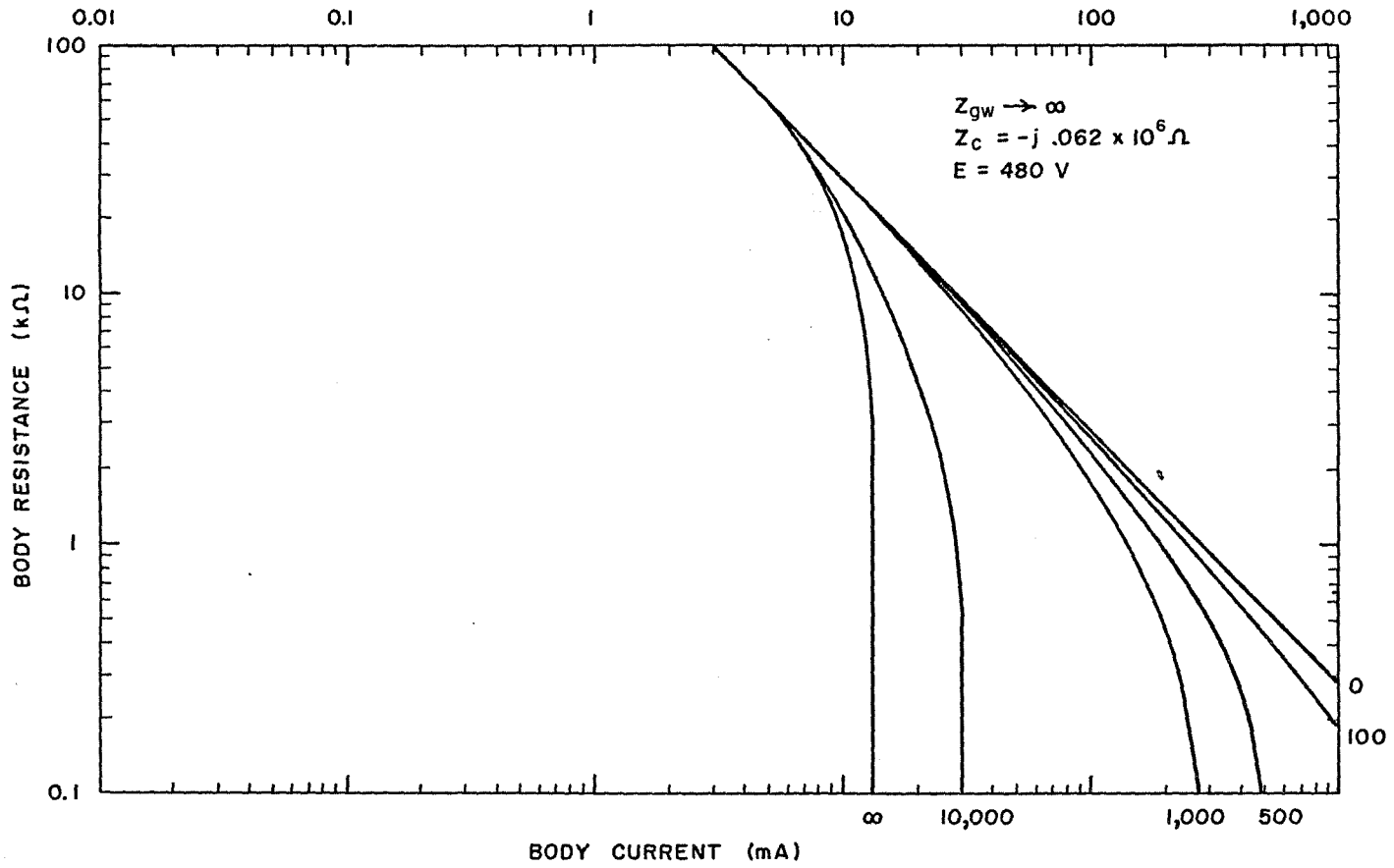


Figure 14. Body current as a function of body resistance (0.1 to 100 k Ω), neutral-grounding resistance (0 to ∞ Ω), grounding-conductor resistance (∞ Ω), and system voltage (480 V).

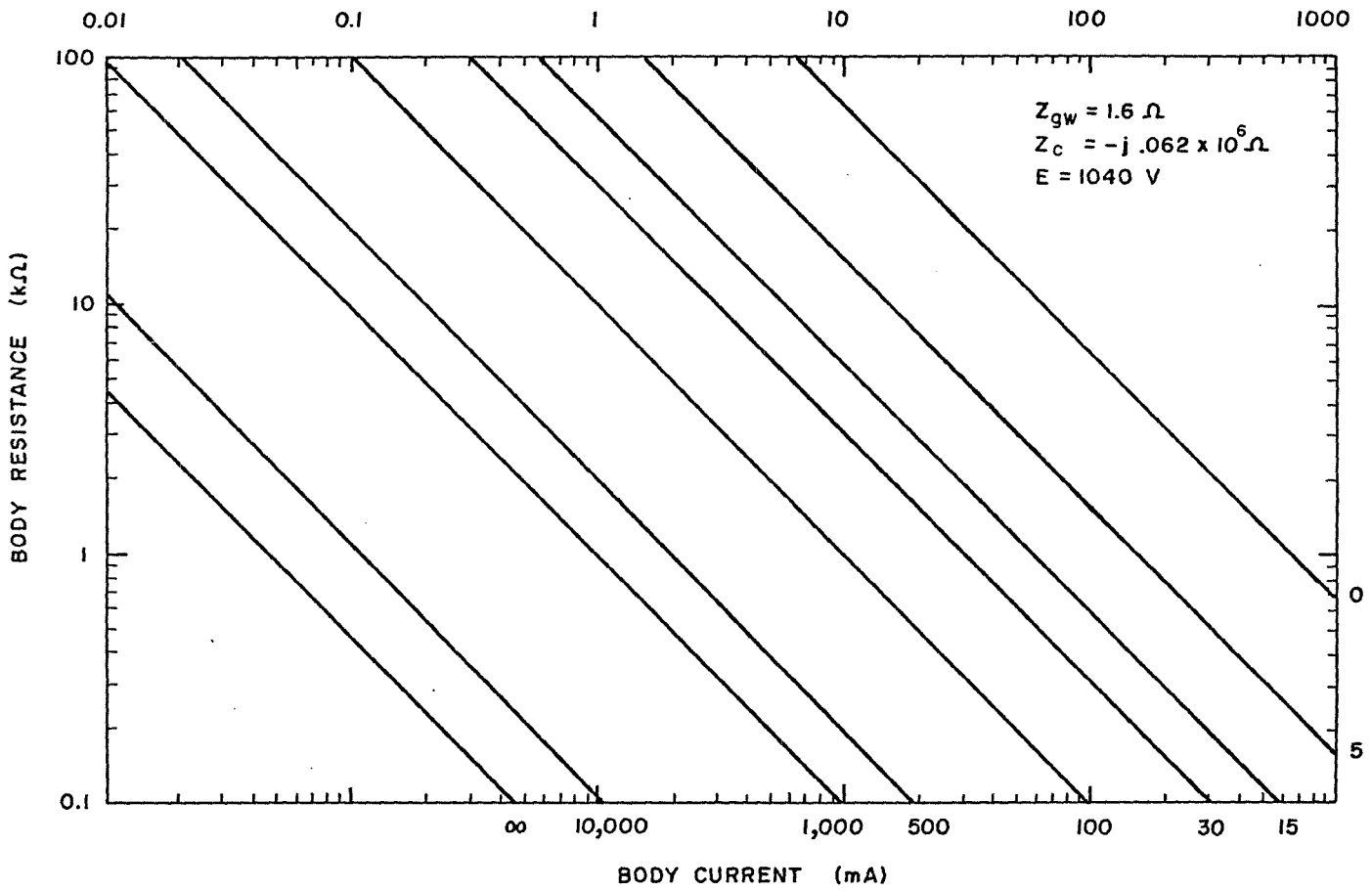


Figure 15. Body current as a function of body resistance (0.1 to 100 k Ω), neutral-grounding resistance (0 to ∞ Ω), grounding-conductor resistance (1.6 Ω), and system voltage (1040 V).

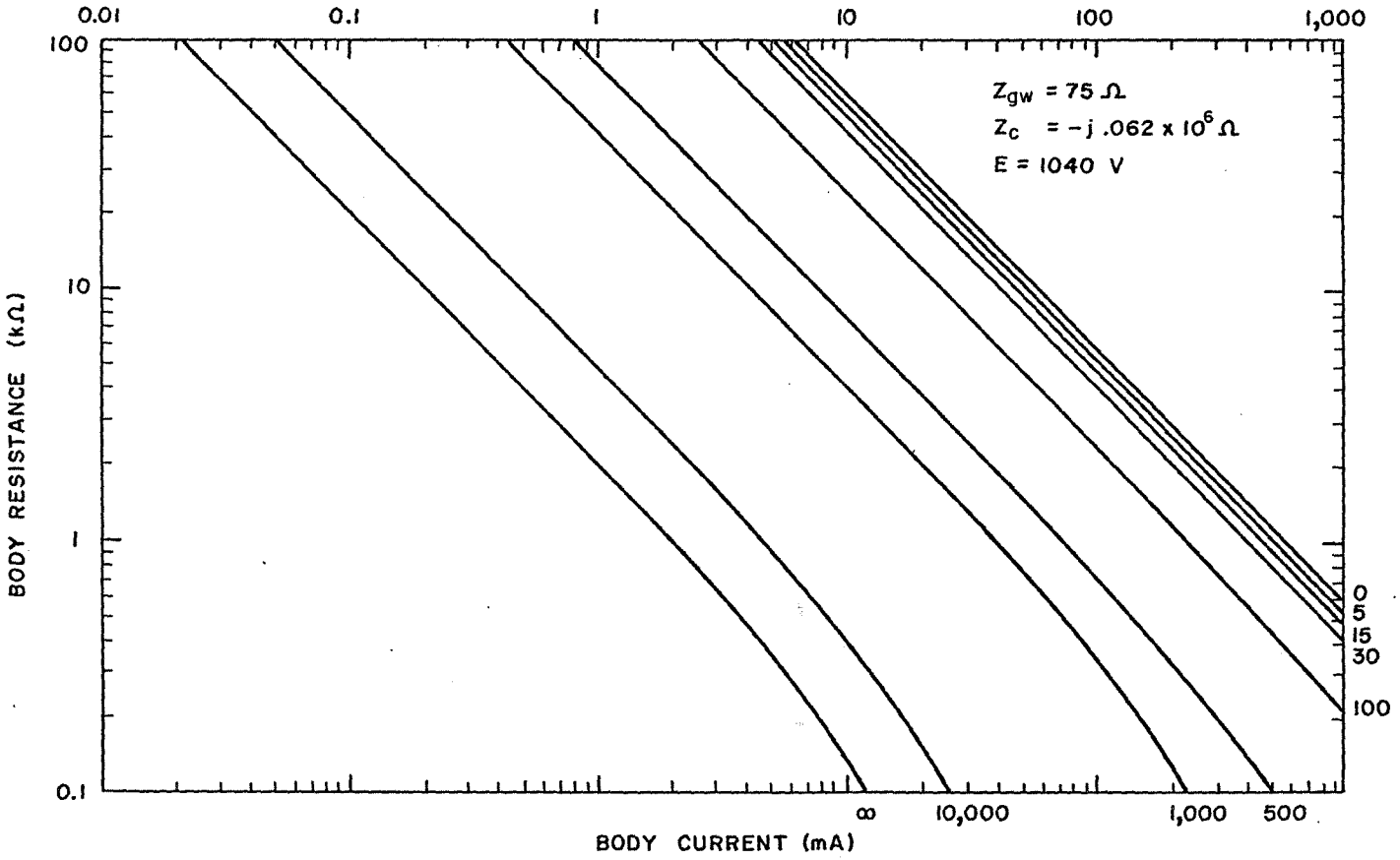


Figure 16. Body current as a function of body resistance (0.1 to 100 k Ω), neutral-grounding resistance (0 to ∞ Ω), grounding-conductor resistance (1.6 Ω), and system voltage (1040 V).

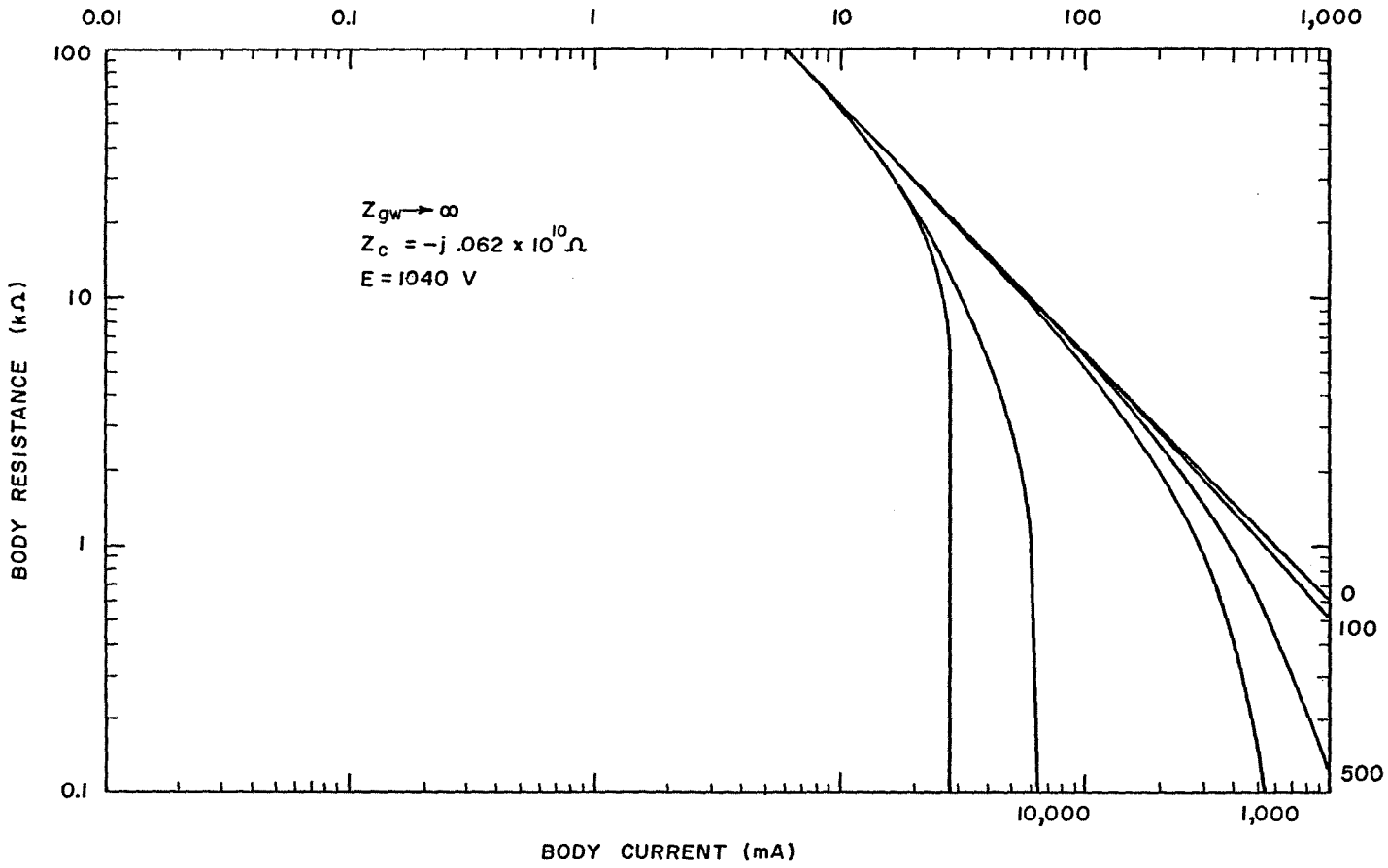


Figure 17. Body current as a function of body resistance (0.1 to 100 k Ω), neutral-grounding resistance (0 to ∞ Ω), grounding-conductor resistance (75 Ω), and system voltage (1040 V).

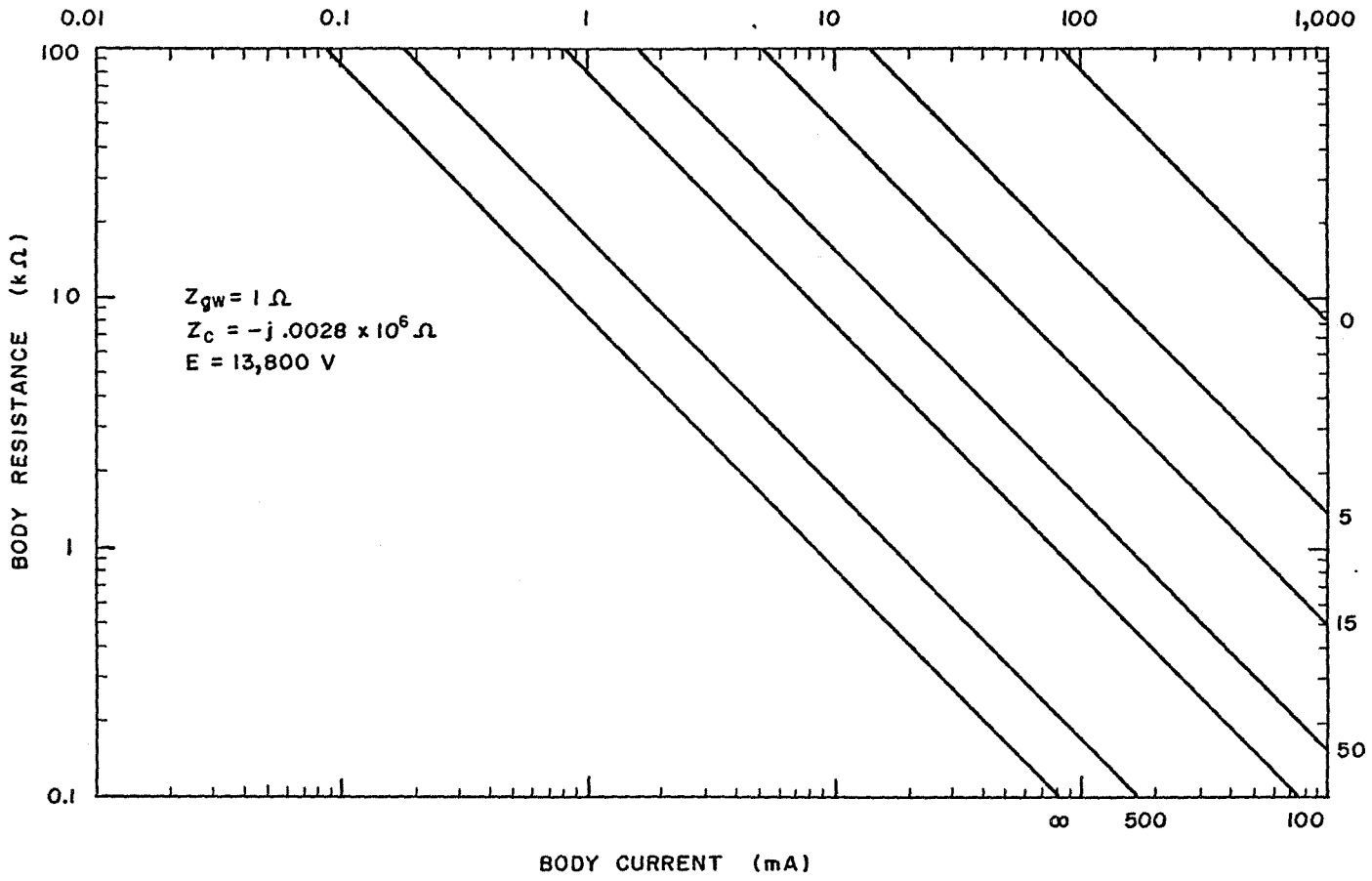


Figure 18. Body current as a function of body resistance (0.1 to 100 k Ω), neutral-grounding resistance (0 to ∞ Ω), grounding-conductor resistance (1 Ω), and system voltage (13,800 V).

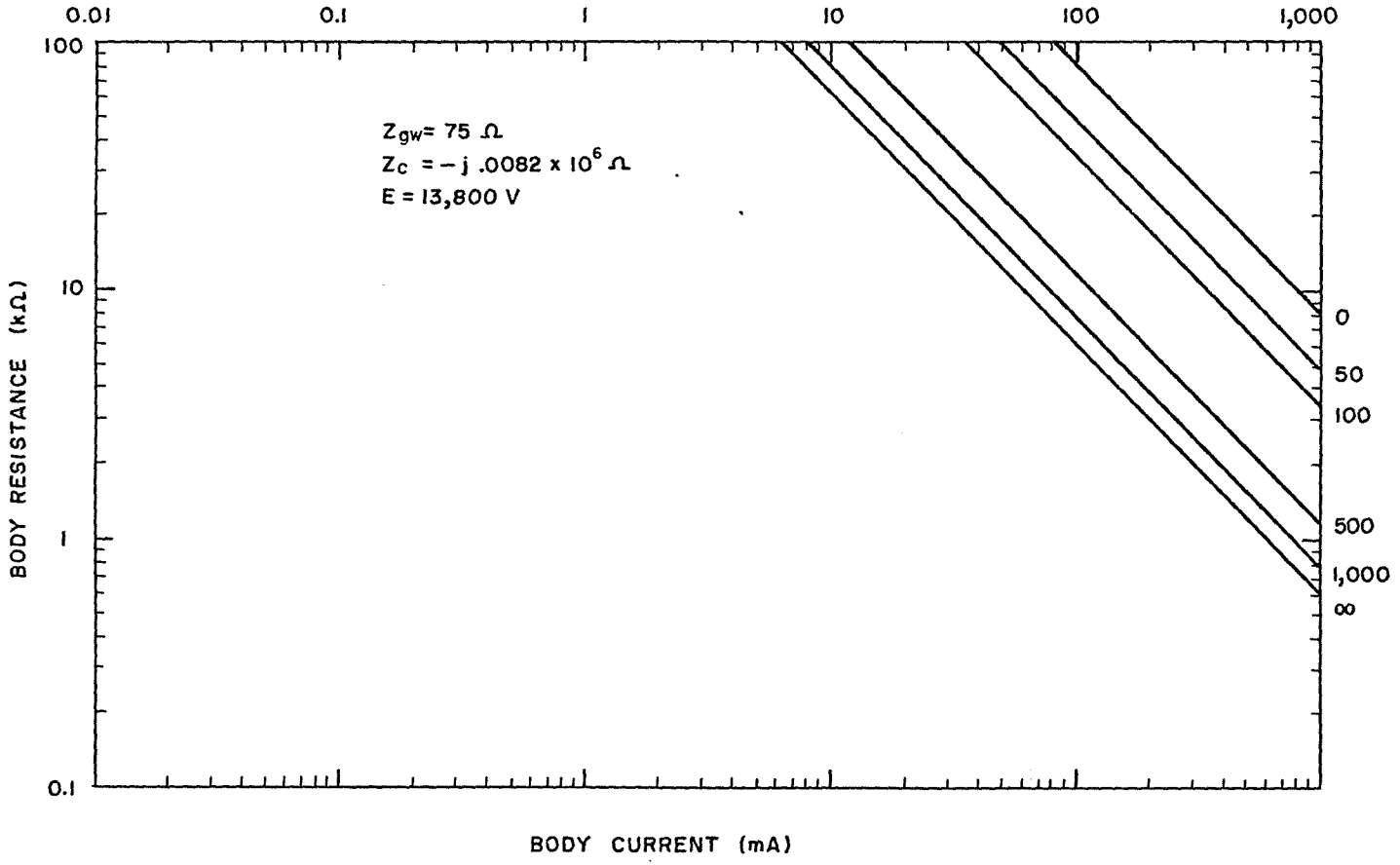


Figure 19. Body current as a function of body resistance (0.1 to 100 k Ω), neutral-grounding resistance (0 to ∞ Ω), grounding-conductor resistance (75 Ω), and system voltage (13,800 V).

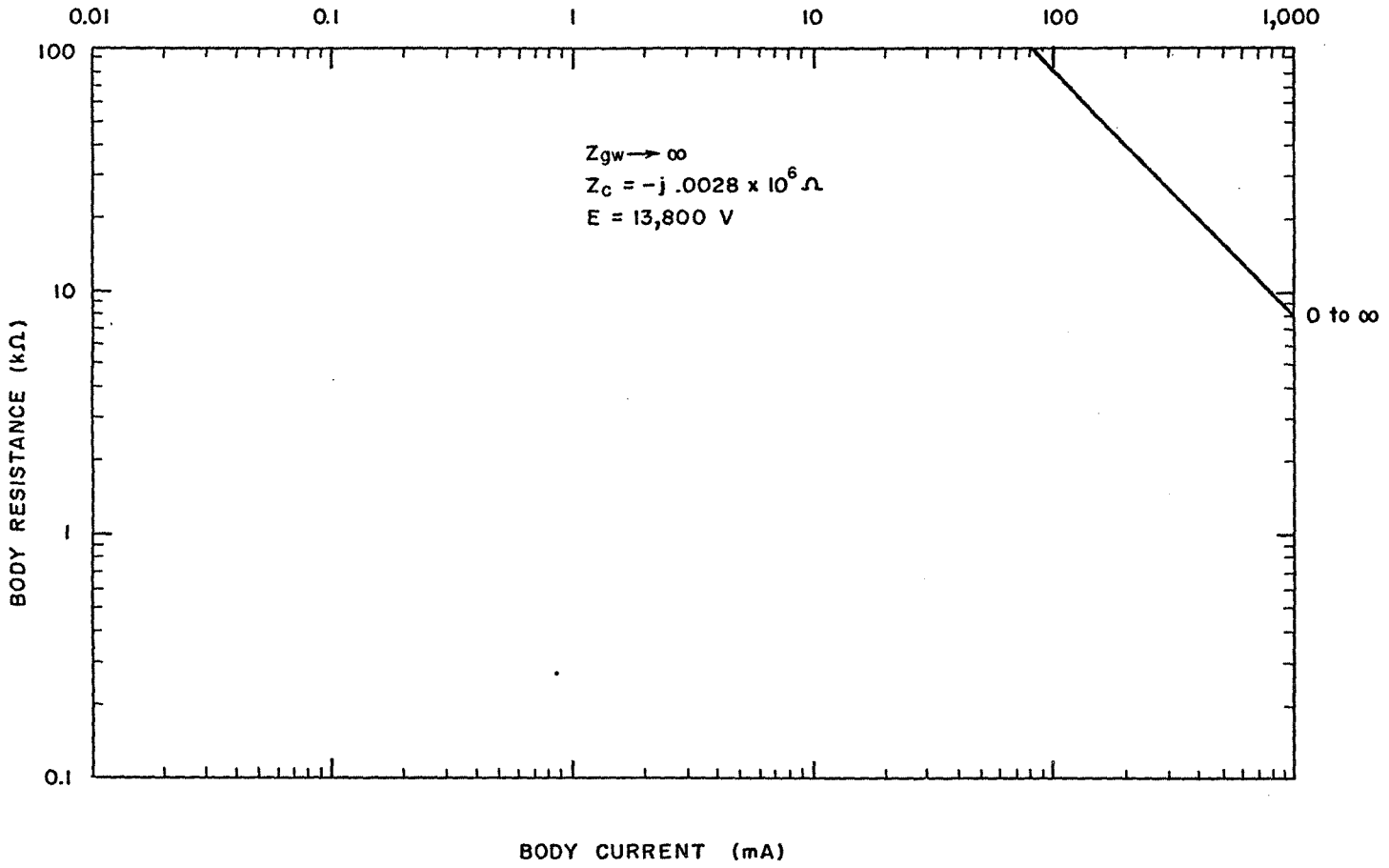


Figure 20. Body current as a function of body resistance (0.1 to 100 k Ω), neutral-grounding resistance (0 to ∞ Ω), grounding-conductor resistance (∞ Ω), and system voltage (13,800 V).

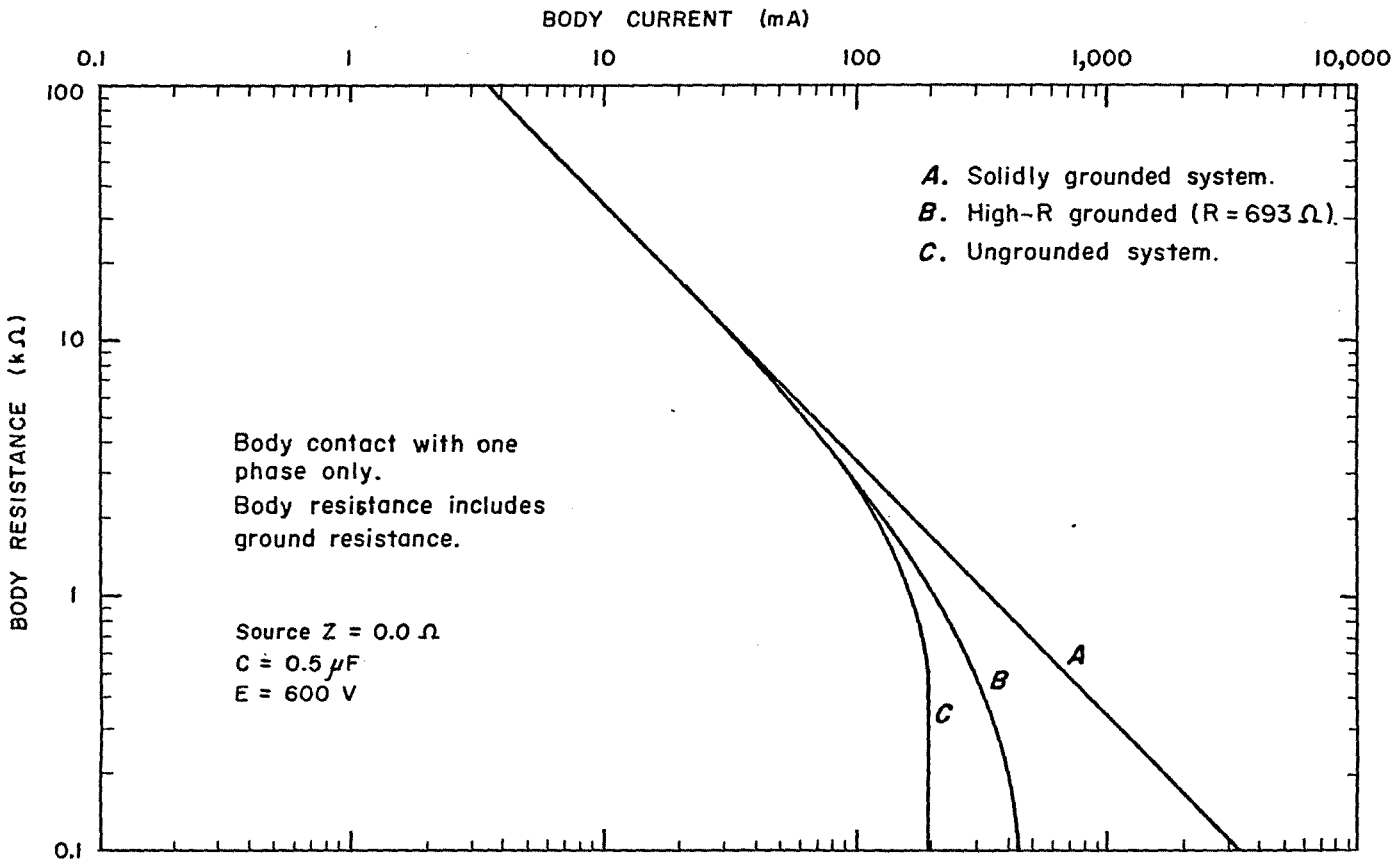


Figure 21. Body current for a direct contact with one phase (600 V).

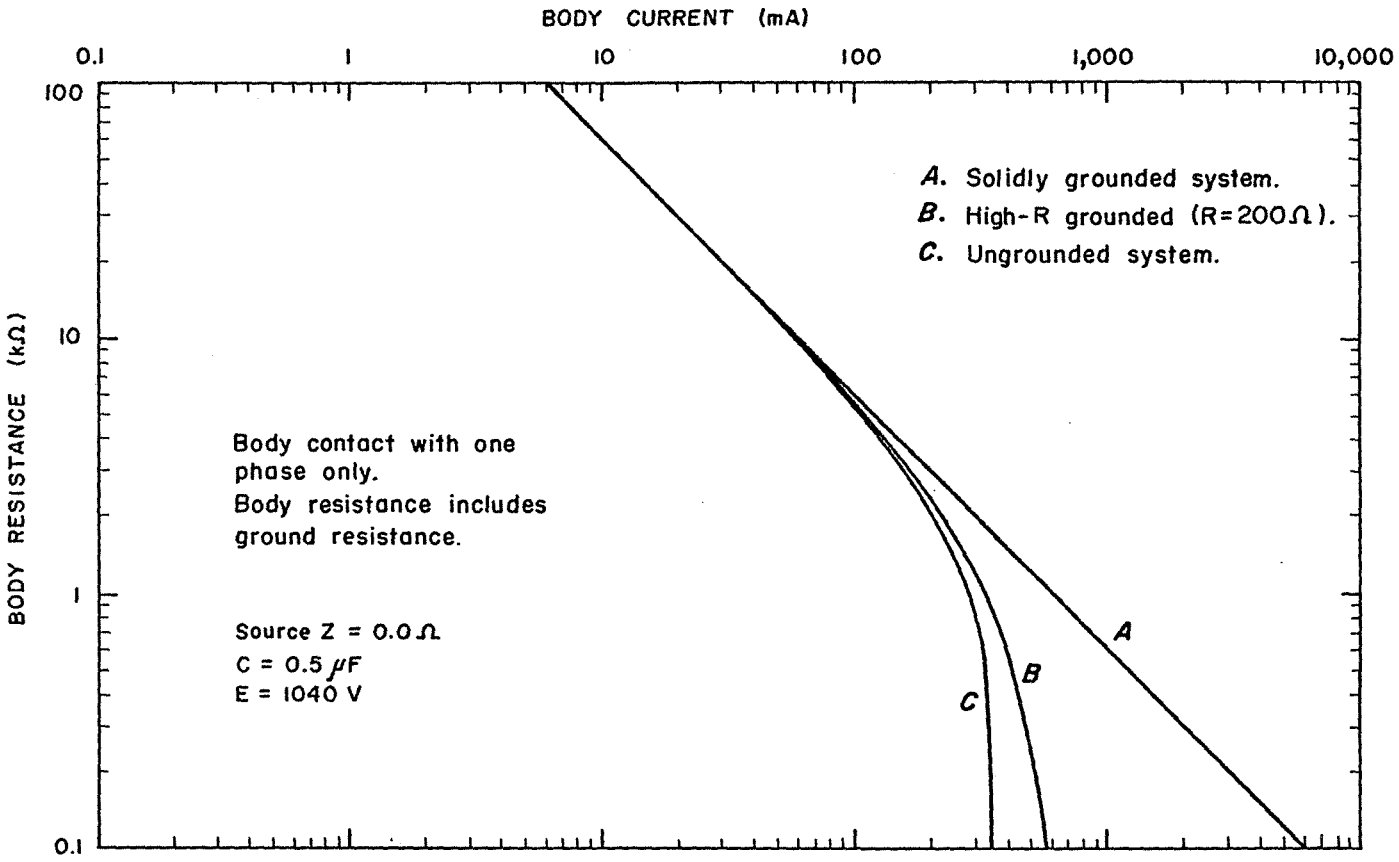


Figure 22. Body current for a direct contact with one phase (1040 V).

The magnitudes of the shock currents shown in Figures 12 through 22 indicate that quite substantial body currents may flow when a system single-line-to-ground fault is combined with equipment-personnel contact. For example, with a 1040-V utilization system and a 30-Ω grounding resistance, 30 mA of body current may flow through a body resistance of 1 kΩ when the grounding-conductor resistance is 1.6 Ω (see Figure 15). This is above the let-go threshold of 10 mA and could cause respiratory paralysis and a fatality if the fault were not cleared promptly. This same current increases to 420 mA if the grounding-conductor resistance becomes 75 Ω (Figure 16). For a completely ungrounded system, this current is still 29 mA (Figure 17). Similar observations may be made at other voltages, body impedances, grounding impedances, and grounding-conductor impedances (i.e., Figures 12 through 22). The effects of system or line impedance, fault impedance, ground-bed impedance, intentionally added shunt capacitance, and load impedance may also be determined.

Figures 21 and 22 show the results of direct body contact with one phase conductor for solidly-grounded, high-resistance-grounded, and ungrounded systems. Figure 21 is for a 600-V utilization system while Figure 22 pertains to a 1040-V utilization system. Both figures clearly show the potential for lethal body currents, even for the ungrounded situation.

Based upon the preceding discussion, it may be seen that a general procedure has been developed for the shock-hazard analysis of three-phase alternating-current systems under any specified system grounding conditions. Interpretation of typical results of this analysis procedure indicates that potential shock hazards may exist under the present practices of ac power distribution and utilization if ground faults are not cleared promptly. Hazard reduction may be achieved by increased grounding impedances or system impedances. Decreasing system voltage or potential grounding-conductor or ground-bed impedances would also contribute to such a hazard reduction. However, some of these design modifications would not be practical due to system operation and protection constraints.

Ground-Fault Protection

Direct Relaying. The simplest form of ac ground-fault protection is direct or neutral relaying. A current transformer is placed about the grounding conductor, between the neutral point of the transformer and the grounding resistor, as shown in Figure 23. The grounding conductor acts as the primary winding of the current transformer, while the secondary winding is connected to the ground-trip relay. If the current through the grounding conductor exceeds a predetermined valued, the ground-trip relay acts to trip the circuit breaker.

Direct relaying is used in both distribution and utilization circuits. For high-voltage distribution at the surface substation, the method is sometimes used as the sole means of ground-fault protection; whereas, in utilization circuits, it is usually used in conjunction with a main circuit breaker as secondary or back-up protection.

The major disadvantage of the direct-relaying method is that it will not detect any ground-current flow if the neutral-grounding resistor fails in an open mode, and the system will continue to operate with no abnormal

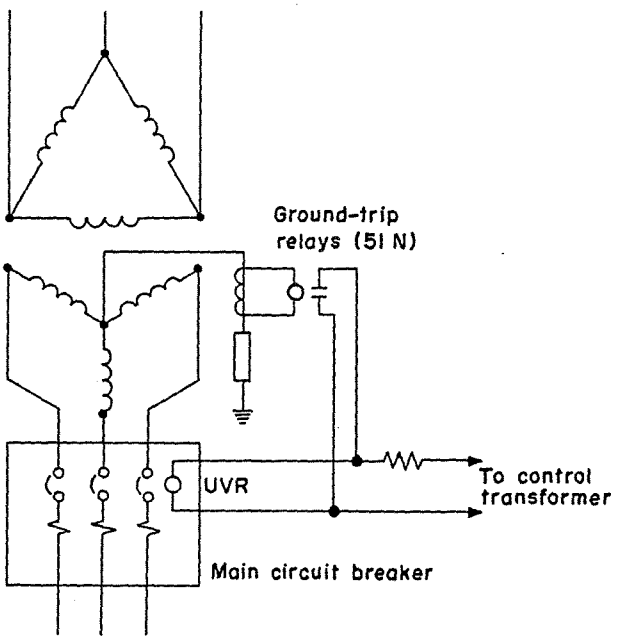


Figure 23. Neutral relaying applied to grounding-resistor current as back-up protection.

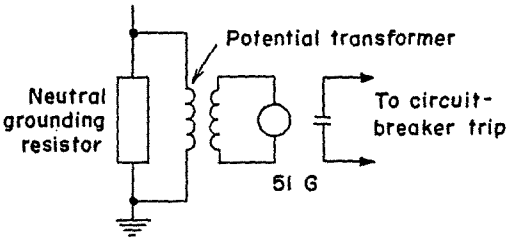


Figure 24. Potential relaying.

indication. Thus, the system essentially becomes ungrounded, posing a personnel hazard.

One method of ensuring the effective operation of a direct-relaying system is to continuously monitor the resistance of the neutral grounding resistor. The monitoring can be accomplished by the same technique used in the impedance-type ground-check system. If the ohmic value of the neutral-grounding resistor changes, the monitor would detect the abnormal condition and trip the associated circuit breaker. A flag should also be displayed by the monitor to provide a quick method for determining why the breaker tripped.

Potential Relaying. Potential relaying, as shown in Figure 24, is often used as a sole means of ground-fault protection at the surface substation and can also be used as back-up protection at the section power center. With this method, the primary winding of a potential transformer is connected across the neutral-grounding resistor, while the secondary winding is connected to the voltage-sensing ground-trip relay. If current flows through the grounding conductor, a voltage is developed across the grounding resistor. When the voltage rises above the preset level, the ground-trip relay causes the circuit breaker to trip.

Unlike direct relaying, potential relaying has the advantage of being able to detect a ground fault with the neutral-grounding resistor in an open mode of failure. However, if the grounding resistor fails in a shorted mode, potential relaying is rendered inoperable. Again, monitoring the resistance of the grounding resistor could eliminate this problem.

Zero-Sequence Relaying. Zero-sequence relaying, also termed balanced-flux relaying, is the most reliable first defense against ground faults. As shown in Figure 25, the circuitry consists of a single window-type current transformer and a ground-trip relay. The three-phase conductors are passed through the transformer core, forming the CT primary. For a balanced condition, the vector sum of the three currents in the primary circuit is zero, and no net current will flow in the secondary. However, during a phase-to-ground fault, the current unbalance in the primary will induce a current flow in the secondary, proportional to the ground-fault current. If the secondary current exceeds the pick-up setting of the ground-trip relay, tripping of the circuit breaker will be initiated.

Zero-sequence relaying is not perplexed by current-transformer error and, therefore, affords very sensitive tripping. The scheme is widely applied at all voltages.

Residual Relaying. Residual relaying is used in conjunction with current transformers placed on the phase conductors, as shown in Figure 26. This relaying scheme is primarily used on high-voltage distribution circuits that require current transformers and inverse-time relays for overcurrent protection. The current transformers and the phase-overcurrent relays are both connected in a wye configuration. The ground-trip relay is connected between the neutral points of the current transformers and the relays.

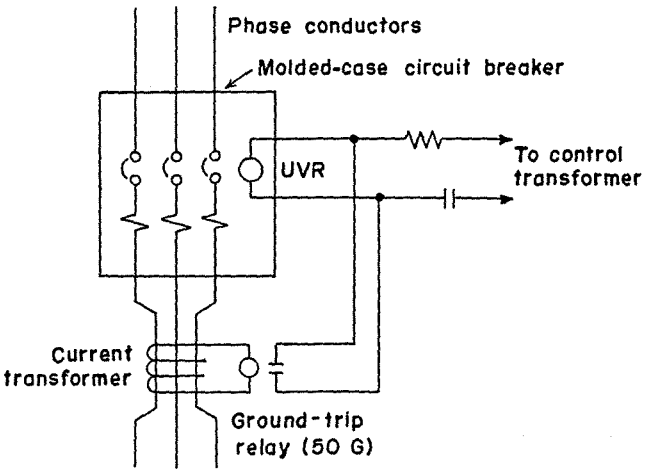


Figure 25. Zero-sequence relaying.

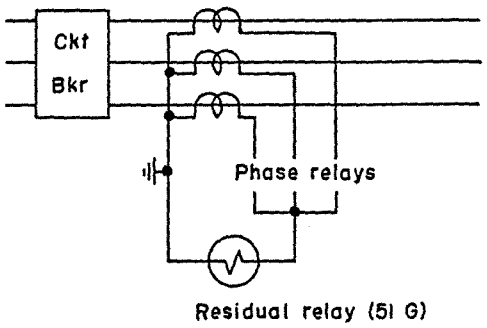


Figure 26. Residual relaying.

The principle of operation of the residual method is similar to that of zero-sequence relaying. However, because of errors due to current-transformer saturation and unmatched characteristics, residually connected relays are often subjected to nuisance tripping. Hence, they cannot have sensitive or low pick-up settings. In many cases, the arrangement will not provide consistent, repetitive tripping, even at presently required tripping levels. For these reasons, the use of residual relaying is not suggested.

Summary

The various types of grounding systems and protective-relaying schemes have been discussed and analyzed in terms of their advantages and disadvantages. On the basis of the analysis, high-resistance grounding stands out as the best selection for most mine power-system grounding applications. The major safety benefits of the system are:

- the near elimination of arcing and flashover dangers,
- the ground connection limits the amplitude of overvoltages,
- the system can be applied where immediate service interruption on the first ground fault is to be avoided,
- shock-hazard reduction is accomplished through limiting the maximum ground-fault current, and
- as more sensitive ground-fault relays are developed, the system can be easily retrofitted for improved personal protection.

Zero-sequence relaying, in conjunction with high-resistance grounding, is the most reliable first defense against ground faults. This type of relaying is not perplexed by current-transformer error and, therefore, affords very sensitive tripping. Potential relaying, connected across the neutral-grounding resistor, should be used as back-up protection to zero-sequence relaying. Potential relaying has the advantage of detecting a ground fault even if the neutral-grounding resistor has failed in an open mode. The potential relay should have a short time delay to provide coordination with the zero-sequence relays.

CHAPTER V

DIRECT-CURRENT SYSTEMS FOR OFF-TRACK VEHICLES

General

Five basic systems of dc ground-fault protection for off-track vehicles are presently being used in the U.S.:

- diode-grounded,
- basic grounding-conductor,
- relayed grounding-conductor,
- neutral-shift, and
- differential-current.

The neutral-shift and differential-current systems can only be used when the machine is powered from the output of a rectifier, such as contained in a section power center. Whereas, the first three systems can be employed when a trolley system is the dc source.

When dc equipment is powered from the trolley system, short-circuit and overload protection is normally provided by a dual-element fuse; however, molded-case circuit breakers are used in some applications. The fuse is mounted in a holder or "nip," which is clamped or hung from the trolley feeder conductor. The return trailing-cable power conductor is clamped to the negative conductor or directly to the rail. Fuses are rarely applied to trailing-cable protection in power-center rectifiers; instead, molded-case breakers or contactors are employed.

Typical Direct-Current Systems

A short discussion of typical systems feeding off-track vehicles follows and considers the advantages and disadvantages in terms of electrical safety. The systems are then analyzed with respect to body currents under electric-shock conditions.

Diode-Grounded System. Direct-current powered vehicles that require cable reels commonly use diode grounding. The system permits the use of a two-conductor cable, which is less expensive and occupies less space on the cable spool, as compared with three-conductor cable. These features make the system attractive, but the diode-grounded system has deficiencies from a safety standpoint.

The simplified diagram of Figure 27 will be used to illustrate the operation of the diode-grounded system for ground faults at various locations. Location 1 of Figure 27 includes the length of the ungrounded conductor from its entrance point on the machine to the main contacts of the M1 contactor. Since the machine uses a cable reel, a slip-ring assembly is required for connecting the incoming power conductors with the machine circuit. Thus, locating a circuit-interrupting device at the immediate cable entrance of the machine is very difficult. As a result, the main contactor is usually the first point on the machine where current can be interrupted. If a fault occurs at location 1, the fault current will flow through the frame of the machine causing diode D1 to become forward biased. D1 then

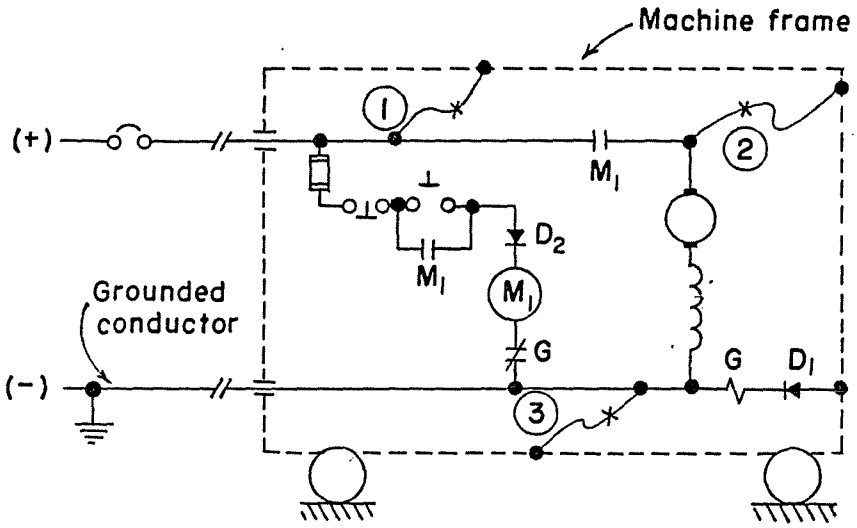


Figure 27. Diode-grounded system with possible faults indicated.

conducts the current through the ground-trip relay G to the grounded conductor. If the fault current exceeds the pick-up setting of the ground-trip relay, the normally-open contacts of the relay, which are in series with the M1 coil, are opened. Opening the contacts of the ground-trip relay results in de-energizing the M1 coil, which in turn causes the M1 contacts to open and de-energize the motor. However, the opening of the M1 contacts does not isolate the fault.

Since the fault is located on the line side of the M1 contacts, isolation is solely dependent upon the opening of the upstream circuit breaker or fuse. Therefore, if the fault resistance is such that the fault current is limited to a value less than the circuit-breaker or fuse setting, the fault will not be isolated. Consequently, the frame potential is raised to a value equal to:

$$V_{frame} = I_f R_g \tag{20}$$

where:

I_f = fault current (A)
R_g = resistance of the grounded conductor (Ω)

Location 2 of Figure 27 is the only "safe" area for a ground fault to occur. The area includes the length of the cable from the load side of the M1 contacts to the motor. For a fault at this location, current flows through the grounding diode D1 and the coil of relay G. If the fault current exceeds the pick-up setting of the relay, the fault is isolated by de-energizing the M1 contactor.

A fault at location 3 renders the diode-grounded system unreliable, since the fault essentially provides a parallel path around the grounding diode D1 and the coil of relay G. Location 3 covers the entire length of the grounded conductor within the machine. For a fault at this location, the frame potential of the machine is elevated whenever the machine is operated. The frame potential is given by:

$$V_{frame} = I_{op} R_g \tag{21}$$

where:

I_{op} = operating current (A).

A fault at location 3 can easily go undetected. As a result, a simultaneous fault at any location of the ungrounded side of the power circuit must depend on the upstream circuit breaker or fuse for isolation, since the ground-fault relay may or may not trip, depending upon the fault resistance at location 3.

The failure of the grounding diode D1 is a common problem associated with the diode-grounded system. With D1 in the shorted mode, the system will operate the same as for the above three fault conditions; however, the frame potential is raised to:

$$V_{frame} = I_{op}R_g. \quad (22)$$

This mode of failure is sometimes indicated by the machine being de-energized when it comes in contact with another frame, which is tied to the dc ground (e.g., a shuttle car bumping a railcar during loading). However, this mode of failure can be undetected for a long period.

If the grounding diode fails in an open mode, all ground-fault protection is lost. If simultaneous faults were to occur at locations 1 or 2 of Figure 27, the frame potential would be raised to a value equal to the supply voltage, and the machine would continue to operate.

Failure of the polarity diode D2 can also create a safety hazard. The purpose of this diode is to protect against the situation of having the negative conductor connected to the positive terminal of the supply voltage and vice versa. This situation can occur while installing a new trailing cable or while making a cable splice. If the diode D2 is shorted and the polarity of the supply voltage is inadvertently switched, the diode-grounded system is rendered totally inoperative; however, the machine would continue to operate. If the diode fails in an open mode, the motor cannot be started since the M_1 coil cannot be energized. The open-mode failure does not present a hazardous condition.

Grounding Conductor. Other methods of grounding dc machines require the use of a separate grounding conductor and Type-G cable. Of these, the basic grounding-conductor system (Figure 28) and the relayed grounding-conductor system (Figure 29) are the simplest. These systems are commonly used when the power source is a trolley system. With the first, a ground fault is detected only by the overload protection on the source side of the trailing cable, and the result is extremely poor sensitivity with respect to ground faults. The ground-fault sensitivity can be improved by adding a ground-fault relay in series with the grounding conductor. However, the current flowing through the relay may not be the total ground-fault current, since a parallel path may be established through the earth.

Neutral-Shift System. The neutral-shift system (Figure 30) uses two resistors to create a dc neutral point for the system and limit ground-fault current. A ground fault on either the positive or negative conductor will cause the neutral point to shift and results in detection by voltage-sensitive relays. The primary limitation of this system is that it cannot discriminate ground faults for individual pieces of equipment fed by the same rectifier. If a ground fault occurs on one machine, all circuits are interrupted.

Differential Current. Differential-current dc ground-fault protection utilizes the neutral of the wye-connected secondary feeding the rectifier. With a delta-connected secondary, a neutral connection can be provided through a grounding transformer. A grounding resistor is inserted in the neutral circuit to limit dc ground-fault current typically to 15 A. Ground-faults are then detected using either a saturable-reactor (Figure 31) or saturable-transformer system (Figure 32).

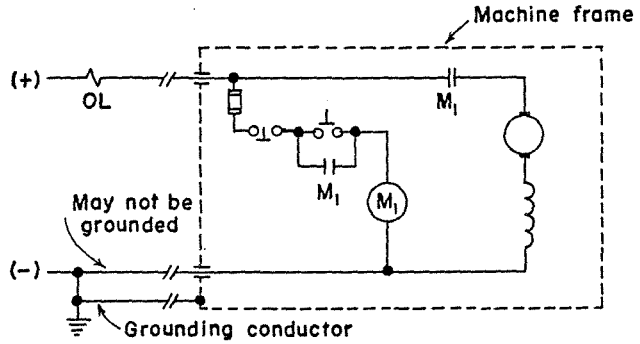


Figure 28. Basic grounding-conductor system.

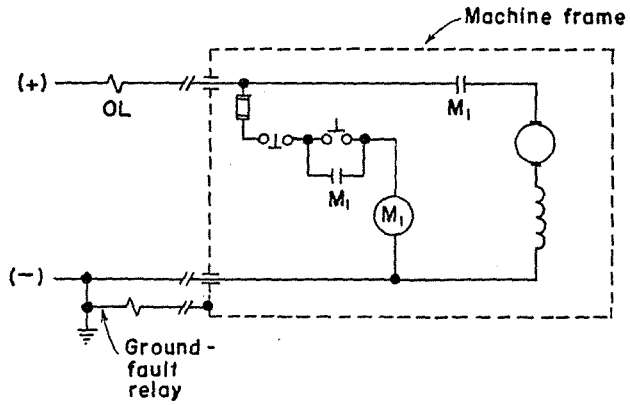


Figure 29. Relayed grounding-conductor system.

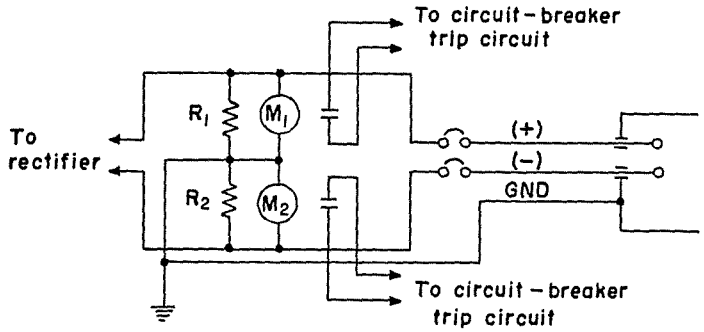


Figure 30. Neutral-shift system.

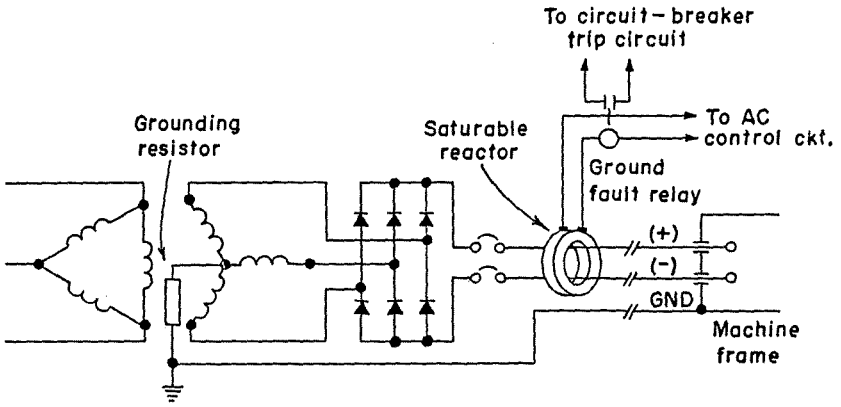


Figure 31. Current-balance direct-current ground-fault relaying using a saturable reactor.

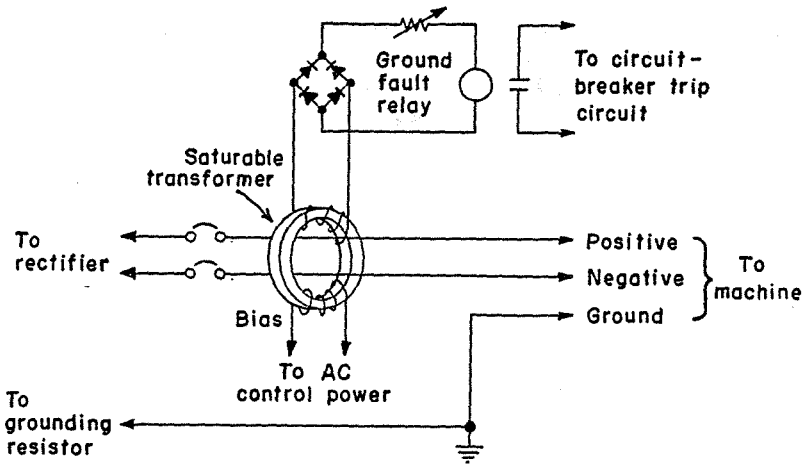


Figure 32. Current-balance direct-current ground-fault relaying using a saturable transformer.

With the saturable-reactor system, a voltage-sensitive ac relay is placed in series with the winding of a reactor, which encircles the positive and negative outgoing conductors. The relay and reactor are excited by a 60-Hz control voltage. Under normal conditions, the current through the positive conductor equals that through the negative conductor, and magnetic fields about both conductors tend to cancel each other. Thus, the reactor winding exhibits maximum impedance and prohibits the ground-fault relay from operating. However, when a ground fault occurs, the currents in the positive and negative conductors become unequal in magnitude, since current flows in the grounding conductor. The magnetic fields about each power conductor are no longer equal, and the resultant magnetic field causes the reactor core to saturate. This in turn reduces the impedance of its winding, causing the ac control voltage to be impressed across the relay. Typical relay pickup is from 4 to 6 A of ground-fault current.

The saturable-transformer system operates on the same concept. Here, the ac control voltage excites the primary of the two-winding torodial transformer. The transformer secondary is connected to a rectifier bridge that has its output feeding an adjustable resistor in series with a dc relay. Under normal operation, alternating current is induced in the transformer secondary, and the rectified direct current causes the relay to pick up its contacts. During a ground-fault, the core again saturates but, in this case, the saturation stops transformer action. In turn, the direct current is removed from the relay, and it resets its contacts to cause circuit-breaker tripping. The resistor enables adjustment of the pickup setting.

In addition to providing sensitive relaying for dc ground faults, another advantage is available as either technique only senses dc unbalance in the conductors passing through the core. By using a detection system for each outgoing dc circuit, each relay system is only sensitive to ground faults existing downstream from its reactor or transformer. Thus, selective dc ground-fault relaying can be realized, an advantage not available with the neutral-shift system.

Body-Current Analysis

Direct-current systems can be lumped into two categories for analyzing body currents under electric-shock conditions. The first category consists of the grounding-conductor and the diode-grounded systems, in which maximum ground-fault current is solely limited by the inherent resistance of each system. The neutral-shift and the differential-current systems comprise the second category, since their maximum ground-fault current is limited by grounding resistors. Both categories will be analyzed for the worst-case condition of direct body contact between an energized conductor and ground.

No Ground-Fault Current Limit. With the grounding-conductor and the diode-grounded systems, no intentional limit is imposed on the ground-fault current. Instead, the fault current is only limited by the resistance of the fault, and the impedance of the cables and the rectifier transformer. Therefore, if a person's body completes a circuit between an energized conductor and ground, the full nominal voltage of the system (most commonly 300 V dc) is impressed across the body since the system impedance is negligible when compared with the body resistance.

For the basic grounding-conductor and diode-grounded system, the simple circuit of Figure 33 can be used for adequately predicting body currents for varying body resistances. Curve 1 of Figure 34 shows the body current plotted as a function of body resistance. Dalziel [1,6] reports that fibrillation occurs at a dc body current of 500 mA for a shock duration of three seconds. This fibrillation level is shown by the dashed line in Figure 34. The dashed line intersects Curve 1 at a body resistance of 600 Ω, which indicates that fibrillation can occur whenever the body resistance is less than 600 Ω.

Ground-Fault Current Limit. The two most apparent means of reducing electric hazards on direct-current systems are:

1. reduce the line-to-ground voltage, and
2. limit the maximum ground-fault current.

Both the differential-current and the neutral-shift systems utilize these two techniques.

The power supply for a differential-current system consists of a three-phase full-wave bridge rectifier, which is fed by the wye-connected secondary of the power transformer, as shown in Figure 35a. The neutral point of the transformer is tied to earth through a grounding resistor. This method of grounding reduces the open-circuit dc line-to-ground voltage to one-half the dc line-to-line voltage. At the same time, the neutral grounding resistor limits the maximum ground-fault current. The ohmic value of the neutral grounding resistor is determined by:

$$R_G = \frac{V/2}{I_{G-F}} \tag{23}$$

where:

V = dc line-to-line voltage
I_{G-F} = maximum ground-fault current desired.

As an example, for a maximum ground-fault current of 25 A on a 300 Vdc system, the ohmic value of the grounding resistor would be 6 Ω.

The worst-case shock condition exists when a person directly contacts an energized conductor (either positive or negative) and completes the circuit to ground, as shown in Figure 35a. For this condition, the rectifier acts as a half-wave bridge rectifier (Figure 35b), and the dc voltage between the neutral point of the transformer and the contacted conductor is one-half the dc line-to-line voltage. This results in the equivalent circuit of Figure 35c, which is used to obtain curves 2 through 5 in Figure 16.

The curves show the body current as a function of body resistance for the indicated ground-fault-current limits. Curve 2 represents the maximum ground-fault-current limit of 25 A; however, the 15-A system is the most common (very little difference would occur if the 15-A system were plotted).

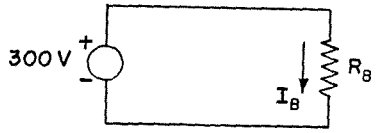


Figure 33. Equivalent circuit of a shock hazard for a basic-grounding-conductor or diode-grounded system.

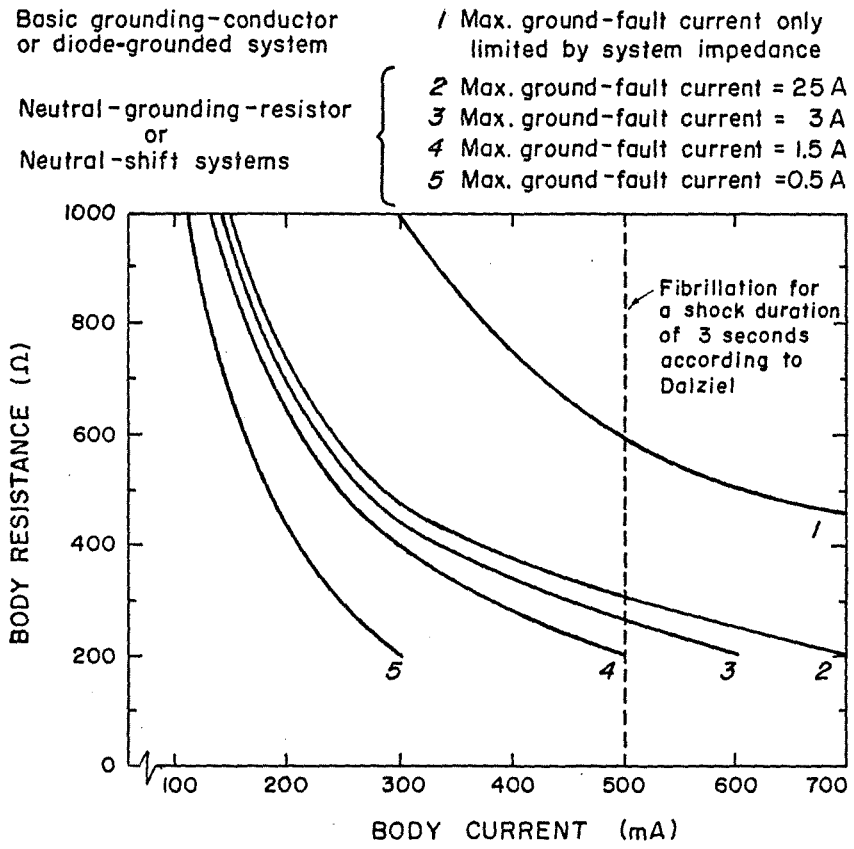


Figure 34. Body current as a function of body resistance for 300-V dc systems.

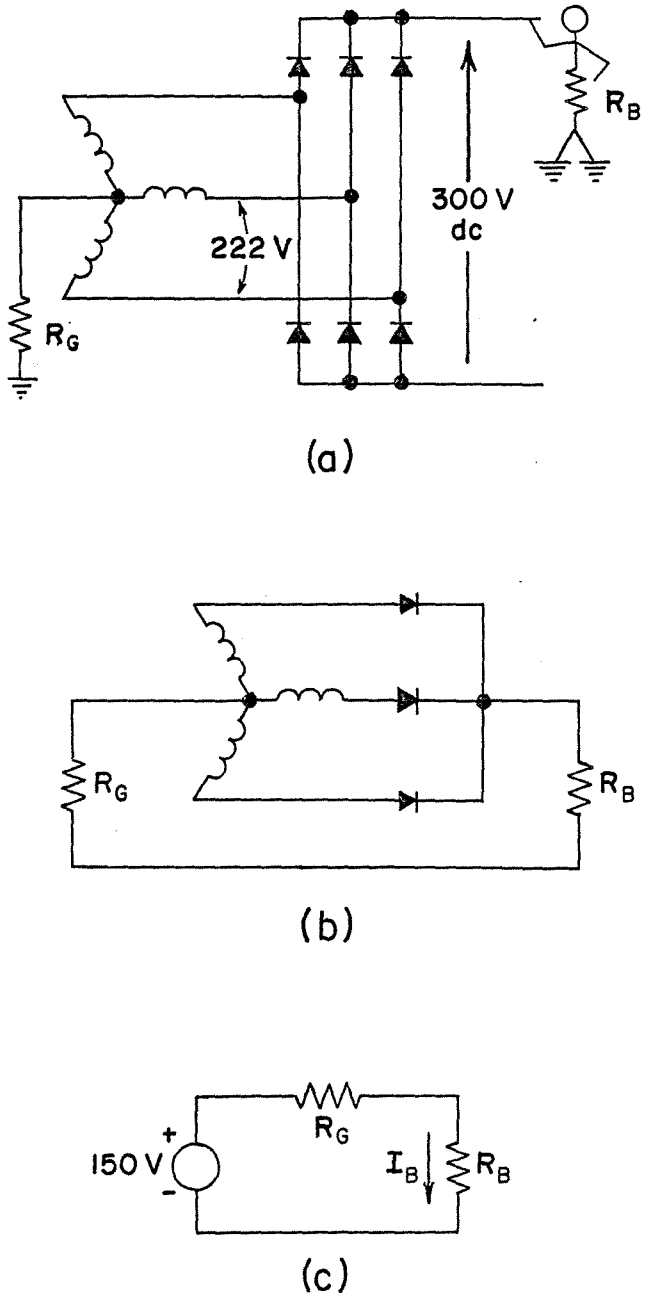


Figure 35. Shock hazard and equivalent circuits for a differential-current system.

The electrical-safety benefits of the differential-current system are immediately obvious if Curve 2 is compared with Curve 1. The large reduction in body current can be totally attributed to the reduction of the line-to-ground voltage from 300 to 150 Vdc. For the 25-A system, the 6-Ω neutral-grounding resistor has a negligible effect on reducing body current. However, increasing the ohmic value of the neutral-grounding resistor can significantly reduce body current, as illustrated in Curves 3 through 5. Curve 4 shows a system which limits the maximum ground-fault current to 1500 mA. For this case, a body resistance of less than 200 Ω (which is unlikely) is necessary to cause ventricular fibrillation according to the findings of Dalziel.

With the neutral-shift system, a neutral point is derived by placing two grounding resistors in series between the positive and negative conductors at the output of a three-phase full-wave bridge rectifier, as shown in Figure 36a. Like the differential-current system, this method also reduces the open-circuit dc line-to-ground voltage to one-half the dc line-to-line voltage. The grounding resistors (R_G) also limit the maximum ground-fault current. The ohmic value of each grounding resistor is determined by:

$$R_G = \frac{V}{I_{G-F}}$$

where:

V = d-c line-to-line voltage

I_{G-F} = maximum ground-fault current desired.

As an example, to obtain a maximum ground-fault current of 25 A on a 300-Vdc system, each grounding resistor would be sized at 12 Ω.

The worst-case shock condition results in the equivalent circuit of Figure 36b. An analysis of this circuit produced exactly the same curves as 2 through 5 of Figure 34.

In summary, the differential-current and neutral-shift systems provide the best protection from electrocution for dc systems. On the basis of Figure 34, the optimum limit for the maximum ground-fault current appears to be 1500 mA (curve 4), and the pick-up of the ground-fault relay should be set in the range of 300 to 400 mA. According to Dalziel's fibrillation predictions, such a system would statistically eliminate direct-current electrocutions.

Summary

The advantages and disadvantages of the various dc systems have been discussed and analyzed. From an electrical-safety standpoint, the neutral-shift and differential-current systems afford the best protection. Their two most apparent means of reducing electrical hazards are:

1. the line-to-ground voltage is reduced to one-half the line-to-line voltage, and

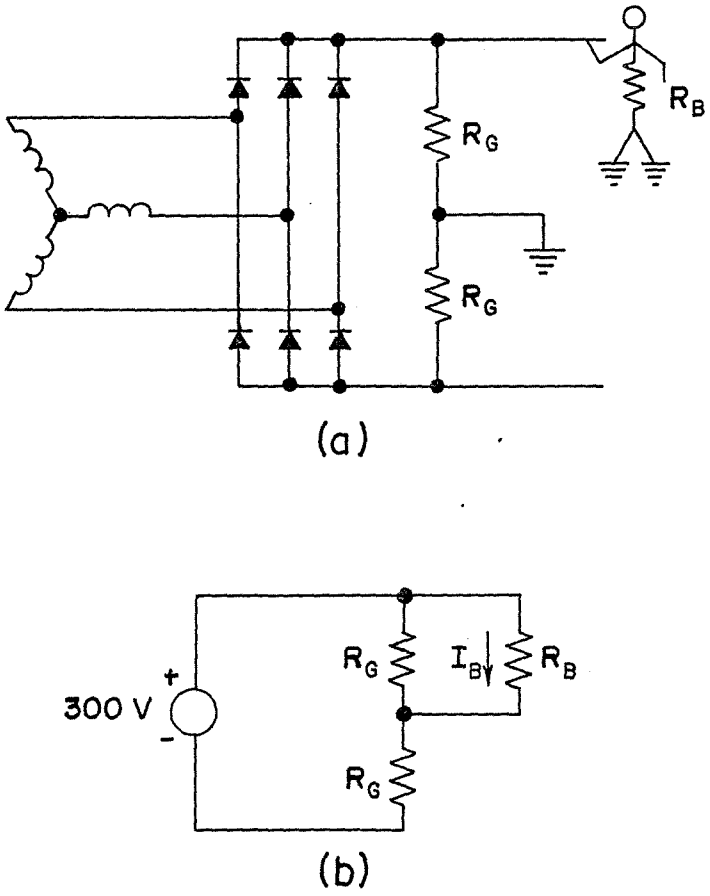


Figure 36. Shock hazard and equivalent circuit for a neutral-shift system.

2. the maximum ground-fault currents are limited by neutral-grounding resistors.

Differential-current systems have a distinct advantage over neutral-shift systems since differential-current relays can be used on each outgoing machine circuit and can differentiate ground faults for each circuit. Whereas, with the neutral-shift system, a ground fault anywhere in the system will result in de-energizing all machine circuits. The neutral-shift system also wastes power through deriving the neutral point with resistors.

The analysis of body currents for the various systems reveals that the optimum limit for maximum ground-fault current is in the vicinity of 1.5 A, and the pickup of ground-fault relay should be set to 300 to 400 mA. Thus, direct-current electrocution would be statistically eliminated on the basis of Dalziel's fibrillation predictions.

CHAPTER VI

RECOMMENDATIONS FOR IMPROVED ELECTRICAL SAFETY

General

As stated earlier, electric-shock prevention can be afforded to maintenance personnel by two means:

1. providing sensitive rapid-response protective relaying, and
2. minimizing exposure to energized components.

The first approach has already been discussed in Chapters III through V. The second approach deals with design modifications to future and/or existing power equipment and machines. The modifications can be simple in concept and may prove to be beneficial from a practical as well as a safety viewpoint. These modifications are discussed in this chapter.

Physical Design Modification

The primary concepts to be considered are dead-front construction, segregation of circuits on a voltage basis, color coding of cables, interlocks, and lock-out devices. These concepts may be employed separately or in combination, with the objective of avoiding inadvertent contact with energized components. While providing contact restraint, the introduced elements should facilitate or, at the least, not significantly hinder rapid trouble-shooting.

Dead-Front Trouble-Shooting Panels. It is possible to perform a large number of trouble-shooting operations without a manual approach of any kind to the vicinity of the high- or medium-voltage portions of a machine circuit. A dead-front, trouble-shooting panel can provide this type of protection. The primary purpose of the panel is to place a physical barrier between the electrician and the electric-control components of the machine. For explosion-proof applications, the hinged panel could be installed in a position slightly recessed behind the outer cover of the enclosure. Test points are installed to penetrate the surface of the hinged panel to allow important voltage measurements, without requiring the repairman to insert his hands or test probes into the actual circuit-component area. The concept nearly eliminates shock exposure to the repairman with little or no increase in overall size of the control case.

The dead-front trouble-shooting concept can be applied to almost any type of electrical-control case. A simplified unit was constructed to demonstrate the concept and is shown in Figure 37. The internal components comprise a simple, two-motor starting circuit. Since the prototype is to be used as a demonstration unit, the electrical components are housed in a portable light-weight aluminum enclosure, rather than a heavy explosion-proof box; however, the ultimate usage was kept in mind at all times. The unit is designed to simplify trouble-shooting procedures, as well as reduce the hazards of electrical shock. Figure 38 shows the dead-front panel with the outer lid of the enclosure removed. The incorporation of test points into the actual diagram of the circuit schematic is an important aspect. This feature could greatly simplify trouble-shooting techniques and possibly

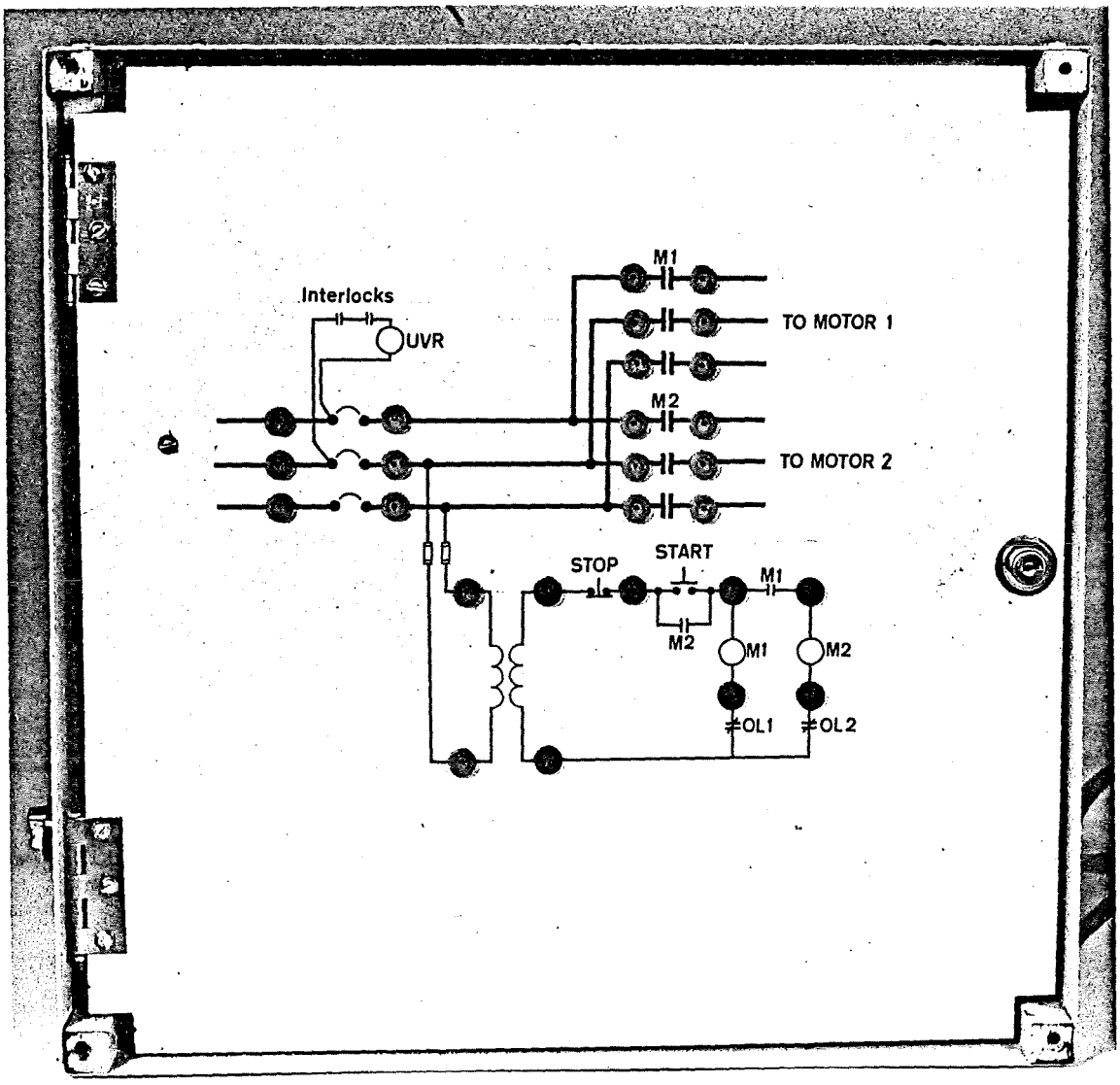


Figure 37. Dead-front trouble-shooting panel.

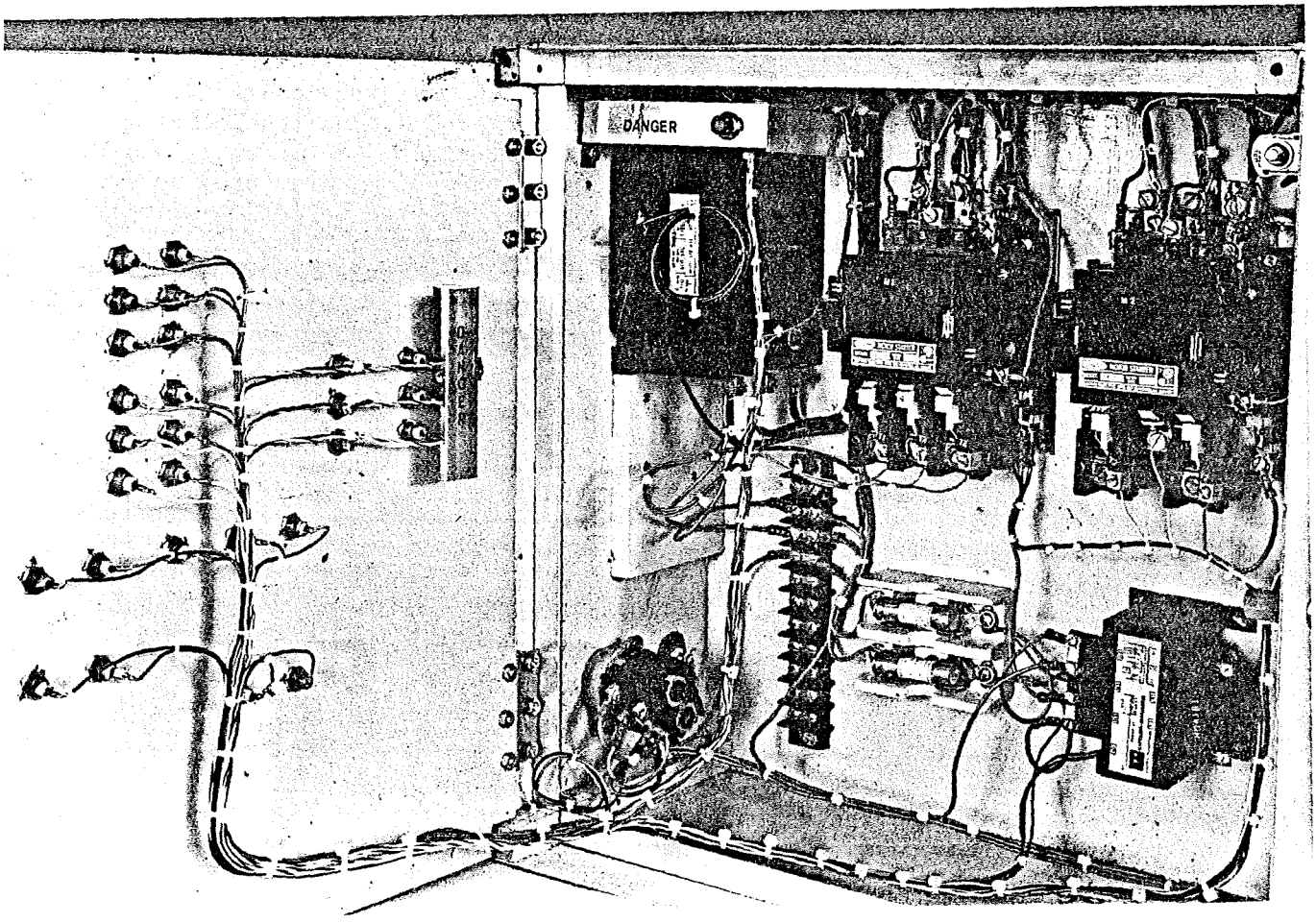


Figure 38. Dead-front panel in the open position.

reduce machine downtime. In addition, the schematic provided on the panel is more permanent than paper schematics, which deteriorate quickly in the dirty, moist environment and are susceptible to being mislaid or lost.

The hinged panel provides a complete barrier between the repairman and the electrical components. Pin jacks are used as test points, and therefore access to voltage measurements is limited to test probes, which nearly eliminates electrical-shock exposure. A key is required to gain access to the internal electrical controls. After being unlocked, the panel can be opened, as shown in Figure 38. However, opening the panel results in the operation of two interlock switches, which are in series with the undervoltage release of the circuit breaker. The opened interlock switches interrupt power to the undervoltage release and trip the circuit breaker. Thus, all internal components, with the exception of the incoming leads of the circuit breaker, are de-energized. A guard with a warning light is placed around the incoming connectors of the breaker to prevent accidental contact, should the repairman fail to de-energize the incoming line. On an actual ac machine used in coal mining, the interlock switches would usually be connected in series with the pilot circuit of the ground-check system rather than to an internal circuit breaker. Opening the panel would trip the upstream circuit breaker, located in the section power center; thus, all power to the control case would be shut off. In this application, the warning light would be retained, whether or not the internal circuit breaker was included.

Many variations of the basic dead-front concept can be applied to control centers. One possibility is to use a dead-front panel made of transparent plastic, such as polycarbonate. Since the electrical controls would be located directly behind the panel, the physical movement of line starters, relays, and contactors could be observed while voltage measurements are made at the isolated test points. With an outer cover, the plastic panel would be protected from most sources of scratching or other damage. Whether or not the transparency of an unprotected panel will be maintained under actual operating conditions depends upon the individual application and should be considered in the design.

A further refinement of the dead-front concept is to replace the test points with visual indicators, such as LEDs or lamps. For routine trouble shooting, accurate voltage measurements are not usually required, and a voltmeter is often just used as an indicator to determine if components in the circuit are energized. In effect, the built-in indicators would serve in place of a tester, and preliminary trouble-shooting could be accomplished simply by visual inspection of the panel.

Dead-Front Circuit-Breaker and Fuse Mounting. The ground-fault protection in mine-power centers relies on de-energizing the undervoltage release to trip the circuit breaker and isolate the faulted line. This leads to the frequently encountered safety hazard of blocking-in the undervoltage release. If nuisance tripping or even a ground fault occurs, some careless repairmen take short cuts just to get the machine back into operation, rather than correcting the problem. Blocking-in the undervoltage release permits the machine to operate, while rendering the ground-fault protection circuit totally inoperative. The machine will continue to operate for an indefinite period, with no indication that ground-fault protection has been lost. This hazardous practice has resulted in many electrical accidents.

The use of dead-front mounting of power-center circuit breakers is one suggestion to discourage the practice of blocking-in the under-voltage release. With this type of mounting, only the circuit-breaker handle is exposed on the outer surface of the panel. Thus, access to the undervoltage release is much more difficult, when compared with surface-mounted breakers, as shown in Figure 39. For a surface-mounted breaker, only the four screws in its cover need to be removed. Whereas, with dead-front mounting, the dead-front panel must first be unbolted from the main frame of the power center. The breaker is then unbolted from the panel, and finally, the screws in the lid of the breaker are removed. In fact, replacement of the entire modular panel might be easier than gaining access to the undervoltage release.

The testing and changing of control-circuit fuses are among the most frequent electrical-maintenance procedures for all types of equipment. Typical fuse holders have uninsulated exposed metal clips, as shown in Figure 40. A rushed repairman will frequently remove the fuses from the holder for testing without de-energizing the circuit, thus placing his hand within close proximity of the energized clips. A slight inadvertent movement of his hand could result in electrical shock. With dead-front mounting, all energized components are enclosed in an insulated housing, as also shown in Figure 40. Therefore, the fuses can be removed and replaced without exposing the repairman to the metallic clips and fuse ends.

Interlock Disable Precautions. Electrical interlock switches are presently used in the high-voltage compartments of mine-power equipment to de-energize the circuit when the exterior protective covers and side panels of the housing are removed. Their use has also been suggested for dead-front trouble-shooting panels. Interlock design should always be oriented toward prevention of its accidental reclosure. Where the interlock is a simple jump-link arrangement, the energized contacts should be female, recessed in insulating plastic. If a sensitive switch is used, the pressure to close the switch should be applied by a protrusion operating through a hole in the panel, behind which the switch is mounted. However, any safety feature can be circumvented by a determined maintenance man if it interferes with his trouble-shooting function. Since some interference by an interlock is unavoidable, the means to circumvent the device should be thought out beforehand by the designer and not left to be tampered with in a manner which permanently damages or disables the interlock. In its most desirable form, the disabling means will automatically clear once the necessity for its use is over. An example would be a latched interlock switch, arranged so that the closure of the cover results in mechanically resetting the latch. Also, a highly visible warning, which indicates that the interlock has been disabled, should be included to remind the electrician that the circuit remains energized (11).

Isolated Test Points Without Physical Barriers. For many electrical controls, the isolation of the entire circuit with a physical barrier may not be possible or desirable. However, a means of improving electrical safety for these situations is to include one or more terminal strips as test points, as shown in Figure 41. The terminal strip(s) should be located such that accidental contact with energized conductors is minimized. Each test point on a terminal strip must be numbered to correspond with a number on the circuit schematic, and all components within the case should be labeled for easy identification. The test points should also be segregated according to

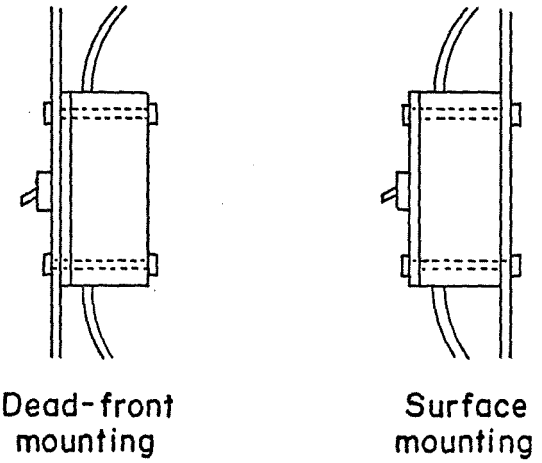


Figure 39. Mounting of circuit breakers.

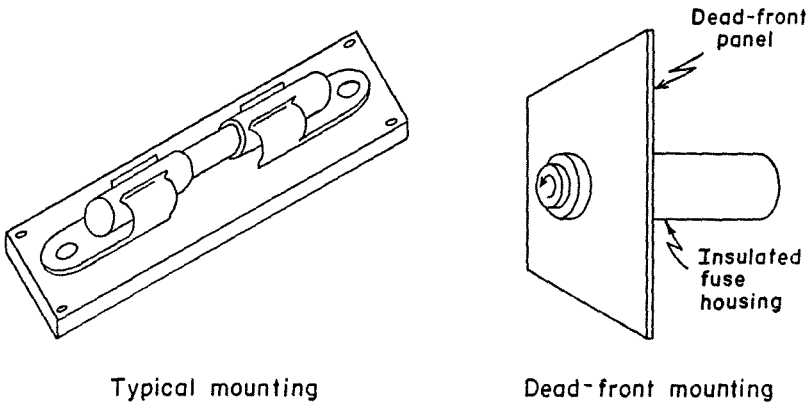


Figure 40. Fuse mountings.

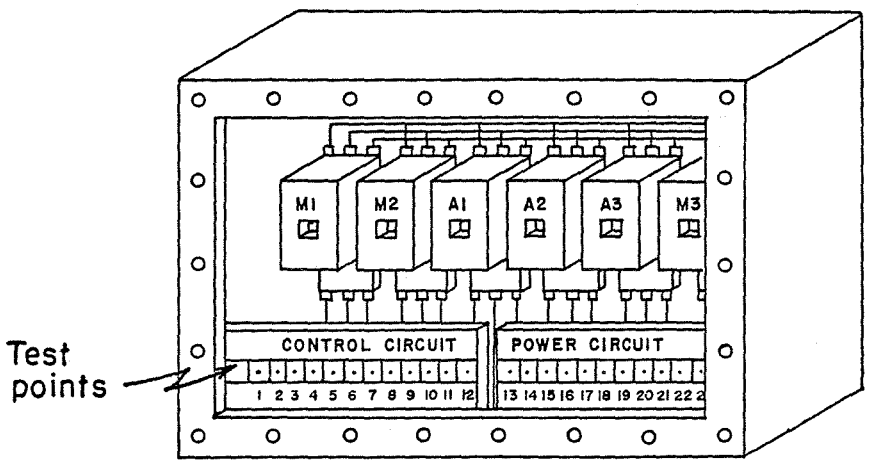


Figure 41. Explosion-proof enclosures with isolated test points.

their voltages. In other words, control-circuit test points of 120 V should be located in an area away from the power-circuit test points of 440 V, 550 V, or 950 V. The electrician would then know the voltage level with which he is dealing. The color coding of conductor insulation might also be helpful in distinguishing different voltage levels.

The main disadvantage of using isolated test points or voltage indications for trouble-shooting is that the amount of wiring is increased. The additional wiring increases as the size of the circuit increases. Figure 42 is a typical schematic of a dc shuttle car. For this particular circuit, a minimum of 29 test points, as shown, are required for trouble-shooting all components. The circuit includes one hydraulic-pump motor and two traction motors. Some shuttle cars which use electric conveyor motors, rather than hydraulic motors, would require additional test points. With very large circuits it may not be feasible to isolate all possible test points. As an example, some continuous miners have two cutter-head motors, two traction motors with solid-state controls, a hydraulic-pump motor, and a gathering-head motor. If isolated test points were to be used for this type of circuit, an analysis would have to be performed to determine which test points are the most critical. The critical test points would then be brought out to the dead-front panel or terminal strips. A maximum of 40 test points appears to be the practical limit for typical underground-mining equipment.

The above discussions primarily deal with underground machine circuitry; however, the concepts are not limited to this application. Dead-front trouble-shooting panels and isolated test points without physical barriers can also be applied to the low- and medium-voltage circuits of power-distribution equipment and electric-powered surface-mining equipment in a similar fashion.

Protective Guards for Exposed Conductors. The control cases of many ac machines primarily contain a main molded-case circuit breaker, line starters with auxiliary switches and thermal overleads, a control transformer, control-circuit fuses, and drum-type switches. More sophisticated circuitry may include an on-board power rectifier or a thyristor-controlled motor starter. Direct-current control cases usually contain contactors, mercury-switch timers and overloads, control fuses, and drum switches. (Starting resistors are usually housed in a separate enclosure for proper heat dissipation.) These devices are normally mounted in a very compact arrangement within an enclosure on the machine, while most of the metallic terminals are left uninsulated. These exposed terminals result in a potential shock hazard during routine electrical trouble-shooting.

Placing plastic guards around exposed metallic terminals could eliminate this hazard without interferring with trouble-shooting procedures, since test holes in the plastic covers can provide access for voltage measurements. The concept is illustrated in Figure 43 which shows a typical three-phase line starter. The incoming and outgoing phase conductors are connected to the line starter by screw-type connectors. The connection of the control circuit to the line-starter coil is also made in a similar fashion. Figure 43 shows the placement of an insulating plastic guard, with test holes, around all exposed metallic conductors. These guards eliminate the possibility of an electrician accidentally contacting an energized conductor on the line starter. Best results would be obtained if the guards were developed by

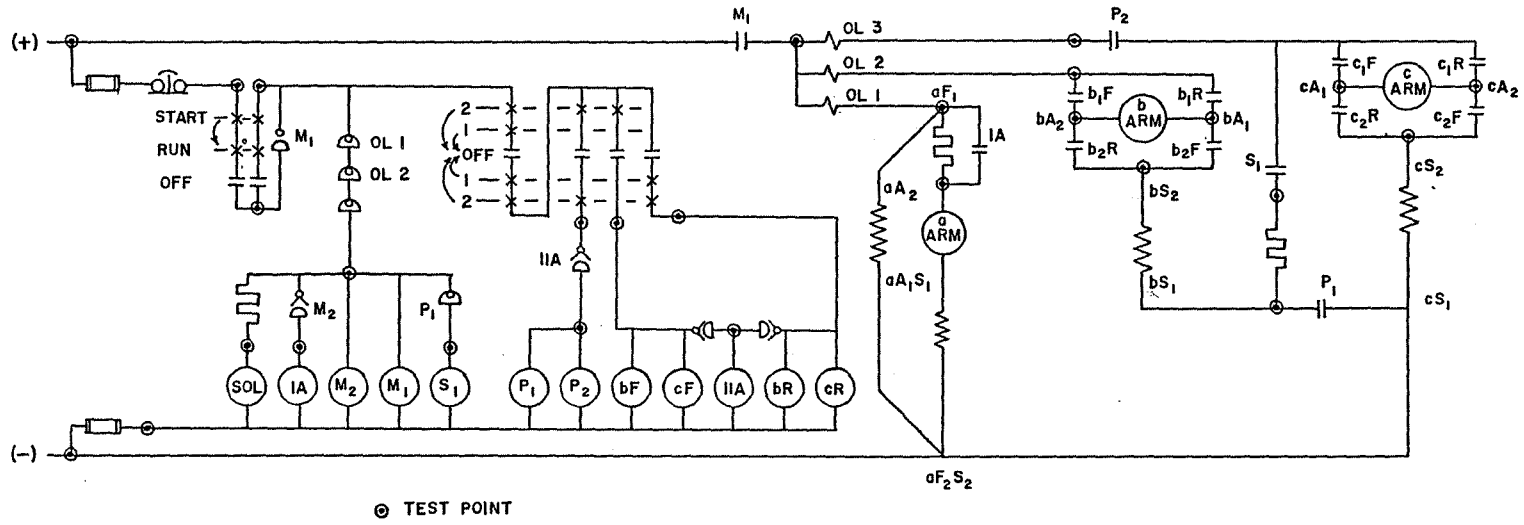


Figure 42. Shuttle-car schematic showing suggested test points for dead-front panel.

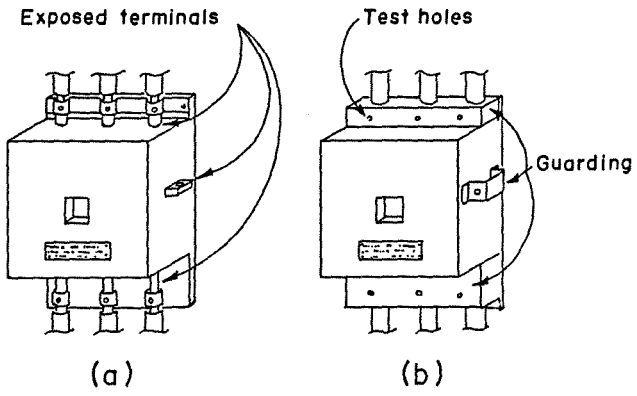


Figure 43. Guards on line starters.

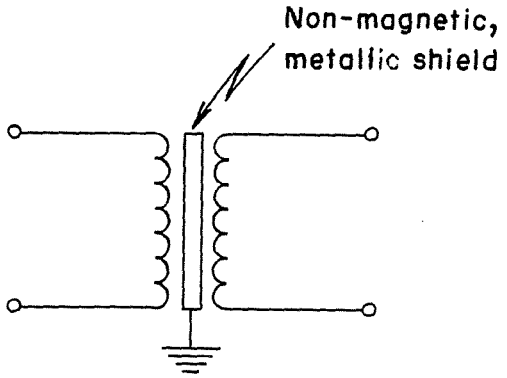


Figure 44. Shielded control transformer.

the line-starter manufacturers. Snapping-type guards, which lock into place, would provide quick access to the de-energized terminals if a conductor or the entire line starter needs replacing.

The guarding concept could be applied to almost all components within control cases, with no significant increase to their overall size. The protection afforded would be comparable to a dead-front trouble-shooting panel, since a physical barrier with accessible test points is placed between the electrician and the energized components; but no additional wiring is required.

Shielding of Control Transformers. An inter-winding fault within a control transformer can result in transferring the power-circuit voltage to the control circuit. This problem can be eliminated by constructing the transformer with a grounded-metallic non-magnetic shield between layered primary and secondary windings, as shown in Figure 44. The shield should be capable of carrying the maximum ground-fault current for the time it takes the control fuses to interrupt and isolate the fault.

Lock-Out Features

The following example illustrates a maintenance-related electrical accident that has occurred numerous times.

A repairman de-energizes the faulty circuit at the power center prior to performing repair work. While the repairman works on the faulty circuit, another worker, who is unaware of the situation or mistakes the cable of the faulty circuit for another cable, energizes the faulty circuit and thus subjects the repairman to electrical shock or electrocution.

Mine-power-center manufacturers have made available lock-out features on cable couplers to prevent the above situation. Locking-type dust covers on gear-mounted receptacles along with keyed couplers are an effective means of reducing the possibility of this hazard. With keyed couplers, the plug of each outgoing circuit is matched to fit only one receptacle. Therefore, a cable-mounted plug cannot mistakenly be connected to the wrong gear-mounted receptacle. The dust covers are hinged to the receptacle or connected by a chain to prevent their being lost while not in use. The hinged covers are preferred from a safety standpoint since their chance of being disengaged from the coupler and lost is less likely than that of the chain-connected type.

Compared with the above, locking-type dust covers for cable-mounted plugs afford better protection. Once the plug is locked, connection to any receptacle is impossible. The covers also prevent damage and dirt accumulation when the plugs are not used. Chain-connected locking-type dust covers are presently available for plugs. However, consideration should be given to the development of hinged dust covers for plugs (Figure 45), since their chance of being lost is minimal.

Another lock-out technique is to drill a hole in the spare pilot-circuit pin of the cable-mounted plug. A padlock can then be inserted in the hole by

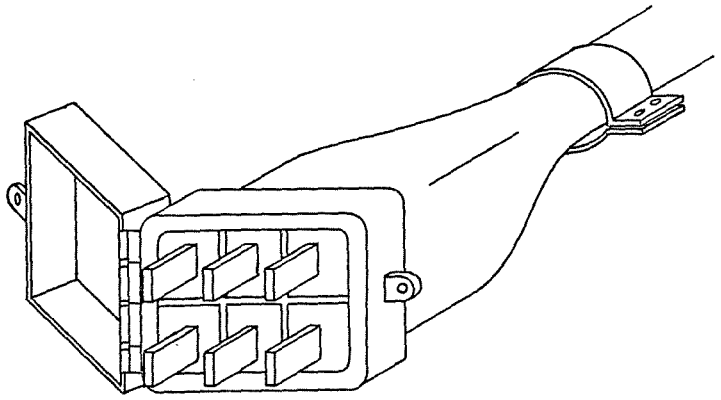


Figure 45. Cable-mounted plug with hinged lockout.

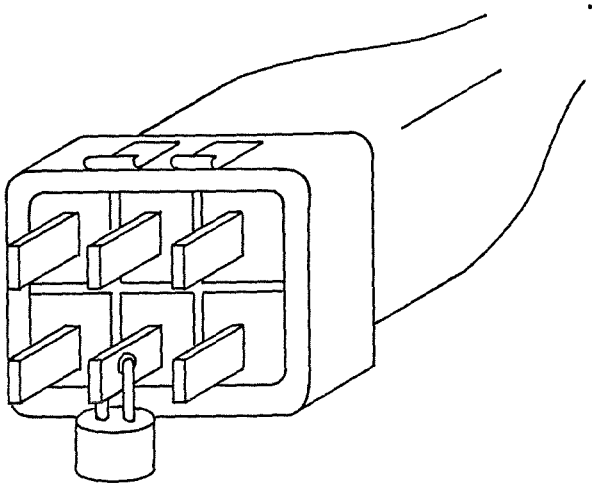


Figure 46. Cable-mounted plug with a pin drilled for lockout.

the repairman, as shown in Figure 46. The technique is extremely simple and inexpensive, but provides excellent lock-out protection by prohibiting plug-receptacle coupling.

The installation of two receptacles for each outgoing machine circuit can also provide lock-out protection, as shown in Figure 47. One receptacle would be used for powering the outgoing circuit while the other is strictly used for locking out the circuit when necessary. Actually, the lock-out receptacle would not truly be a receptacle since its housing would contain no internal contacts. This receptacle would only perform a lock-out function. The housing of the receptacle should be designed with an opening in its outer surface to provide a visual disconnect. The lock-out receptacle would also protect the plug from damage while the associated circuit is not in use.

The techniques discussed above have been totally directed toward cable lock outs. However, lock-out techniques can also be applied within ac machines as back-up protection. Toggle switches can be connected in series with the incoming pilot circuit and located in equipment control cases. During repair work, the toggle switch would be switched to the open position, thus prohibiting the upstream circuit breaker from being reset. This lock-out procedure should only be used as back-up protection, since it is dependent upon the proper operation of the ground-check system. If the under-voltage release is blocked in, opening the pilot circuit will not prevent the resetting of the circuit breaker. Therefore, only lock-out procedures which utilize a visual disconnect should be relied on for primary protection.

Cable Design

Color-Coded Cables. Although lock-out features provide an excellent means of electric-shock protection, they still cannot prevent the repairman from making the mistake of de-energizing and locking out the wrong circuit. Since cables of the various machines are often entangled, it is difficult to trace a cable back to the power center to ensure the correct circuit is de-energized. This problem easily could be eliminated by simply coding the jacket of each outgoing trailing cable with a different color. Thus, cable identification would no longer be a problem.

The concept of color coding the outer insulation jacket of cables is not new. Approximately 15 years ago, cable manufacturers recognized the safety benefits of this concept and attempted to develop cable jackets with various colors. However, neoprene, which was the sole material used for cable jackets, was not well-suited for the coloring process. The process only produced dull, washed-out colors and detrimentally affected the physical properties of the jacket. Also, the jacket changed colors when exposed to ultraviolet light. Because of these problems, the further development of color-coded cables ceased (12).

New cable-jacket material has since been developed. Cables with a Hypalon jacket can now be color coded. The rugged quality of Hypalon is well-suited for trailing-cable applications. The additional cost of this cable is only a few percent of the cost of a cable with a black neoprene jacket, but the exact increase in cost depends on the size of the cable. Hypalon and NBR/PVC cables are presently being used by a few surface-mine operators for distinguishing various voltage levels. However, NBR/PVC cables

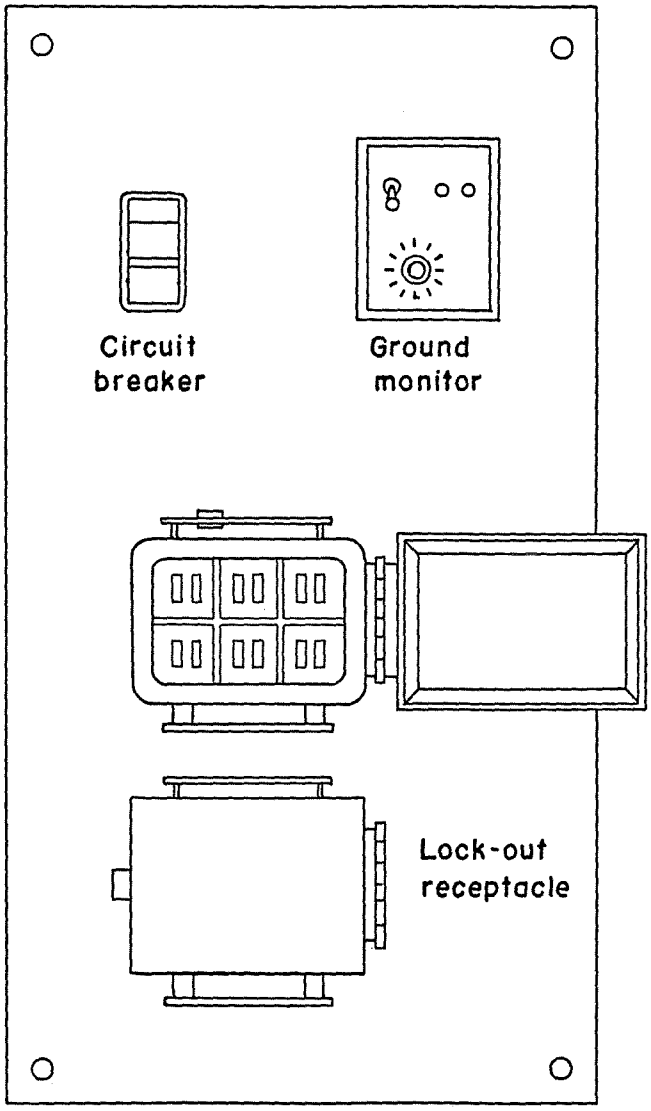


Figure 47. Lock-out receptacle.

are not recommended for cable-reel applications since heat causes the PVC to breakdown, which results in circumferential cracking.

Shielded Trailing Cables. Trailing cables which supply power to mobile mining equipment are probably the most abused components of the mine-power system. These cables are dragged along the bottom (floor) and around corners of pillars, resulting in the continuous deterioration of their insulation. Thus, workers, who are frequently required to handle the cables to facilitate the tramming of machinery, become exposed to potential shock hazards. The hazards are further increased by the wet conditions found in many mines.

The possibility of eliminating this problem may exist through the use of shielded trailing cables. Shielding provides a means for the early detection of insulation deterioration. In addition, should the insulation be intentionally violated (for example, a nail is driven into an energized cable for the purpose of tapping the power or when an electrician accidentially cuts into an energized cable while making a splice), the shielding allows for immediate detection.

The standard copper-braid shielding, which is presently used for high-voltage applications, is not well suited for trailing-cable use because of its deterioration during flexing. However, semi-con or conductive-rubber materials do provide the required flexibility. The high resistivity of these materials limit their application to very sensitive ground-fault detectors. Therefore, the use of shielded cables in conjunction with the sensitive ground-fault interrupters, suggested earlier, could greatly enhance the overall safety of the system through improved cable safety [13].

Protective Gloves

A major portion of electrical accidents in the mining industry could probably be eliminated if electricians were required to wear insulated gloves while performing all electrical maintenance and installations. This solution, however, is not always practical since gloves are often clumsy and cumbersome, particularly while trying to perform detailed wiring or trouble-shooting. Yet, insulated gloves can be an effective means of reducing the electrical hazards of handling cable, since their use does not interfere with the job. Mine operators should be encouraged to issue insulated gloves to all mine personnel, and the required use of these gloves should be incorporated into the safety policy of the company. Wearing insulated gloves should be mandatory while handling energized cables.

Even the application of thin, flexible, insulating-rubber gloves for detailed work should be investigated. The insulating strength, durability, and puncture resistance of the gloves would be the primary concerns, and preliminary testing of these qualities is suggested prior to in-mine testing.

Component Arrangement

Portable mine-power equipment, such as power centers and switchhouses, are usually constructed as a unit and housed in a single enclosure. However, this is not the case for some semi-permanent installations. Separate switch boxes, circuit breakers, and so forth are often mounted to a board in a haphazard manner with spaghetti-like wiring. These types of installations

are confusing and difficult to trouble-shoot. A little foresight with respect to component arrangement could remedy the problem. An effort should be made, whenever possible, to organize and group individual components into a single electrical unit, and separate components within the unit should be properly labeled for easy identification. An attempt should also be made to segregate circuits on the basis of their voltages.

The concept of voltage segregation can also be applied (as has been done by some power-center manufacturers) to mine-power centers, as shown in Figure 48. The power center is sectionalized into three separate compartments: high-voltage, transformer, and low- or medium-voltage compartments. Physical barriers isolate each compartment, and interlock switches are typically located around the top and side covers of the high-voltage and transformer compartments. The normally-open contacts of the switches are connected in the pilot circuit of the incoming distribution cable. With the covers in place, the interlock switches are depressed, and their associated contacts are closed, which provides a closed path for the pilot circuit. However, when the cover is removed, the switch contacts are opened, thus causing the upstream circuit breaker to trip because of the loss of continuity in the pilot circuit. The use of interlock switches is also suggested for low- and medium-voltage compartments. These interlocks can be connected in series with the undervoltage release of the main circuit breaker (if used), thus avoiding tripping at the outby switchhouse. A visual warning should be used to indicate that the conductors up to the line side of the main circuit breaker remain energized.

Component arrangement for personnel safety also applies to substations. The following is a list of recommendations.

1. Substation components should be mounted on concrete pads, and ample clearance between adjacent components should be provided to allow for easy accessibility for inspection and repair work.

2. Overhead conductors should be suspended beyond a person's normal reach to prevent accidental contact. A minimum of eight feet is suggested.

3. If circuit breakers and protective relays are located in a separate building, all components within the building should be housed in metal-clad enclosures, and rubber mats should be placed on the floor around the enclosure.

4. The fence enclosing the substation area should be no less than eight-feet high. The fence should be provided with a door or gate, which should be locked at all times, except when authorized personnel are present. The fence should extend to the ground to prevent crawling underneath and should be grounded to the station ground bed. Danger signs should be posted on all sides of the fence.

5. Two separate ground beds (a station ground bed and a ground bed for the circuit feeding the machinery) should be installed and separated by 50 feet to prevent voltages produced across the

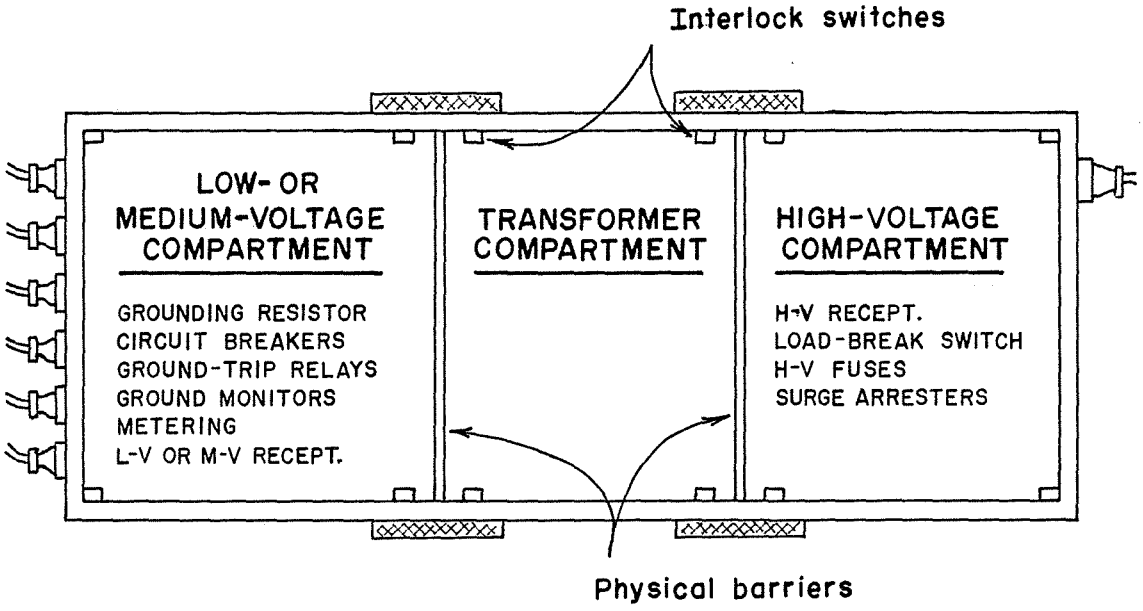


Figure 48. Separate compartments of a power center.

station bed from being transferred to the safety bed. The resistance value of the ground beds should be 5 Ω or less.

6. Protective gear, such as insulated gloves, hook sticks, and rubber mats, should always be available at the substation.

Alternating Current

The discussions and recommendations of this and the next section are directed toward the protective-relaying practices presently being used in the mining industry, but some may also apply to ground-fault relays with improved sensitivities, which were discussed earlier.

Connection of Ground-Fault Relays. Most modern ac power centers use zero-sequence relaying for ground-fault protection on each outgoing machine circuit. The normally-open contacts of the relay usually parallel the undervoltage release of its associated circuit breaker (this connection is also commonly used with direct-neutral and potential relaying). When the pick-up current of the ground-fault relay is exceeded, the contacts close and short-out the undervoltage-release coil. This technique was originally adopted to eliminate nuisance tripping due to bounce and vibration, which hampered circuits that have normally-closed contacts connected in series. One problem, however, with parallel contacts is that ground-fault protection is lost if the relay is removed from its socket. To prevent this loss of protection, power to the undervoltage release should be supplied through a jumper in the ground-fault relay case, as shown in Figure 49. With this modification, the undervoltage release circuit is opened, and the breaker cannot be closed if the relay is removed from its socket. It should be noted that improved relays now permit normally-closed contacts of the ground-fault relay to be connected in series with the under-voltage release without encountering nuisance tripping. No jumper is required with this type of connection.

Test Circuits. A major problem with present ground-fault protection schemes is that they do not operate in a fail-safe mode. In other words, if any component (i.e., current transformer, relay, or their associated wiring) fails, ground-fault protection is lost without any indication. Therefore, test circuits, which reliably verify proper operation, should be considered imperative. The test circuits should utilize primary injection into the current transformer and be permanently installed in the power center. An example of such a circuit is illustrated in Figure 50. A control transformer with a 12-V secondary is used as a current source. The 12-Ω resistor is inserted in the circuit to limit the secondary current to 1 A. The six turns around the secondary of the current transformer at 1 A produce the same effect as 6 A of ground-fault current, which corresponds to 40% of the ground-fault current for a 15-A system. Depressing the test button, therefore, simulates a ground fault at 40% of the maximum ground-fault current, and the associated circuit breaker should trip.

Visual Indication of Ground Faults. A visual indication of a ground fault should also be given at the power center. A common method is to mount a red warning light on the exterior of the power-center enclosure. The circuit is shown in Figure 51. The light-bulb voltage should be matched to

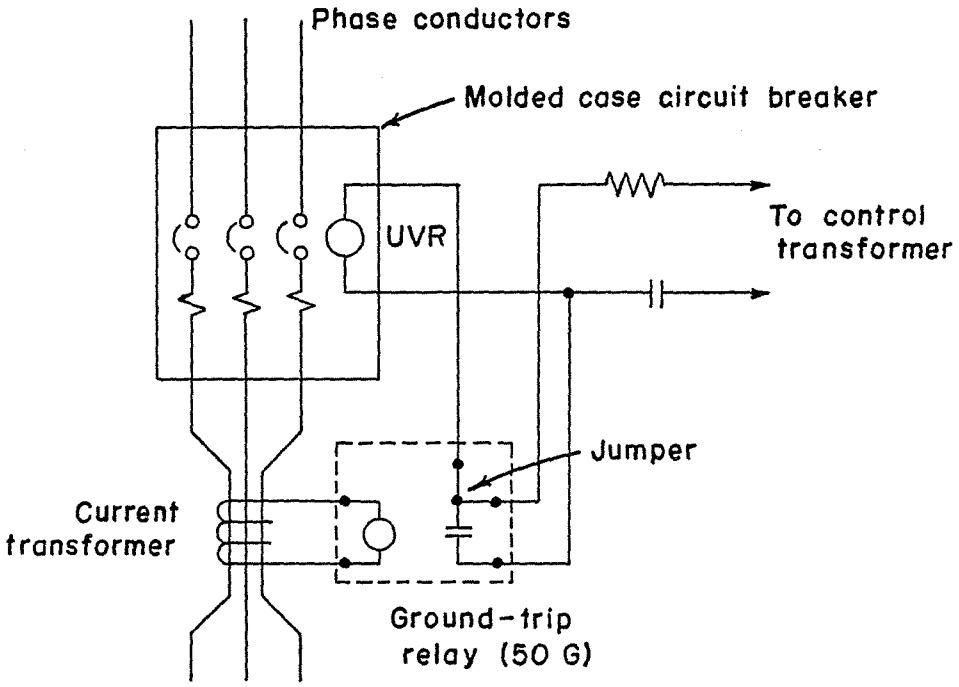


Figure 49. Zero-sequence relaying with jumper in relay case.

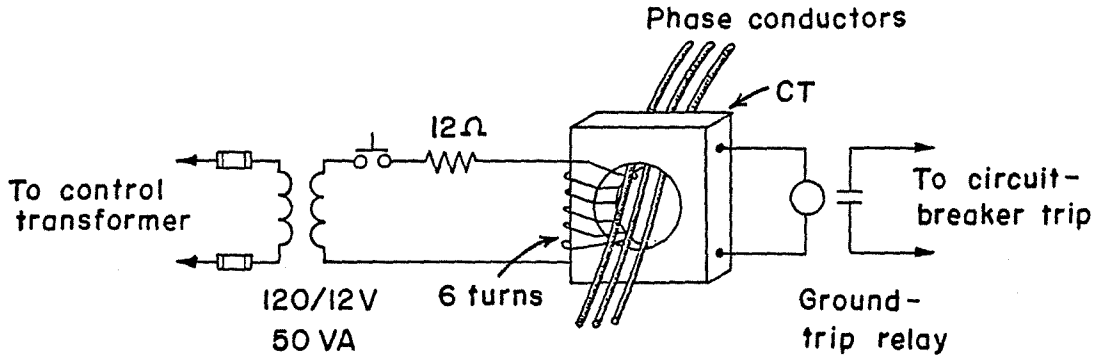


Figure 50. Typical test circuit for zero-sequence relaying.

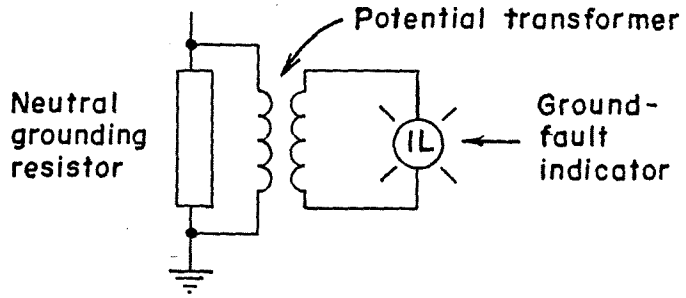


Figure 51. Ground-fault indicator.

the potential transformer to give maximum brilliance for maximum ground-fault, which is especially useful when primary ground-fault relaying is inoperative either through tampering or malfunction.

Tripping Targets. Visual indicators for each type of protective relaying for low- and medium-voltage circuits would be a valuable trouble-shooting tool. Whenever a circuit breaker trips, there is no indication of the type of protection that caused the power interruption: instantaneous, time-delayed, or ground-fault. Therefore, time must be spent in trying to pinpoint the problem. Inverse-time relays, commonly used on high-voltage circuitry, display a target to specifically indicate the type of protection that initiated tripping. The application of this concept to low- and medium-voltage circuits could reduce the time spent on trouble-shooting and the downtime of the system. For the ground-fault system, a simple relay which operates a target can be connected to the existing circuitry and mounted on the external panel of the power center. However, for instantaneous and time-delayed protection, the modifications would not be as simple, since both types of protection are normally incorporated within the tripping unit of the molded-case circuit breaker.

Neutral-Grounding-Resistor Monitoring. A potentially dangerous situation occurs if the neutral-grounding resistor fails in an open mode. Since the resistor is not monitored by the ground-check system, an open circuit can easily go undetected, effectively resulting in an ungrounded system. When using zero-sequence, direct, or residual relaying, a ground fault will not result in tripping the circuit breaker. Tripping, will occur with potential relaying, but potential relaying has the disadvantage of being rendered inoperative if the neutral-grounding resistor is shorted, which results in a solidly grounded system. Thus, a combination of a voltage- and current-sensing scheme is essential for providing protection in the event that the neutral-grounding resistor is open or short circuited and a ground fault occurs. However, even with this combined relaying scheme, no indication of an open or shorted resistor is given. An indication of either condition can be obtained through monitoring the change in resistance of the neutral-grounding resistor. Actually, monitoring the entire grounding conductor back to the neutral point of the transformer is suggested.

Direct-Current Ground-Fault Protection

The neutral-shift and differential-current (saturable-reactor and saturable-transformer) systems provide the safest methods of ground-fault protection for the following reasons.

1. Direct-contact electric-shock hazards are reduced since the line-to-ground voltage is one-half of the line-to-line voltage.

2. The frame potential of a machine under a ground-fault condition is directly proportional to the magnitude of the fault current. Therefore, reducing the ground-fault current causes the resulting frame potential to be lowered.

3. The amount of energy dissipated at the ground fault is drastically reduced. Thus, the hazards of burning and arcing, which are especially dangerous in a mining environment, are minimized.

The relaying sensitivity of both systems is also superior to the diode-grounded and grounding-conductor systems. Both systems are also well-suited to future design modifications for improved electrical safety through the further reduction of maximum ground-fault current and relay pick-up settings.

The obvious safety advantages of the neutral-shift and differential-current systems are numerous. However, the differential-current system has a distinct advantage over the neutral-shift system. The differential-current system can be applied to each outgoing machine circuit, which permits discrimination of ground faults for individual pieces of equipment. Whereas, for the neutral-shift system, if a ground-fault occurs on one machine, all circuits are interrupted.

Ground-Check Monitors. Ground-check monitors are not presently required for dc machine circuits. However, significant safety benefits can be obtained by monitoring the integrity of the grounding conductor, because ground-fault protection is rendered useless without the grounding conductor intact. The neutral-shift and the differential-current schemes, which require rectifiers as a power source, allow the application of ground-check monitors. Pilotless monitors possibly could be applied directly to systems using two-conductor type-G or Type-SHD cables, but pilot models would require a two-conductor G-GC or SHD-GC type, which needs development. Regardless, the monitors must have an ac control-voltage source, and the power-center rectifiers make the source readily available. This convenient situation is not the case when the face equipment is powered by trolley systems, and an ac source is not available.

Ground-check monitors cannot be applied to diode-grounded systems, because the grounded conductor also serves as the return conductor and an open circuit will not permit the machine to operate.

Test Circuits for Diode-Grounded Systems. Although the diode-grounded system has deficiencies in electrical safety, it is still commonly used. One main reason is that many of the old mines still use the trolley system as the means of powering dc face equipment. Furthermore the diode-grounded system is commonly used with dc powered vehicles that employ cable reels. The system permits the use of a two-conductor Type-W cable, which is less expensive and requires less space on the cable spool, as compared with a two-conductor Type-G cable that includes a grounding conductor.

Some measures can be taken to improve the effectiveness of the diode-grounded system. First of all, the sensitivity of the ground-fault relay should be increased. Although the increased sensitivity will not eliminate the existing problems of the system, it will allow for the incorporation of test circuits within the machine. Figure 52 shows a sensitive ground-fault detector (GFI) connected in the circuit of a diode-grounded machine.

A major problem with the diode-grounded system is monitoring the integrity of the grounding diode D_1. Figure 53 shows one possible circuit for testing the reverse leakage current of the diode on an intermittent

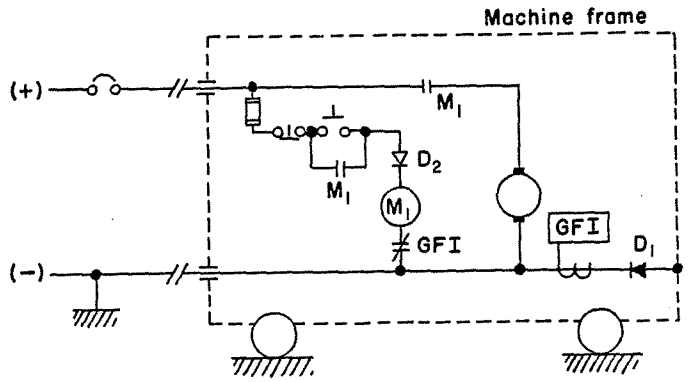


Figure 52. Diode-grounded system with ground-fault interrupter.

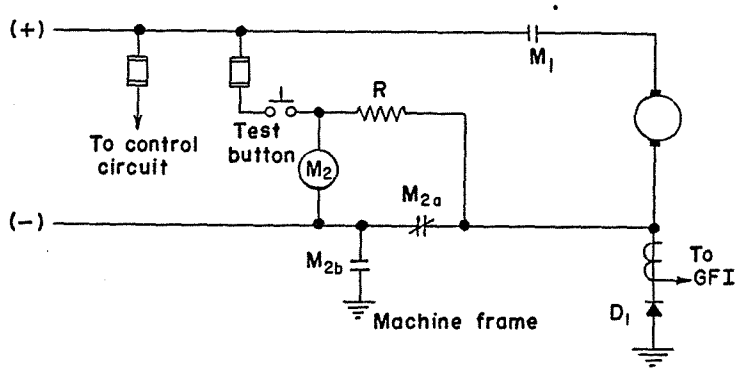


Figure 53. Test circuit for reverse leakage current through the grounding diode.

basis. Depressing the test button energizes the M_2 coil, which causes the M_{2a} contacts to open while the M_{2b} contacts close. (A mechanical interlock should be provided to ensure that one set of contacts is closed while the other is open.) At the same time, a positive voltage is applied to the cathode of the grounding diode. If the reverse leakage current exceeds the reference setting of the ground-fault detector, a visual indication would be given. The maximum normal reverse-leakage current for a grounding diode is approximately 15 mA. Mining machines may use from one to three grounding diodes (two or more in a parallel configuration); therefore, the normal leakage current may range from 15 mA to 45 mA, which is well below the suggested 500-mA dc fibrillation level.

Testing the proper operation of the diode-grounded system is also a problem. Some mine operators connect a bank of resistors (bonder) to the machine frame by means of a hand clamp. The other side of the resistance bank is connected to a fused nip. The trolley feeder is then touched with the nip, while the machine's pump motor is running. If the ground-fault system is operating properly, the motor circuit is de-energized. With sensitive ground-fault protection, smaller resistors can be used, and the test circuit could be incorporated into the machine's circuitry, as shown in Figure 54. The resistor R_1 limits the maximum allowable test current, and the amount of current can be varied by R_2. When the test button is depressed, test current flows through the machine frame and the grounding diode, simulating a fault in the ungrounded conductor.

The proper operation of the polarity diode is another important aspect for safe operation of the diode-grounded system. One present means of testing the polarity diode is to connect the positive conductor of the trailing cable to the negative source and the negative conductor to the positive source. If the machine starts, the polarity diode has failed in a shorted mode. An easier and quicker method is to incorporate a test circuit into the circuitry of the machine, as shown in Figure 55. When the test button is depressed, coil A becomes energized and causes contacts A_1 and A_4 to open, while contacts A_2 and A_3 close. (Again, a mechanical interlock should be provided to prevent A_1, A_2, A_3, and A_4 from opening or closing all at the same time.) This procedure reverses the polarity of the voltage that is applied to the diode. If the start button is depressed while the test button is depressed, the pump motor should not start. Again, if the motor starts, the diode is shorted.

Application of the Bureau of Mines' GFI. The Bureau of Mines has funded the development of a dc ground-fault interrupter. A Hall-effect probe is used as a current sensor, and the device is designed to monitor the following functions:

(a) positive (+) current amplitude,
(b) negative (-) current amplitude,
(c) positive (+) rate of change of current (di/dt),
(d) negative (-) rate of change of current (di/dt),
(e) positive (+) deviation of current amplitude from a reference, and
(f) negative (-) deviation of current amplitude from a reference.

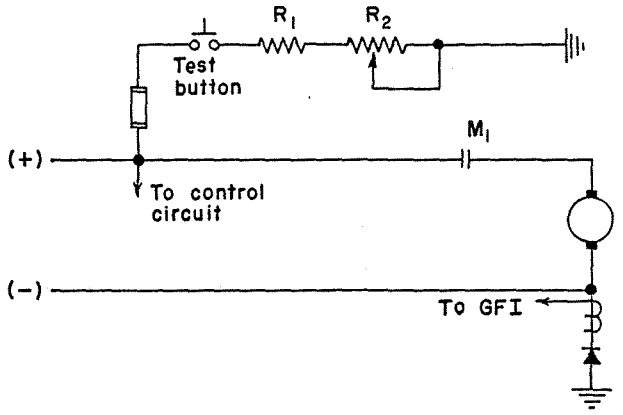


Figure 54. Circuit for testing the proper operation of the diode-grounded system.

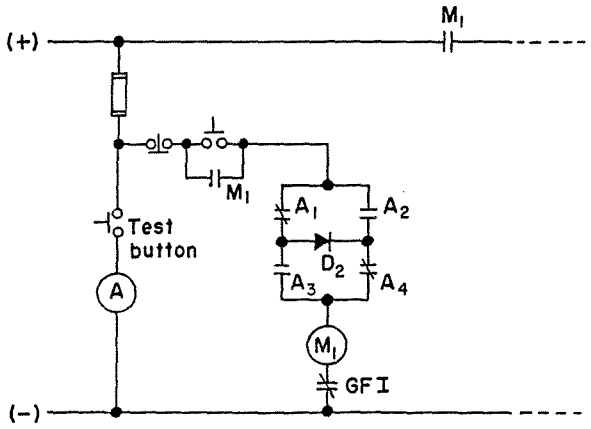


Figure 55. Circuit for testing the polarity diode.

The GFI was supplied to contract personnel to determine its applicability to mining. An analysis of the device reveals that the majority of its functions is unnecessary. Current amplitude alone is usually sufficient for shock-prevention techniques; however, some of the additional functions may prove to be beneficial for applications with the diode-grounded system.

The GFI could be connected as shown in Figure 52. Function (a) (+ current amplitude) could be used to monitor fault current through the grounding diode. Since this function operates within a range of 0 to 2.5 A, the sensitivity of the diode-grounded system could be greatly enhanced.

Function (c) (+ di/dt) could possibly be used to distinguish fault currents from induced currents flowing through the grounding diode. However, future research would be required to establish a difference in the rise times of fault currents, as compared with induced currents. If a difference could be established, improvement in sensitivity, without sacrificing selectivity, may be realized if function (a) works in conjunction with function (c), rather than independently. Function (a) should be "anded" with function (c) to provide sensitive and discriminative protection. A second (+) amplitude function, which is set at a higher trip level with a time delay, should also be provided as a means of back-up protection, as shown in Figure 56. The suggested connection of Figure 56 can be accomplished by the simple relay logic of Figure 57.

With the diode-grounded system, the reverse leakage current of the grounding diode cannot be easily monitored on a continuous basis, since the frame of the machine is usually insulated from earth by rubber tires. However, the frame does contact the earth ground periodically. During these intermittent period, function (f) (- deviation from a reference) may be used to monitor the integrity of the diode. As stated earlier, the maximum allowable reverse leakage current for a grounding diode is approximately 15 mA. Since mining machines may use from one to three grounding diodes, the maximum allowable leakage current may range from 15 mA to 45 mA. The reference for the deviation function can be set at the appropriate leakage current. Thus, a deviation from this reference can be set to trip at a designated level. Function (b) (- current amplitude) could serve as back-up protection for function (f).

Although this sensitive ground-fault interrupter might improve the characteristics of the diode-grounded system, it cannot eliminate the system's deficiencies, which were mentioned earlier. Personnel protection is best accomplished by using a separate grounding conductor with sensitive ground-fault relaying at the power center.

Example of a Power Center with Incorporated Safety Features

Figure 58 illustrates the application of some of the suggested safety features in a mine-power center. The incoming power is supplied to the power center via the high-voltage cable coupler. The receptacle (typically with female contacts) is cable mounted, while the plug (male contacts) is gear mounted. Although the conductor pins are recessed in the coupler housing, dust caps should be provided to protect the contacts and to act as a lockout when disengaged.

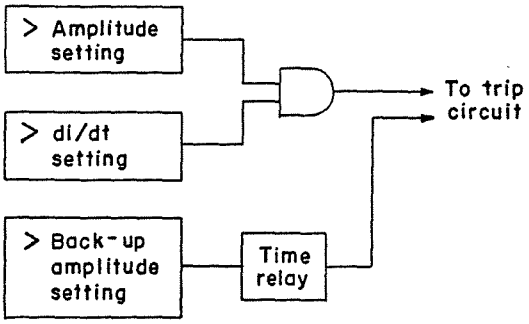


Figure 56. Discriminating ground-fault protection.

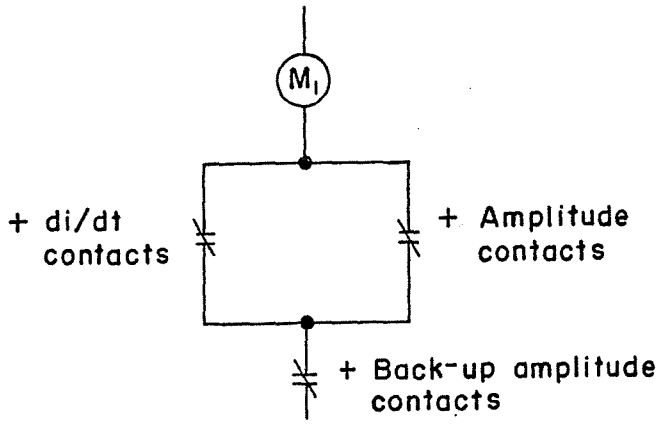


Figure 57. Relay connection for Figure 56.

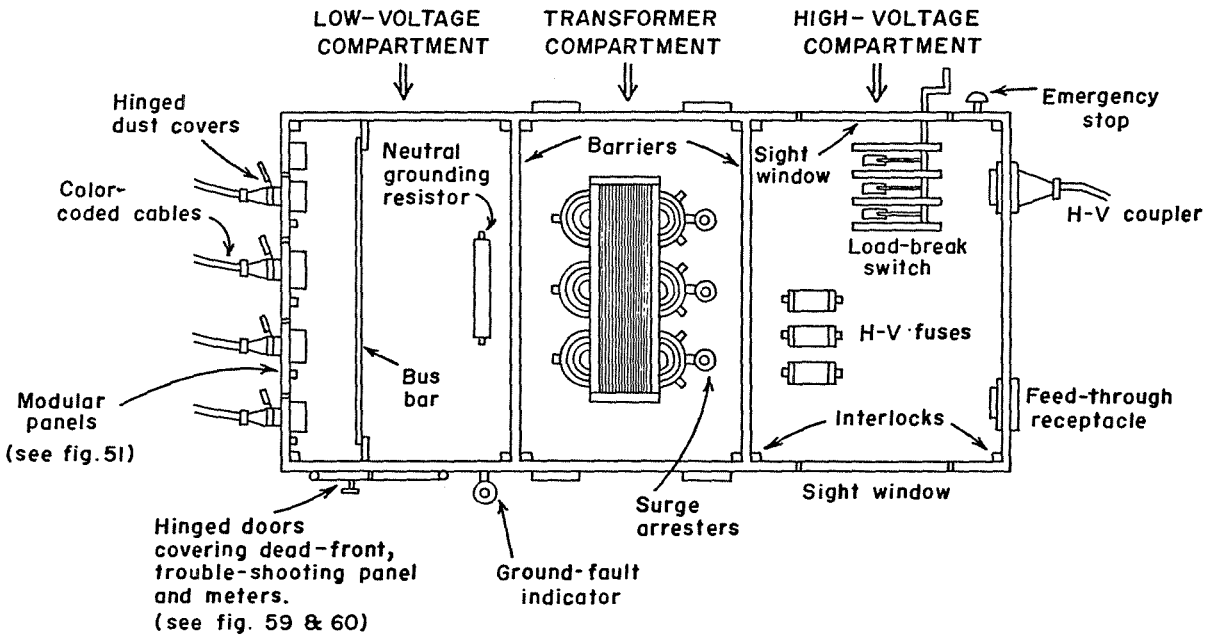


Figure 58. Top view of power center with incorporated safety features.

When being disconnected, the coupler is designed such that the pilot contact is broken first, the phase conductors second, and the grounding conductor last. (This sequence is required by federal regulations for coal mines.) The pilot circuit should be interlocked with the upstream high-voltage circuit breaker which protects the incoming line. If the incoming circuit is energized, the power will be tripped by the associated ground-check monitor, prior to breaking the phase contacts of the coupler. Having the ground conductor break last ensures that the frame is tied to the high-voltage ground whenever the power center is energized.

A feed-through receptacle, as shown in Figure 58, permits the continuation of distribution power through the power center to other high-voltage loads. The feed-through receptacle contacts should be female. If the receptacle is not being used, a dust cap should be provided. The cap must short the pilot contact to the grounding contact to provide a closed path for the ground-check monitor of the upstream circuit breaker. Therefore, if the cap is removed, the upstream breaker will trip, and the breaker cannot be reset unless the cap is in place.

Interlock switches should be strategically located around the top and side covers of each compartment of the transformer. The normally-open contacts of the switches in the high-voltage and transformer compartments should be connected in series with the pilot circuit of the incoming distribution cable, while the interlock switches in the low-voltage compartment can be connected in series with the undervoltage release of the power-center main circuit breaker. Since the incoming leads of the main circuit breaker will remain energized after tripping, a warning light should be used to indicate this situation.

An emergency-stop button, which functions similarly to the pilot-circuit interlocks, should also be provided. If the stop button is depressed, its contacts are opened, opening the incoming pilot circuit, and thus tripping the upstream circuit breaker. The switch should not automatically reset to the normally-closed position after being depressed; instead, manual resetting of the switch should be required. Therefore, the switch can serve a back-up lock-out function.

Surge arresters are usually mounted in the high-voltage compartment of the power center; however, Figure 58 shows the arresters mounted in the transformer compartment. The physical location of surge arresters is important for effective operation. The two critical aspects are the conductor lengths (from the arrester to the phase conductor and to the power-center frame ground) and the distance between the arrester and the transformer. To maximize the effectiveness of arrester performance, the arrester leads should be as short and straight as possible, and the arresters should be as close to the transformer terminals as possible. Thus, mounting the arresters at the transformer's primary terminals provides the best transient-overvoltage protection.

Figure 58 also shows barriers placed on both sides of the transformer. These barriers provide voltage segregation by physically separating each compartment. Therefore, access to each compartment can only be gained by removing a cover or side panel.

The low-voltage (or medium-voltage) compartment houses the neutral-grounding resistor, bus work, circuit breakers, protective relaying, test circuits, and outgoing receptacles. A dead-front, trouble-shooting panel could also be located within one side panel of this compartment, as shown in Figures 59 and 60. Hinged doors provide an outer protective covering for the panel and permit easy access.

A portion of the trouble-shooting panel is illustrated in Figure 60, where the actual schematic of the low-voltage portion of the power center is incorporated. The wye-connected secondary of the power transformer is shown feeding a main circuit breaker. The neutral point of the transformer is connected to ground through the neutral-grounding resistor, which limits the ground-fault current. Potential relaying is used as back-up protection for ground faults. The ground-trip relay (GTR or 51G) should have a short time delay to provide tripping coordination with the zero-sequence relaying of the outgoing machine circuits. A lamp is connected across the potential transformer to provide a visual indication of a ground fault in the event that ground-fault protection is lost.

A ground-check system could possibly be connected between the transformer neutral point and the frame ground to monitor the integrity of the grounding resistor. Special attention must be given to the design of this device since the full line-to-neutral voltage can be applied to its output terminals under a ground-fault condition.

The contacts of the ground-trip relay and the low-voltage-compartment interlocks are connected in series with the undervoltage release of the main circuit breaker. Thus, if any of these contacts are opened, all power to the secondary bus is shut off. A warning light is connected across the primary of the main circuit-breaker control transformer to indicate that the incoming leads of the main circuit breaker remain energized even though the breaker is tripped.

Figure 60 also shows the portion of the dead-front, trouble-shooting panel for a single machine circuit. The circuit components and their arrangement are very similar to the main circuit, except that zero-sequence relaying is used for ground-fault protection. A test circuit using primary injection of the current transformer is also included with the ground-fault protection scheme.

The modular arrangement of each outgoing machine circuit is illustrated in Figure 61. Each modular panel consists of a dead-front-mounted circuit breaker and control fuses, the ground-check monitor, the ground-fault protection scheme, the ground-trip test circuit, and the cable receptacle with locking dust cover. Color-coded trailing cables and plugs with locking dust covers should also be used.

The above example illustrates the application of some of the suggested shock-prevention techniques to a mine-power center. Many of the techniques are not limited to power-center applications and can be applied to various types of power-system equipment and mining machinery. If a few of these techniques are tried, it is hoped that other new approaches to personnel protection will suggest themselves.

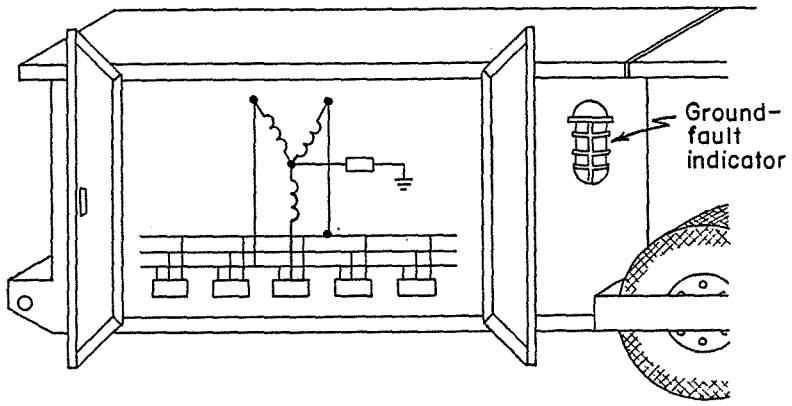


Figure 59. Dead-front, trouble-shooting panel.

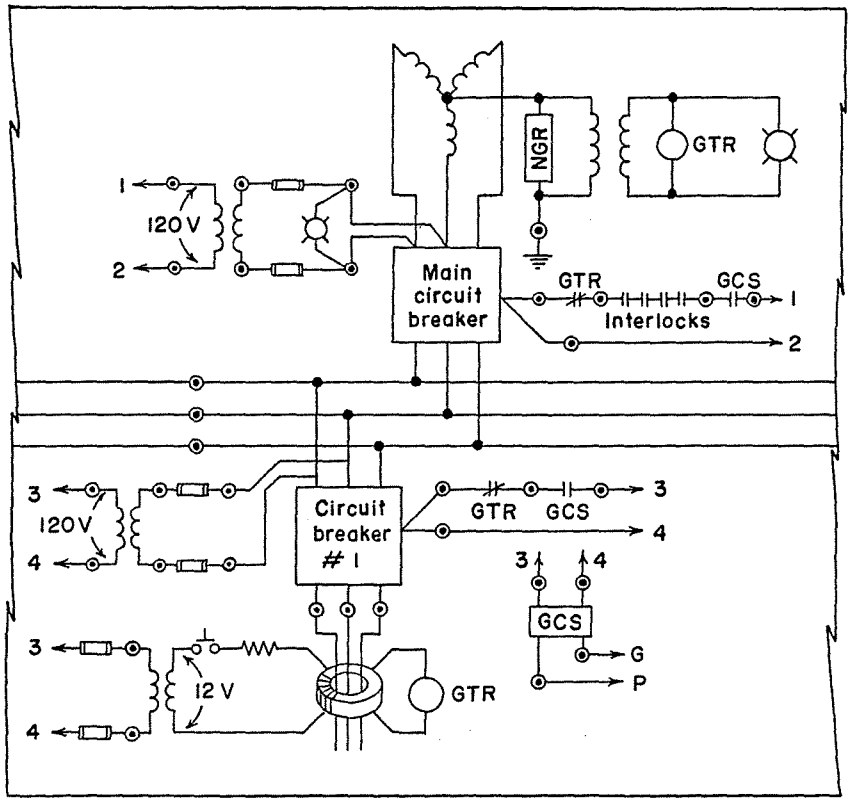


Figure 60. Portion of dead-front, trouble-shooting panel.

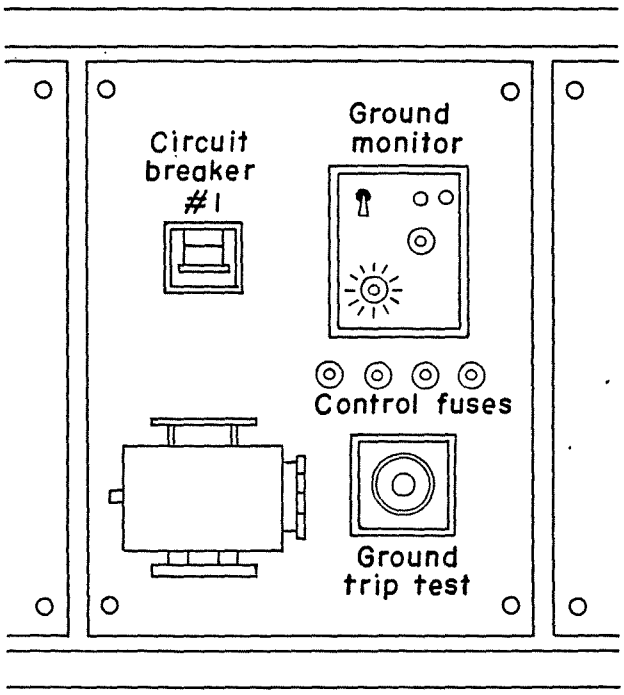


Figure 61. Modular construction for each outgoing machine circuit.

Summary

The following list is a brief summary of the recommendations generated in this report. The intent of the recommendations is to aid in the prevention of electric-shock hazards for all mine workers, and a special emphasis is placed on the protection of maintenance personnel.

Ground-Fault-Relay Characteristics to Prevent Ventricular Fibrillation.

1. The maximum ac ground-fault currents for low- and medium-voltage systems should be limited to 500 mA.

2. The operating characteristics of ac ground-fault relaying on low- and medium-voltage systems should have a maximum 50-mA pickup current with a maximum 100-ms delay.

3. The maximum dc ground-fault currents should be limited to 1.5 A.

4. The operating characteristics of dc ground-fault relaying should have a maximum 400-mA pickup current with a maximum 100-ms delay.

Alternative-Current Protection Relaying.

1. The high-resistance grounded system should be used whenever possible and mandatory when portable or mobile electrical equipment is involved.

2. Zero-sequence relaying should be used for ground-fault protection of each outgoing circuit.

3. Potential relaying should be used as back-up ground-fault protection to zero-sequence relaying.

4. The contacts of ground-fault relay should be connected in series with the undervoltage release of the circuit breaker. If the contacts are connected in parallel, a jumper should be provided in the relay case to prevent the loss of protection if the relay is removed.

5. The grounding circuit should be monitored back to the neutral point of the transformer to ensure the integrity of the grounding resistor.

6. Built-in test circuits, which utilize primary injection of the current transformer, should be installed in each ground-fault relaying circuit.

7. A back-up visual warning, which indicates that a ground fault exists on any outgoing circuit, should be given at power centers.

8. Whenever a circuit breaker trips, tripping flags should be developed to indicate which type of protection (instantaneous, time-delayed, or ground-fault) caused the tripping.

Direct-Current Protective Relaying.

1. High-resistance grounding should be used whenever possible and mandatory when portable or mobile equipment is involved.

2. Saturable-reactor or saturable-transformer relaying should be used for the protection of each outgoing machine circuit.

3. Potential relaying should be used as back-up protection.

4. Built-in test circuits, which utilize primary injection of the saturable reactor or saturable transformer, should be installed in each ground-fault relaying circuit.

5. Ground-check monitors should be used on all outgoing machine circuits. The ground circuit should also be monitored back to the neutral point of the transformer.

6. A back-up visual warning, which indicates that a ground fault exists, should be given at power centers.

7. Tripping flags should be used, as mentioned earlier in item 8 of ac protective relaying.

8. Diode-grounding of mining equipment should be eliminated. However, if diode grounding remains, the sensitivity of the ground-fault relay should be increased, and test circuits should be incorporated into the machine circuitry to check the proper operation of the system, the reverse leakage current of the grounding diode, and the integrity of the polarity diode.

Physical Design Modifications.

1. Dead-front trouble-shooting panels should be used whenever possible.

2. If dead-front trouble-shooting panels cannot be employed, consideration should be given to the use of isolated test points without a physical barrier.

3. Dead-front mountings should be used for all externally accessible components in mine power equipment, especially circuit breakers and control fuses.

4. Interlock switches should be used (particularly for high-voltage circuits) on lids and covers of electrical equipment to prevent access while the circuit is energized.

5. Plastic guards with test holes should be placed around exposed metallic terminals and conductors in control cases.

6. Control transformers should be constructed with a grounded non-magnetic metallic shield between layered primary and secondary windings to prevent interwinding faults.

Lock-Out Features.

1. Hinged, locking-type dust covers for cable-mounted plugs should be developed for trailing-cable circuits.

2. If locking-type dust covers are not used, holes should be drilled in spare connector pins of cable-mounted plugs to allow padlocks to be inserted for preventing plug/receptacle coupling.

3. A separate receptacle housing can be installed on the power center for the sole purpose of locking out a circuit.

4. A toggle switch, connected in series with the incoming pilot circuit, should be located in the control case to prevent reclosure of the circuit breaker feeding the machine.

Cables.

1. Color-coded trailing cables should be used for distinguishing the various circuits at power centers.

2. Color-coded cables can also be used for distinguishing the various voltage levels.

3. The use of semi-con shielded trailing cables, in conjunction with sensitive ground-fault interrupters, should be investigated.

Protective Apparel.

1. The wearing of insulated gloves should be mandatory while handling energized cables.

2. The application of thin, flexible, insulating-rubber gloves for detailed electrical work should be investigated.

Component Arrangement.

1. An effort should be made, whenever possible, to organize and group individual electrical components into a singly-housed unit.

2. Electrical components should be properly labeled for easy identification.

3. Circuits should be segregated on the basis of their voltage whenever possible.

Substation Considerations.

1. Substation components should be mounted on concrete pads, and ample clearance between adjacent components should be provided to allow easy accessibility for inspection and repair work.

2. Overhead conductors should be suspended beyond a person's normal reach to prevent accidental contact.

3. If circuit breakers and protective relays are located in a separate building, all components in the building should be housed in metal-clad enclosures, and insultaing (e.g., rubber) mats should be placed on the floor around the enclosures.

4. The fence enclosing the substation area should be no less than 8-ft high. The fence should be provided with a door or gate, which should be locked at all times, except when authorized personnel are present. The fence should extend to the ground, and danger signs should be posted on all sides.

5. Two separate ground beds (a station bed and a safety bed for the mine loads) should be installed 50 feet apart. The resistance of the ground bed should be 5 Ω or less.

6. Protective gear, such as insulated gloves, hook sticks, and rubber mats, should always be available at the substation.

CHAPTER VII

CONCLUSIONS

Statistics from the Mine Safety and Health Administration (MSHA) show that maintenance personnel are the primary victims of electrical accidents in the mining industry. This high incidence can be attributed to the repairman's frequent exposure to electrical hazards. Chapter II of this final-report volume commenced the discussion of these hazards, and several recommendations have been made in Chapter VI. Of these, reduced electrical exposure through the use of dead-front construction and other physical barriers between the control circuit and the trouble-shooter, in combination with test points, interlocks, and circuit lock-out features, can play a significant role in decreasing electrical accidents. Sensitive ground-fault relaying, which is capable of detecting and isolating a ground fault prior to electrocution, should also be applied to provide protection in the event that preventive measures fail. Dalziel's ventricular-fibrillation curve defines the ultimate time/current characteristic of such a relaying system. It is hoped that these suggested safety techniques serve as a starting point in a campaign to enhance electrical safety for all mine workers and particularly maintenance personnel.

Future Research and Development

Not all of the recommendations are readily available. Therefore, the following list is suggested for future research and development.

1. The research presented in Volume II of this final report should be continued to develop an ac ground-fault relay and current sensor for low- and medium-voltage systems that have the following characteristics: pick-up current at 50 mA with a maximum delay of 100 ms. The relaying system should be designed to operate with a very-high-resistance-grounded system, which limits the ground-fault current to a maximum of 500 mA (or less). Thorough laboratory tests should be performed on the device with standard cables of various configurations and with semicon-shielded cables. In-mine testing should follow if laboratory tests prove successful.

2. Following the relay and cable research performed under Bureau of Mines Contract J0199106, a dc ground-fault relay and current sensor should be developed to operate within the following characteristics: pick-up current at 300 to 400 mA with a maximum delay of 100 ms. The relaying system should be a differential-current system and a neutral-grounding resistor should limit the maximum ground-fault current to 1.5 A (or less). Again, laboratory tests should be performed on the device with standard cables and with semicon-shielded cables, followed by in-mine testing.

3. A ground-check monitor should be developed to monitor the integrity of the neutral-grounding resistor. Special care must be given to the design of this device since the full line-to-neutral voltage can be impressed across the device during a line-to-ground fault.

4. A ground-trip relay, intended for low- and medium-voltage circuits, with a tripping target should be developed to indicate which kind of protection initiated circuit-breaker interruption.

5. Circuit breakers that contain internal overcurrent sensing should be modified to include tripping targets to indicate which kind of protection (short circuit or overload) initiated circuit-breaker interruption.

6. A thorough investigation should be performed on all types of power equipment and mining machinery to determine the applicability of dead-front trouble-shooting panels and/or isolated test points. Panels should then be developed for in-mine testing.

7. Dead-front fuse holders for control fuses should be developed.

8. Plastic guards with test holes should be developed for placement around exposed metallic terminals and conductors in control cases.

9. Hinged locking-type dust covers for cable-mounted plugs should be developed for trailing-cable applications.

10. The application of thin, flexible, insulating-rubber gloves for detailed electrical work should be investigated.

REFERENCES

1. Dalziel, D. F. "Electric Shock Hazards," IEEE Spectrum, No. 2, Feb. 1972, No. 8, Aug. 1972, No. 12, Dec. 1972, No. 3, March 1973.

2. Titus, C. H., "Evaluation and Feasibility Study of Isolated Distribution Systems in Underground Coal Mines," final report on U.S. Bureau of Mines Contract No. H0111465, April 1972.

3. As reported by Bridges, J.E., "An Investigation of Low Impedance, Low Voltage Shocks," IEEE Transactions PAS, vol. PAS-100, No. 4, April 1981.

4. Jacimovic, S., "Allowable Values of Step and Touch Voltages," IEEE Preprint CH1740-0/82/0000-0095.

5. Dalziel, C. F., and F. P. Massoglia, "Let-go Currents and Voltages," AIEE, May 1956.

6. Dalziel, C. F., "Effect of Waveform on Let-go Currents," AIEE Transactions, Dec. 1943.

7. Bendersky, D., and V. W. Klein, "Electrical Practices in Metal/ Non-Metal Mines and Mills," final report on U.S. Bureau of Mines Contract J0387203, Oct. 1980.

8. Personal Communications with Merle Venters, MSHA, Denver, CO.

9. Morley, L. A., Mine Power Systems, Volumes I and II, final report on U.S. Bureau of Mines Contract No. J0155009, January 1982.

10. General Electrics System Grounding for Low-Voltage Power Systems, General Electric Corp., Industrial Sales Division, Schenectady, NY.

11. Novak, T., and G. J. Conroy, "Design Practices to Minimize the Probability of Shock During Control Box Maintenance," in U.S. Bureau of Mines IC8893, Sept. 1982.

12. Personal Communications with Mike Kopchik, Jr., Rome Cable, Rome, New York.

13. Morley, L. A., J. Tomlinson, and D. Kline, "Portable Trailing Cables, Splices, and Couplers Design and Installation Considerations," final report on U.S. Bureau of Mines Contract J0199106, Feb. 1982.

APPENDIX I

SHOCK-PREVENTION BIOGRAPHY

The following references on the subject of electrical-shock prevention were assembled by Jacimovic in reference 4.

1. Altman, K. A., "Ventricular Fibrillation," J.A.M.A., vol. 190, No. 8, 1964.

2. Armitage, A. K., J. H. Burn, and A. J. Gunning., "Ventricular Fibrillation in the Isolated Rabbit Heart," Brit. J. Pharmacol., vol. 137, 1957.

3. Beattie, E. J., J. M. Keshishian, N. B. Ames, and B. Blades, "The Electrical Resistance of the Heart," Ann. Surg., vol. 137, 1953.

4. Beck, C. S., W. H. Pritchard, H. S. Feil, "Ventricular Fibrillation of Long Duration Abolished by Electric Shock," J.A.M.A., vol. 135, 1950.

5. Berger, K., "Considerations Fondamentales a Propos de la Revision des Prescriptions Relatives a la Mise a la Terre D'installations a Haut Tension," Bull. A.S.E., May 1961.

6. Bieglemeir, G., and K. Rotter. "Elektrische Widerstande und Strome im Menschlichen Korper," Elektrotechn. u. Maschinenb., March 1971.

7. Brown, E. G., "Role of Hyperkalemia in Production of Ventricular Fibrillation Following Hipercapnia," Proc. Soc. Exp. Biol. and Med., 1955.

8. Bruner, M. R., "Hazards of Electrical Apparatus," Anesthesilogy, vol. 28, No. 2, 1967.

9. Burch, G. E., and T. Winsor, "Osnovi Elektrokardiografije," Beograd-Zagreb, 1958.

10. Burn, J. H., "The Cause of Fibrillation," Brit. Med., May 1960.

11. Carrescia, V., "Pericoli di folgorazione e misure di sicurezza inerenti all'uso di apparecchi elettromedicali che utilizzano elettrodi e cateteri itracardiaci," L'Eletrrotecnica, vol. LVIII, No. 5, 1971.

12. Cumel, P., "Etude experimentale des effets cardiaques des courants electriques, Consequences theorique et interet clinique: la genese de la fibrillation cardiaque I utilisation des stimulateur artificiels, le traitement des trouobl du rythme cardiaque," These Paris, 1965.

13. Dalziel, C. F., "Study Shock Effects on Muscular Control," Electrical World, vol. 109, March 1938.

14. Dalziel, C. F., "Danger of Electric Shock," Electrical West, vol. 80, No. 4, 1938.

15. Dalziel, C. F., "Effect of Electric Current on Man," Electric Engineering, vol. 60, Feb. 1941.

16. Dalziel, C. F., J. B. Lagen, "Practical Aspects of Electric Shock," Electrical West, vol. 86, No. 3, 1941.

17. Dalziel, C. F., J. B. Lagen, "Muscular Paralysis Caused by Electric Current," Electronics, vol. 14, No. 3, 1941.

18. Dalziel, C. F., J. R. Burch, M. Milleis, "Electric Shock Investigation," California Engineer, vol. XIX, No. 7, April 1941.

19. Dalziel, C. F., "Resuscitation After Electric Shock," Electrical West, vol. 86, No. 4, 1941.

20. Dalziel, C. F., J. B. Lagen, J. L. Thurston, "Electric Shock," AIEE Transactions, vol. 60, 1941.

21. Dalziel, C. F., "Electricity Made Safe," California Monthly, vol. KLVIII, Jan. 1941.

22. Dalziel, C. F., E. Odgen, C. E. Abbott, "Effect of Frequency on Let-go Currents," AIEE, vol. 62, Dec. 1943.

23. Dalziel, C. F., "Effect on Waveform on Let-go Currents," AIEE Transactions, vol. 62, Dec. 1943.

24. Dalziel, C. F., "Dangerous Electric Currents," AIEE Transactions, vol. 65, August/Sept. 1946.

25. Dalziel, C. F., "Controlling Electrical Hazards," Electrical Engineering, vol. 66, August 1947.

26. Dalziel, C. F., T. H. Mansfield, "Perception of Electric Current," Electrical Engineering, Sept. 1950.

27. Dalziel, C. F., "Obtaining Safety in Experimental Electrical Laboratories," Electrical Engineering, vol. 70, Feb. 1951.

28. Dalziel, C. F., "Perfezionamento nei Pronti Sccorsi al Colpiti da Corrente Elettrica," Securitas, Sept./Oct. 1952.

29. Dalziel, C. F., "A Study of the Hazards of Impulse Current," AIEE Transactions, vol. 72, Oct. 1953.

30. Dalziel, C. F., "Effetti Quantitativi Dell' Eletricita sull' Uomo," Securitas, March/April 1954.

31. Dalziel, C. F., "440 V More Deadly than 2300 V," Electrical World, vol. 141, May 1954.

32. Dalziel, C. F., "The Threshold of Perception Currents," Electrical Engineering, vol. 73, No. 7, 1954.

33. Dalziel, C. F., and F. P. Massoglia, "Let-go Currents and Voltages," AIEE Transactions, vol. 75, May 1956.

34. Dalziel C. F., "Effects of Electric Shock on Man," IRE Transactions on Medical Electronica (PGME-S), July 1956.

35. Dalziel, C. F., "Threshold 60-Cycle Fibrillating Currents," AIEE Transactions (PAS), Oct. 1960.

36. Dalziel, C. F., "Improvements in Electrical Safety," AIEE Transactions on Communications and Electronics, Part I, vol. 81, May 1962.

37. Dalziel, C. F., "Help Prevent Electrocutions," Electrical West, vol. 127, Oct. 1964.

38. Dalziel, C. F., "Electric Shock Hazards of Fresh Water Swimming Pools," IEEE Transactions on Industry and General Applications, July/August 1966.

39. Dalziel, C. F.,and R. Lee, "Reevaluation of Lethal Electric Currents," IEEE Transactions IGA-4, Sep./Oct. 1968.

40. Dalziel, C. F., "Lethal Electrick Currents," IEEE Spectrum, No. 2, 1969.

41. Dalziel, C. F., "Electric Shock Hazards," IEEE Spectrum, No. 2, 8, and 12, 1972, No. 3., 1973.

42. Dalziel, C. F., "Importance of Current as to the Sequalae," Technical report, 2nd International Colloquium on the Prevention of Occupational Rise Electricity, Koln, 1972.

43. Drinker, C. H. "The Use of Drugs in Resuscitation from Electric Shock," J.A.M.A., May-August 1945, p. 6555-656.

44. Ferris, L. P., B. G. King, P. W. Spence, and H. G. Williams, "Effect of Electric Shock on the Heart," Electrical Engineering, May 1936.

45. Francois, R. C., and J. Cabanes, "Etute des Accidents Electriques ayant Entraine le deces ou une Incapacite Permanente Partielle des Accidentes, Arch. Mal. Prof., vol. 23, March 1962.

46. Frenkel, G., "Modern Problems of Electropathology," (In Russian), Proceedings of Electrical Injury Conference, Kirgiz Academy of Sciences, 1957.

47. Frenkel, G., "Modern Problems of Electropathology," Proceedings of Electrical Injury Conference, Kirgiz Academy of Sciences, 1957.

48. Friedman, A. P., "What is the best treatment for electric shock?" J.A.M.A., vol. 175, 1961, p. 188.

49. Freiberger, H., Der elektrische Widerstand des menschlichen Korpers gegen technischen Gleich und Wechselstrom, Berlin, 1934.

50. Gilbert, T. C., "How Low is a Safe Voltage?" Electrical Review, vol. 158, No. 21, 1956.

51. Girling, F., "Vasomotor Effects of Electrical Stimulation," Amer. J. Physiol., July 1952.

52. Glazenap, M., V. Manoilav, and K. Tenter-Yu, Electrical Injury Investigation Technique (In Russian), Collection of works, "Problems of Electropathology, Electrical Injuries and Accident Prevention," Kirgiz Academy of Sciences, 1964.

53. Gobbato, F., P. Turchetto, and G. Zagarese, "La sincope cardiaca da elettrocuzione sperimentale," Minerva Medica, vol. 54, No. 82, 1963.

54. Gurvich, N., "Heart Fibrillation and Defibrillation During Electrical Injury," (In Russian), Proceedings of Electrical Injury Conference, Kirgiz Academy of Sciences, 1957.

55. Halpern, R., A. O. Weber, and M. D. Torrance, "Electrical Fibrillation of the Human Heart," J.A.M.A., vol. 175, No. 2, 1961.

56. Heppe, R. J., "Step Potentials and Body Currents near Grounds in Two-Layer Earth," IEEE Transactions (PAS), vol. 98, No. 1, 1979.

57. Hunt, H. F., "Electro-Convulsive Shock and Learning," Tranactions of the New York Academy of Sciences, No. 27, 1965.

58. Jacimovic, S. D., "Rail Step and Touch Potentials Along ac Electrified Railroad Systems," Elektroprivreda, No. 3-4, Beograd, 1966.

59. Jacimovic, S. D., "Permissible Values of Voltage and Current from a Safety Point of View in 25 kV, 50 Hz Electrified Railroad Systems," Tehnika, No. 5, Beograd., 1970.

60. Jacimovic, S. D., "Electrocution and Permissible 'Step' and 'Touch' Current and Voltage Values," Elektroprivreda, No. 1-2, Beograd., 1971.

61. Jacimovic, S. D., "Electrocution and Maximum Permissible Values of 'Step' and 'Touch' Current Voltage with Special Consideration to 25 Hz Electrified Railway Lines." Doctor of Science Thesis, Sarajevo University, Yugoslavia.

62. Jacimovic, S. D., "Permissible Values of 50 Hz 'Step' and 'Touch' Current and Voltage," paper read at SEITH Conference, Zadar, 1973.

63. Jacimovic, S. D., "Field Treatment in Case of Electric Shock," paper read at SEITH Conference, Zadar, 1973. (Later published in Zeleznice and Technika, Beograd.)

64. Jacimovic, S. D., "Importance of Electric Current Path and Distribution, and Electric Resistance of the Human Body to 'Step' and 'Touch' Voltage Values," Tehnika, No. 12, Beograd., 1974.

65. Jacimovic, S. D., "Study of Electrocution Based on Experiments with Animals," Technika, Beograd, 1974.

66. Jacimovic, S. D., "'Step and Touch' Potential Distribution in Railroad Electrified at 25 kV, 50 Hz, Single Phase," Zeleznice, No. 4, Beograd, 1974.

67. Jellinek, S., "Biologische effekte von blitz und stromschalag," Triangle, No. 3, 1957, p. 104-110.

68. Kiselev, A. P., "Threshold Values of Industrial Frequency Safe Current," (In Russian), Proceedings of MIIT, vol. 171, 1963.

69. Kiselev, A. P., L. K. Meshcheryakov, and I. D. Ravikovich, "Effect of Frequency in AC Installations on Electrical Safety," (In Russian), In collection of articles "Problems of Electropathology, Electrical Injuries and Safety," Kirgiz Academy of Sciences, 1964.

70. Kiselev, A. P., "Human Body as Element of Electrical Circuit," Proceedings of MIIT, vol. 226, 1966.

71. Knickerbocker, G. G., and W. B. Kouwenhoven, "Electrical Techniques and the Heart in Health and Disease," Electrical Engineering, Oct. 1961.

72. Knickerbocker, G. G., E. M. Becker, and W. B. Kouwenhoven, "A Portable Defibrillator," AIEE Transactions, Dec. 1963.

73. Koch, W., Erdungen in Wechselstromanlagen uber 1 kV, Berlin, 1955.

74. Kouwenhoven, W. B., and O. R. Langworthy, "Effect of Electric Shock," IEEE Transactions, vol. 49, Jan. 1930; vol. 50, Sep. 1931.

75. Kouwenhoven, W. B., and O. R. Langworthy, "What are Effects of Electric Shock?" Electrical Engineering, June 1931.

76. Kouwenhoven, W. B., and O. R. Langworthy, "Nerve Injuries From Electric Shock," Electrical Engineering, Dec. 1931.

77. Kouwenhoven, W. B., O. R. Langworthy, and D. R. Hooker, "The Current Flowing Through the Heart Under Conditions of Electric Shock," American Journal of Physiology, April 1932.

78. Kouwenhoven, W. B., and O. R. Langworthy, "Heart Injuries from Electric Shock," Electrical Engineering, April 1932.

79. Kouwenhoven, W. B., and O. R. Langworthy, "Further Research in Injuries from Electric Shock," Electrical Engineering, Oct. 1932.

80. Kouwenhoven, W. B., "Effect of Alternating Electrical Currents of the Heart," American Journal of Physiology, Feb. 1933.

81. Kouwenhoven, W. B., D. R. Hooker, and E. L. Lotz, "Electric Shock Effects of Frequency," AIEE Transactions, vol. 55, April 1936.

82. Kouwenhoven, W. B., "Electrical Accidents," Electrical Engineering, vol. 56, Sep. 1937.

83. Kouwenhoven, W. B., "Effects of Electricity on the Human Body," Electrical Engineering, March 1949.

84. Kouwenhoven, W. B., "Pole Top Method of Artificial Respiration," American Journal of Physiology, vol. 133, June 1941.

85. Kouwenhoven, W. B., and W. R. Milnor, "Electric Defibrillation," AIEE Transactions, vol. 74, March 1955.

86. Kouwenhoven, W. B., "Effects of Capacitor Discharges on the Heart," AIEE Transactions, vol. 75, 1976.

87. Kouwenhoven, W. B., W. R. Milnor, G. G. Knickerbocker, and W. R. Chestnut, "Closed Chest Defibrillation of the Heart," Surgery, No. 3, 1957.

88. Kouwenhoven, W. B., and W. R. Milnor, "Field Treatment of Electric Shock Cases," AIEE Transactions, Pt. III, vol. 76, April 1957.

89. Kouwenhoven, W. B., and W. R. Milnor, "The Effects of High Voltage, Low Voltage Capacitance Electrical Discharges in the Dogs," IRE Transactions, Professional Group on Medical Electronics, Institute of Radio Engineers - New York (PGME - II), 1958.

90. Kouwenhoven, W. B., G. G. Knickerbocker, R. W. Chestnut, W. R. Milnor, and D. J. Sass, "AC Shocks of Varying Parameters Affecting the Heart," AIEE Transactions, May 1959.

91. Kouwenhoven, W. B., G. G. Knickerbocker, W. R. Milnor, and J. R. Jude, "Field Treatment in Electric Shock Cases," Electrical Engineering, 1960.

92. Kouwenhoven, W. B., and G. G. Knickerbocker, "Closed Chest Cardiac Message," J.A.M.A., vol. 173, No. 10, July 1960.

93. Kouwenhoven, W. B., "Body Current in Live Line Working, " IEEE Transactions (PAS), April 1966.

94. Kouwenhoven, W. B., "Effects of Electric Current on the Heart," National Safety News, Nov. 1962.

95. Larcan, A., "Desordes metaboliques et electrocution," Ann. Chir. Plastique, No. 4, 1962.

96. Lee, W. R., "The Nature and Management of Electrical Accidents," Brit. J. Industr. Med., No. 19, 1961.

97. Lee, W. R., "The Nature and Management of Electric Shock," Brit. J. Anaesth., No. 36, 1964.

98. Lee, W. R., "The Mechanisms of Death from Electric Shock," Medicine Science and the Law, vol. 5, No. 1, 1965.

99. Lee, W. R., "Deaths from Electric Shock in 1962 and 1963," Brit. Med. Journal, September 1965.

100. MacKay, R. S., K. L. Mooslin, and S. L. Leeds, "The Effects of Electric Currents on the Canine Heart with Particular Reference to Ventricular Fibrillation," Ann. of Surgery, vol. 134, 1951, p. 173-185.

101. Manoilov, V. E., "Factors and Conditions Influencing Electrical Injury Consequences (In Russian). Proceedings of Electrical Safety Conference, Kirgiz Academy of Sciences, 1957.

102. Manoilov, V. E., Fundamentals of Electrical Safety, Moscow, 1966, (In Russian), 1975 (In English).

103. Merchandise, P., "Les accidents cardiovasculaires provoques par le courant electrique, Le Scalpel, No. 1, 1958.

104. Neubuerger, K. T., R. W. Whitehead, E. K. Rutledge, and F. G. Ebaugh, "Pathologic Changes in the Brains of Dogs Given Repeated Electrical Shocks," Maer. J. Med. Sc., vol. 204, 1942.

105. Osypka, P., "Messtechnische Untersuchungern uber Stromstarke Einwirkungscauer und Strom weg bei elktrischen Weschselstrom unfallen an Mensch und Tier Bedentung und Auswertung fur Starkstromanlagen, Elektromedizin, No. 3-5, 1964.

106. Paparoli, G., "Influenze dell' elettrotrauma sul processo coagulativo, Boll. Soc. Ital. di Biol. Exper., No. 31, 1955.

107. Picards, J. M., "Reanimation respiratoire et cardiovasculaire chez les electrocutes", Ann. Chir, Plast., No. 7, 1962.

108. Poznanskaya, N. B., "Ionic Permittivity of Human Skin (In Russian), Bulletin of Experimental Biology and Medicine, vol. 6, 1938.

109. Poznanskaya, N. B., "Topographical Distribution of Human Body Resistance (In Russian), Fizioterapiya, No. 1, 1940.

110. Snedecor, G. W., and W. G. Cochran, Statistical Methods, The Iowa State University Press, Ames, Iowa, U.S.A., 1967.

111. Starmer, C. F., R. E. Whalen, and H. D. McIntosh, "Hazards of Electric Shock in Cardiology," American J. of Cardiology, vol. 14, Oct. 1964.

112. Starmer, C. F., R. E. Whalen, H. D. McIntosh, "Determination of Leakage Currents in Medical Equipment," American J. of Cardiology, vol. 17, March 1966, p. 437-438.

113. Strumza, M., and D. Quivy, "Sur la coagulabilite sanquine dans e' anozie," J. Physiology, 1957.

114. Sunde, E. D., Earth Conduction Effects in Transmission Systems, New York, 1967.

115. Sverak, J. G., W. K. Dick, T. H. Dodds, and R. H. Heppe, "Safe Substation Grounding - Part I," IEEE, vol. PAS-100, No. 9, 1981.

116. Schermer, S., The Blood Morphology of Laboratory Animals, Philadelphia, 1967.

117. Schmid, R. "Medizin-ein lebenslanges studium," Arzteblatt fur Baden-Wurttemberg, No. 10, 1959.

118. Schrank, W., Schutz gegen Beruhrungsspannungen, Berlin, 1958.

119. Tanin, S. A., "Sur la coagulabilite sanquine dans l.anozie," J. Physiology, No. 49, 1957, p. 285.

120. Tomashevich. V. V., and M. T. Turkmenov, "Concerning the Changes in Blood Circulation in Consequence of Electrical Injury," Proceedings of Electrical Injury Conference, Kirgiz Academy of Sciences, 1957.

121. Vaylov, A. M., "Human Body Electrical Resistance, Proceedings of MIIZT, vol 229, 1964.

122. Weeks, A. W., and L. Alexander, "The Distribution of Electric Current in the Animal Body: An Experimental Investigation of 60 Cycle Alternating Current, J. Industriel Hygiene and Toxiology, vol. 21, Dec. 1939.

123. Weinberg, D. I., J. L. Arley, R. E. Whalen, and H. D. McIntosh, "Electrical Shock Hazards in Cardiac Catheterization," Electrical Engineering, Jan. 1963.

124. Westinghouse Electric International Co., "What you Should know About Electrical Hazards."

125. Zoll, P. M., A. J. Lininthal, and Norman Zarsky, "L. R. Ventricular Fibrillation, New England J. of Medicine, vol. 262, No. 3, Jan. 1960.

126. Zykova, K. I. Theses and reports for the Scientific Session on Fibrinolysis at the Leningrad Research Blood Transfusion Institute, June 1965.

APPENDIX II

COST ESTIMATES FOR MAINTENANCE - PERSONNEL PROTECTION RECOMMENDATIONS

The contract requires that estimates be performed on the cost impact on the mining industry if the recommendations made in this report are implemented. Because of the large number of recommendations, as well as the difficulty of accurately predicting modification costs, two tables have been prepared. Table 6 provides an estimate of the materials and labor for each recommendation and is based on 1982 dollars and the experience of project personnel. Table 7 supplements Table 6 and estimates the cost of labor and components, again based on 1982 dollars.

Table 6. Estimated materials and labor for implementing recommendations for protection of maintenance personnel.

Recommendation	Materials	Labor
(1) Dead-front trouble-shooting panel with schematic and 30 test points or indicator lights. (Note 1)	$350	3 man days
(2) Dead-front mounting of circuit breakers.	(Note 2)	(Note 2)
(3) Dead-front mounting of fuses. (Note 3)	$30.00	¼ man day
(4) Isolated test points without physical barrier. (Note 1)	4 ft of 3x3x1/8-in 30 pinjacks, identification labels 150 ft of wiring.	1 man day
(5) Locking-type dust covers for cable-mounted plugs on low- and medium-voltage trailing cables.	(Note 4)	½ man day
(6) Hole drilled in a spare pin of a cable-mounted plug for lock-out purposes.	-	¼ man day
(7) Spare lockout receptacle at power center.	1 gear-mounted receptacle housing	½ man day
(8) Lock-out toggle switch connected in series with the incoming pilot circuit and located in the machine's control case.	1-SPST toggle switch, mounting bracket, associated wiring.	¼ man day
(9) Color-coded trailing cable.	A maximum additional cost of 5% over the standard cables with black neoprene jackets.	(Note 5)
(10) Sensitive ac GFI to prevent ventricular fibrillation.	(Note 4)	1 man day
(11) Ground-fault relays with jumpers.	1 ground-fault relay and socket.	¼ man day

Table 6. (Continued)

Recommendation	Materials	Labor
(12) Semicon-shielded cables for trailing-cable applications.	500 ft. - 4/0 semicon-shielded cable or other appropriate size.	(Note 5)
(13) ac ground-fault test circuit using primary injection	1 push-button switch 120/V ac 2/A, 1 control transformer 50/VA, 2 control fuses 120/V ac, 0.2/A, 1 15-W resistor.	½ man day
(14) Ground-fault-indicator lamp.	1 shock-resistant pendant-type lamp, socket, 1 100-W bulb.	¼ man day
(15) Tripping flags on low- and medium-voltage protective relaying.	(Note 4)	½ man day
(16) Neutral-grounding-resistor monitor.	1 impedance-type ground monitor.	½ man day
(17) Guarding of exposed energized conductors and terminals.	(Note 6)	(Note 6)
(18) Ground monitors for dc equipment	1 ground monitor, 1 2-conductor trailing cable with grounding conductor and pilot (Note 4)	1 man day
(19) Sensitive dc GFI's to prevent ventricular fibrillation.	(Note 4)	1 man day
(20) Test circuit for reverse leakage current through the grounding diode for diode-grounded systems (Note 1)	1 sensitive GFI, 1 control fuse 300 V dc 1/A, 1 push-button switch 300/V dc 1/A, 1 300-V dc contactor with two sets of mechanically interlocked contacts, 1 300-W resistor.	2 man days

Table 6. (Continued)

Recommendation	Materials	Labor
(21) Circuit for testing the proper operation of the diode-grounded system.	1 dc sensitive GFI, 1 push-button switch 300/V dc 1/A, 1 300-W resistor, 1 300-W potentiometer, 1 control fuse 300/V dc, 1.2A.	1 man day
(22) Circuit for testing the polarity diode of the diode-grounded system.	1 push-button switch 300/V dc 1/A, 1 300-V dc relay with 4 sets of contacts, 3/A 300V dc.	½ man day
(23) Insulated gloves for handling trailing cables.	1 pair of insulated gloves.	-
(24) Interlock devices that will remove power from circuit when covers are removed.	1 interlock switch and mounting bracket.	½ man hr.

1. Should be done at the manufacturing or rebuild stage.
2. Should be done at the manufacturing or rebuild stage with minimal or no additional cost.
3. Price is based on the fact that such fuse holders are available. If development costs are involved, the costs are difficult to estimate.
4. Not presently available. Development costs are involved, but see Volume II of this final report on sensitive GFIs for ac.
5. Should be installed during routine cable changes; therefore, no labor costs are involved.
6. Varies greatly with individual application.

Table 7. Cost estimates for items in table 6 based on 1982 dollars.

Labor costs, typical:

Electrical engineer:	$35/hr.
Electrical supervisor:	$30/hr.
Electrician:	$12.75/hr.
Mechanic:	$12.75/hr.

Material costs:

4	ft - 3x3x1/3-in. angle iron	$ 1.00
30	- pinjacks	21.00
1	- interlock switch, catwisker	28.50
150	ft - 18-AWG 600-V stranded wire at 6¢/ft	9.00
1	- gear-mounted receptacle housing	125.00
1	- SPST toggle switch	2.00
1	- low- or medium-voltage ground-fault relay and jacket	87.00
1	- push-button switch, 120V ac 2A	2.50
1	- 50-VA control transformer	20.00
2	- 2-A fuses at 50¢/each	1.00
1	- 15-W resistor	3.00
1	- shock-resistant pendant-type lamp socket	11.50
1	- 100-W light bulb	.50
1	- ground-check monitor:	
	impedance-type	180.00
	continuity-type	575.00
1	- sensitive GFI, 100-mA 100-ms characteristic	255.00
1	- 300-V dc DPST contactor	58.00
1	- 300-W resistor	28.00
1	- insulated gloves (pair)	14.50