

U.S. DEPARTMENT OF LABOR MSHA



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USBM Contract No. H0122058

CIRCUIT BREAKER DEVELOPMENT AND APPLICATION

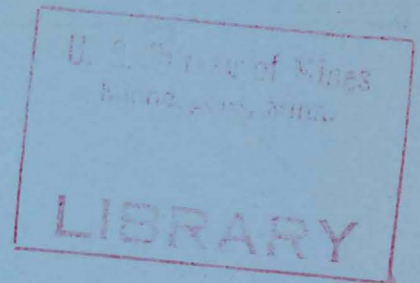
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DEPARTMENT OF THE INTERIOR
BUREAU OF MINES
WASHINGTON, D. C.

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During performance of this contract numerous discussions were held with people familiar with the coal mining industry both in and outside of Westinghouse and our thanks to them are recorded. In particular the cooperation and assistance provided by Mr. E. Litchfield and Mr. J. Murphy of the Bureau of Mines and Mr. A. Cellerini of the Westinghouse Distribution and Control Equipment Division at Beaver is gratefully acknowledged. Research technician Mr. R. Ivey was involved throughout the project and made significant contributions to the testing and fabrication of the prototype units.

FOREWARD

This report was prepared by Westinghouse Electric Corporation, Research Laboratories, Pittsburgh, Pennsylvania under U. S. Bureau of Mines Contract No. H0122058. The contract was initiated under the Coal Mine Health and Safety Research Program. It was administered under the technical direction of the Pittsburgh Mining and Safety Research Center with Mr. E. L. Litchfield acting as the technical project officer. Mr. J. A. Herickes was the contract administrator for the Bureau of Mines.

This report is a summary of the work recently completed as part of this contract during the period July 1, 1972 to June 30, 1973. This report was submitted by the authors on July 13, 1973.

This technical report has been reviewed and approved.

TABLE OF CONTENTS

SECTION 1.	PROGRAM OBJECTIVES AND RESULTS	1-1
1.1	Background.	1-1
1.2	Program Objectives.	1-2
1.3	Results	1-3
SECTION 2.	CHARACTERISTICS OF MINE DC ELECTRICAL SYSTEMS. . . .	2-1
2.1	Introduction.	2-1
2.2	Summary of Mine Electrical Systems Surveys. . .	2-1
2.3	Resistance and Inductance of Typical Mine DC Power Supplies.	2-3
2.4	Resistance and Inductance of Typical Cable Arrangements.	2-13
2.5	Complete Mine System Parameters Including Cable and Power Supplies.	2-16
2.6	Effect of Multiple Parallel Substations	2-18
2.7	Mine System Loads	2-20
2.8	Electrical System High Frequency Characteristics	2-20
2.9	High Frequency Characteristics of DC Power Supplies	2-23
SECTION 3.	DC CIRCUIT BREAKERS FOR MINE APPLICATION	3-1
3.1	Candidate Circuit Breakers.	3-1
3.2	Circuit Breaker Trip Settings for DC Operation. .	3-2
3.3	Testing Candidate Circuit Breakers.	3-5
3.4	Circuit Breaker Descriptions.	3-8
3.5	First High Power Test Series On Candidate Circuit Breakers.	3-9
3.6	Second High Power Test Series On Candidate Circuit Breakers.	3-16
3.7	Third High Power Test Series.	3-27
3.8	Endurance Tests on Selected Molded Case Circuit Breakers Satisfactory for 300 Volt and 600 Volt DC Mine Use	3-27

3.9	Molded Case Circuit Breaker Transient Current Rating.	3-38
3.10	Circuit Breaker Current Rating for Mine Application.	3-38
3.11	Circuit Breaker Shunt Trip Requirements	3-47
3.12	The Selected Circuit Breakers and Application Guidelines.	3-47
SECTION 4.	DISCRIMINATING CIRCUIT BREAKER.	4-1
4.1	Introduction	4-1
4.2	Operating Principles of Discriminating Circuit Breakers	4-2
4.3	Components of Discriminating Circuit Breaker . .	4-4
4.4	Power Circuit Breaker.	4-6
4.5	Discriminating Circuit Breaker Control Unit. . .	4-6
4.6	3 kHz Power Oscillator	4-12
4.7	AC Filters for Legitimate Loads.	4-17
SECTION 5.	SOLID STATE SWITCHES	5-1
5.1	Introduction	5-1
5.2	Solid State DC Circuit Breaker	5-1
5.3	Primary Design Considerations.	5-4
5.4	Solid-State Breaker Design Example	5-4
5.5	Expected Performance of Solid-State Breakers . .	5-9
5.6	Cost	5-11
SECTION 6.	TESTING PROTOTYPE DISCRIMINATING CIRCUIT BREAKER. . .	6-1
6.1	Circuit Breaker Enclosure.	6-1
6.2	Control Unit	6-3
SECTION 7.	REFERENCES.	7-1
APPENDIX 1.	TO DETERMINE THE EFFECT OF BREAKER TRIP SETTING AND BREAKER UNLATCHING TIME ON THE CIRCUIT BREAKER ENERGY DISSIPATION	A1-1
APPENDIX 2.	TO DETERMINE THE EFFECT OF CABLE AND LOAD IMPEDANCE ON CIRCUIT BREAKER ENERGY DISSIPATION	A2-1
APPENDIX 3.	CIRCUIT BREAKER EQUIVALENT ARC VOLTAGE.	A3-1

APPENDIX 4.	SELF-INDUCTANCE OF IRON RAILS	A4-1
APPENDIX 5.	WORST CASE CURRENT AND INDUCTANCE PARAMETERS FOR MULTIPLE PARALLEL SYSTEM.	A5-1
APPENDIX 6.	SPECIFICATIONS FOR TRANSFORMERS AND CHOKES REQUIRED FOR DISCRIMINATING CIRCUIT BREAKER.	A6-1
APPENDIX 7.	DESCRIPTION OF DISCB LOGIC CIRCUIT OPERATION. . . .	A7-1
APPENDIX 8.	ACTIVE IMPEDANCE MULTIPLIER FOR MINE GROUND FAULT DETECTOR SYSTEM	A8-1
APPENDIX 9.	CIRCUIT BREAKER MODIFICATIONS	A9-1

SECTION 1. PROGRAM OBJECTIVES AND RESULTS

1.1 Background

Direct current electrical systems are used in most coal mines primarily to power the main haulage trains and secondarily to feed other equipment and passageway lighting. Electrical power is supplied from rotary machines or static rectifier equipment and is distributed through the mine by open trolley wires and feeder cables. The rails of the haulageway are used as a current return path. This exposed power distribution system is very vulnerable to conditions which lead to undesired leakage currents and short circuits and, consequently, the possibility of fires or other hazards to personnel.

Present techniques and equipment have been utilized in so far as practical to improve the safety of the dc electrical system; however, there still appears a need for further improvement. Because of this need, this program was sponsored by the Bureau of Mines to investigate two specific technical areas related to improvement of dc electrical system safety. One area included the determination of the characteristics of mine electrical systems and their protection requirements and the verification of the adequacy of available protective devices for mine service. Despite the widespread application of industrial protective equipment in mines, there was little detailed technical information available related specifically to the performance of this equipment in service. Our task was not only to develop useful information regarding mine system protection, but also to define and verify the adequacy of the protective devices available. The second area of investigation called for development of a practical technique for detecting low level electrical fault or leakage currents. Conventional protective devices

cannot discriminate between a normal current and a fault current of comparable magnitude. The specific detailed objectives related to the preceding areas are given below.

1.2 Program Objectives

1. Define the dc electrical system parameters under which protective devices must operate in a coal mine.
2. Determine and tabulate currently available circuit breakers, preferably molded case breakers, expected to be applicable for 300 volt, 2500 ampere and 600 volt, 1200 ampere mine service.
3. Verify by test the degree of adequacy of the circuit breakers identified in (2) to perform fault current interruption at the current levels defined in (1) above.
4. Investigate possible design modifications to available breakers to improve their ability to meet required performance characteristics.
5. Investigate alternative practical methods for mine electrical system protection, specifically solid-state switches.
6. Investigate techniques for providing a discriminating control sensitive to low level fault and leakage currents.
7. Determine discriminating control system design parameters and develop the necessary circuitry and components.

8. Build a laboratory prototype of a discriminating control circuit breaker to prove design concepts and manufacturing feasibility.

1.3 Results

Mine electrical system parameters were determined using the data contained in survey reports of five different coal mines. The typical electrical characteristics of the trolley-rail distribution system were calculated and worst case conditions for fault protection were defined. Calculated system parameters were corroborated by underground measurements in a working coal mine.

Twenty possible suppliers of circuit breakers were solicited for comments on the applicability of their products to 600 volt and 300 volt dc systems. From the responses there emerged four suppliers whose circuit breakers, although not claimed to be proven for this application, were worthy of evaluation. Circuit breakers were obtained from these four manufacturers and tested to determine their adequacy for mine use. Three catalog models of molded case breakers, two manufactured by Westinghouse and one by General Electric, were determined to be adequate for mine use. One of the Westinghouse circuit breakers required a minor modification to improve the dielectric strength between poles.

High current interruption tests up to 600 volts; 17,200 amperes; 0.24 millihenrys, and 300 volts; 16,200 amperes; 0.22 millihenrys were performed. Interruption tests included wide variations in circuit inductance and fault current levels which subjected the breaker in some cases to conditions exceeding those in a mine electrical system. It was found that some of the candidate breakers were satisfactory at high currents, yet failed to pass low current, high inductance tests due to their failure to sustain a high arc voltage.

By means of endurance tests on the selected circuit breakers it was determined that failure after many operations was fairly predictable and occurred when the arc chutes had absorbed about 1300

kilojoules per pole. From this data an operating life can be predicted based on the severity of operation and number of interruptions. It was also determined that the maximum capability for energy dissipation in a single operation of the selected molded case breakers was about 75 kilojoules per pole.

From this test data a set of application guidelines has been prepared so that the user can employ the selected circuit breakers to maximum advantage. Data and procedures have been developed for calculating the normal continuous current rating based on the pulsed load requirements of typical mine operation.

The use of solid-state circuit breakers has been considered and it is concluded that the present state of development of both devices and circuitry would permit fabrication of solid-state breakers having ratings and performance compatible with the mine electrical systems. The major advantages of solid-state breakers are, freedom from wear, consistency of performance with repeated operation, complete absence of arcing, and their ability to operate more rapidly and thereby reduce the energy supplied to low impedance faults. A significant disadvantage is their relatively high cost compared to conventional breakers.

Concepts for providing a fault discriminating circuit breaker were investigated and one scheme was selected for development. In the selected approach a high frequency ac signal (3 kilohertz) is applied to the dc trolley wires and feeder cables. When an illegitimate load appears on the system, the change detected in the ac signal due to the illegitimate load is used to cause the circuit breaker to trip. High frequency measurements of mine system characteristics were made to determine the optimum frequency for the discriminating system. Laboratory tests of the detection and control circuitry indicate that illegitimate currents as low as 20 amperes may be detected. To prevent normal loads from tripping the discriminating circuit breaker, filters must be added to each load to block the high frequency signal. Passive

filter design requirements have been determined and specified. To overcome the large size (1000 pounds for a 50 ton locomotive) and high cost of passive filters, an electronic active filter concept has been proposed and will be further developed during the continuation of this contract.

A laboratory prototype of the discriminating breaker suitable for evaluation in a mine has been built and tested.

SECTION 2. CHARACTERISTICS OF MINE DC ELECTRICAL SYSTEMS

2.1 Introduction

Mine electrical systems differ widely depending upon the particular mine and it is difficult to define a general arrangement. One concludes that a typical mine system includes all manner of ac-dc converting equipment operating singly or in parallel and interconnected with a wide variety of cable sizes and steel rails.

In determining the probable requirements for dc circuit breakers, it was thought desirable to consider worst case situations, also it was found convenient to discuss separately the effects of power sources, cables, and loads.

2.2 Summary of Mine Electrical System Surveys

In order to define the working requirements of candidate dc circuit breakers that could interrupt the supplies to the feeder and trolley wires, it was necessary to determine the range of resistance and inductance variations to be expected in typical mine systems. The Bureau of Mines made available for this evaluation data from electrical survey reports of five different mines. These surveys (Ref 1) contain a general discussion of the mine power supplies and types of converting equipment at different substations. Further the numbers and types of feeder cable and trolley wires were enumerated and details of the track were given, including calculation of resistances for positive and negative conductors in the various mine workings. In these mine surveys the possible short circuit currents were calculated for single substation operation and also for normal operation with power sources in parallel. The possible bolted fault conditions were presumed to occur at ends of feeder cables or trolley wires and fault currents were calculated from the nominal system voltage and calculated resistance.

That is, the voltage regulation effect of the substation caused, for example, by armature reaction in the dc generator, or arc overlap in the mercury arc rectifiers was omitted. It was pointed out in the reports that estimated short circuit currents were probably higher than might actually occur because of the assumption of idealized zero resistance connections and zero resistance faults. Even so, some possible application difficulties were found due to the relatively low fault currents which made circuit breaker discrimination difficult in some cases.

In the calculations of short circuit currents the resistance of copper conductors was calculated from the relationship,

$$R_{\text{feeder}} = (10.58 \times \text{Distance in feet}) / (\text{Circular Mils Conductor}) \quad \text{ohms}$$

and for the rails the expression

$$R_{\text{rails}} = (\text{Distance in feet}) / (\text{Pounds per Yard of Rail} \times 1873) \quad \text{ohms}$$

Where conductors were paralleled these effects were accounted for by using suitable paralleled resistance values.

A summary of the mine survey data is given in Table 2.1 and from the surveys and the tabulated data the following conclusions were drawn concerning typical mine electrical systems.

1. A multiplicity of ac-dc conversion equipment is used in coal mines and in normal operation these different equipments may be paralleled or operated singly.
2. A typical maximum rating for a conversion unit is 500 kW. (From discussion with equipment manufacturers and mining engineers, it was found that 750 kW and 1000 kW solid-state rectifier units may also be used.)

3. A typical fault current for a 3000 kW, 600 volt system is 2300 amps and the maximum is about five times this.
4. Typical fault current for a 3500 kW, 300 volt system is 7500 amps and the maximum is about seven times this.
5. The feeder and trolley conductors are predominantly copper varying from 211.6 kcmil to 1000 kcmil. Steel rails, which may be used exclusively or in parallel with copper conductors for return currents, vary from 40-85 lbs/yard.
6. The polarity of the trolley wire may be positive or negative with respect to the rails.

2.3 Resistance and Inductance of Typical Mine DC Power Supplies

The dc supply for mine systems may be silicon rectifiers, mercury arc rectifiers, m-g sets, or synchronous converters. It is desired for purposes of system analysis to represent any of these by the equivalent circuit shown below in Figure 2.3-1.

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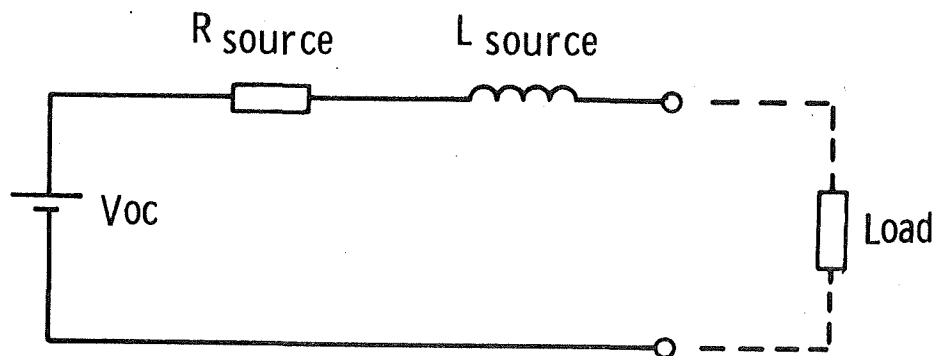


Fig. 2.3-1—Representation of mine DC power system

Table 2.2-1. Summary of data collected from survey reports

	<u>Mine No.</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>
Max dc volts		615	275	300	300	295
Synchronous Converters		6 at 400 kW 2 at 300 kW 1 at* 500, 1 at* 400 kW 1 at* 300, 1 at* 200 kW		3 at 300 kW *1 at 200 kW	4 at 300 kW	1 at 200 kW 1 at 200* kW
M.G. Sets			3 at 300 kW *1 at 300 kW *1 at 200 kW	6 at 300 kW *1 at 200 kW		1 at 300 kW *1 at 200 kW
Ignitron Rectifier or Mercury Arc Rectifier			8 at 300 kW	5 at 300 kW	2 at 500 kW	
Silicon Rectifier				2 at 500 kW	6 at 500 kW 2 at 300 kW	2 at 500 kW 1 at 200 kW 1 at 100 kW
2-4 Total kW Rated Capacity		3000	3300	5600	5800	1800
Max Feeder Distance (ft)		3960	3100	2900	3440	2880
Min Feeder Distance (ft)		50	50	40	40	60
Max Conductor Size - kcmil		500	1000	1000	1000	1000
Min Conductor Size - kcmil		211.6	211.6	211.6	300	211.6
Feeder Most Common Conductor Size - kcmil		500	500		1000	500
Trolley Most Common Conductor Size - kcmil		211.6	(211.6 & 400)		350	350
Max Calculated Fault Current (Amperes) Assuming Bolted Faults & All Plant Connected		11,784	46,774	84,286	16,296	39,706
Max Short Circuit Current From One Unit		5607	46,774	79,482		36,506
Typical Fault Current For Normal Working		2300	7900	9900		4800

* Standby Units

On the following pages are calculations of typical parameters for each type of dc source. Table 2.3-2 lists these parameters for dc supplies of various ratings. The data shows that rotating machines and rectifiers of equivalent ratings have similar short circuit currents, but rectifiers have less inductance, therefore, a higher rate-of-rise of fault current.

2.3.1 Rectifiers

The operation of both silicon rectifiers and mercury arc rectifiers are essentially the same except that the mercury arc rectifiers have a higher forward voltage drop. In order to simplify the tabulations the differences of rectifier forward drop will be neglected. This assumption is conservative and will result in a somewhat higher calculated fault current than actually will exist in some systems.

In mine power supplies two different rectifier circuits are in general use; the three-phase bridge and the six-phase double wye. With silicon rectifiers the three-phase bridge is used almost exclusively. Reference (2) shows that the operation of both these circuits are equivalent and gives a detailed description of their operation. The steady-state regulation curve of either circuit is shown in Figure 2.3-2.

It can be seen that the effective source resistance is not a constant but is lower in the overload range than it is for short circuit. The equivalent source resistance for both the overload and short circuit condition may be calculated if the per unit reactance and resistance of the transformer rectifier is known. Typical values, which were obtained from mine dc power supply manufacturers, are given in Table 2.3-1.

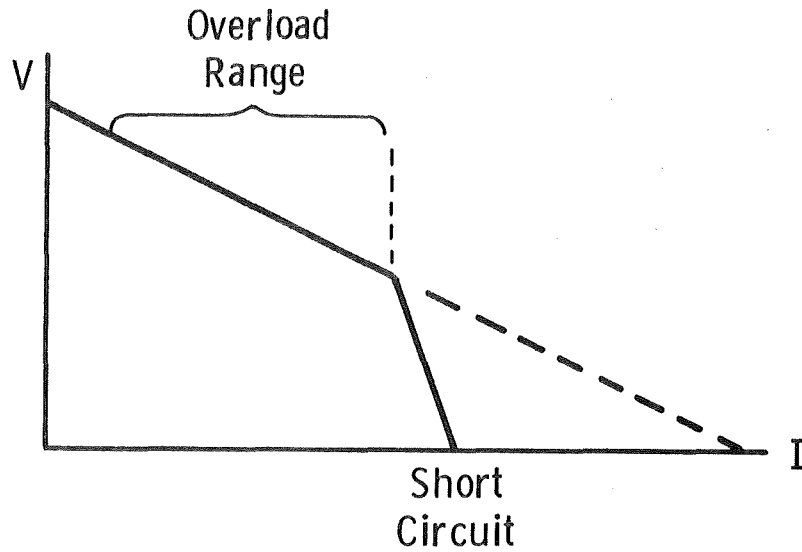


Fig. 2.3-2—Showing voltage regulation of rectifier power supply

Table 2.3-1. Typical per unit values for rectifier transformers

<u>kW Rating</u>	<u>% R</u>	<u>% X</u>	<u>% Z</u>
150	2.8	12.5	12.8
300	1.4	7.5	7.6
500	1.1	7.5	7.6
750	1.1	7.5	7.6
1000	1.1	7.5	7.6

The equivalent dc parameters of resistance and inductance calculated from these per unit values are given in Table 2.3-2.

As an example of these calculations, constants for a 500 kW rectifier are calculated below. Assume a three-phase bridge circuit, a 600 volt rated dc output, and an infinitely stiff source feeding the transformer rectifier. The ac impedance can be calculated as

$$V_{\text{line-neutral}} = \frac{V_{\text{dc}}}{1.35 \sqrt{3}} = \frac{600}{1.35 \sqrt{3}} = 256 \text{ volts}$$

$$I_{\text{line}} = 0.816 I_{\text{dc}} = 0.816 (833) = 680 \text{ amperes}$$

$$Z_{\text{1pu}} = \frac{256}{680} = 0.377 \Omega$$

Therefore,

$$R_{\text{ac}} = (0.011) (0.377) = 4.15 \text{ m}\Omega$$

$$Z_{\text{ac}} = 0.076 (0.377) = 28.6 \text{ m}\Omega$$

$$X_{\text{ac}} = (0.075) (0.377) = 28.2 \text{ m}\Omega$$

$$L_{\text{ac}} = \frac{X}{377} = \frac{28.2 (10)^{-3}}{377} = 75 \mu\text{H}$$

For the overload range the equivalent dc circuit impedance is

$$R_{\text{source}} = (6f L_{\text{ac}} + 2 R_{\text{ac}}) = 360 \times 75 (10)^{-6} + 2 \times 4.15 (10)^{-3}$$

$$R_{\text{source}} \approx 35 \text{ m}\Omega$$

For the short circuit case

$$R_{\text{source}} = \sqrt{3} Z_{\text{ac}} = \sqrt{3} 28.6 (10)^{-3} \Omega \approx 49 \text{ m}\Omega$$

$$\text{Thus, } I_{\text{short circuit}} = \frac{600}{49 (10)^{-3}} = 12,000 \text{ amperes}$$

The equivalent source inductance is essentially constant and equal to

$$L_{\text{source}} = 1.65 L_{\text{ac}} = 1.65 \times 75 (10)^{-6} = 124 \mu\text{H}$$

For a 300 volt, 500 kW transformer rectifier, the dc voltage is halved and the current doubled over that in the 600 volt case. Thus, for a 300 volt, 500 kW rectifier:

$$R_{\text{source}} = 8.8 \text{ m}\Omega$$

$$L_{\text{source}} = 31 \mu\text{H}$$

$$I_{\text{short circuit}} \equiv 24,400 \text{ amperes}$$

During the first cycle (16.7 millisecc) of a fault, the rectifier short circuit current may have a transient over-shoot as shown below in Figure 2.3-3.

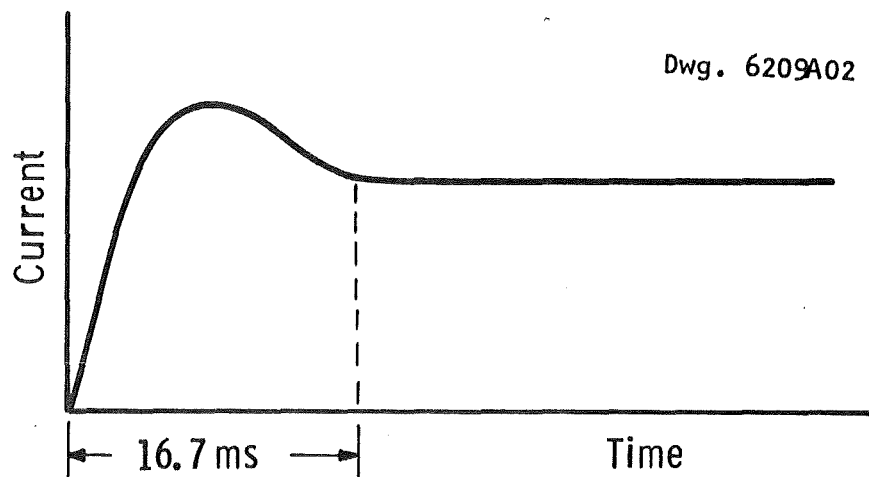


Fig. 2.3-3—Illustrating transient over-shoot of fault current from rectifier power supply

The peak current occurs after half a cycle (8.3 milliseconds) and the magnitude of the peak current increases with an increasing X/R of the supply. At most, the peak over-shoot is twice the steady-state value. Since the transient will normally be over before the circuit breaker opens, the overshoot has been ignored in the equivalent circuit representation.

2.3.2 Rotating Machines

A plot of short circuit current vs time for a dc generator is shown below in Figure 2.3-4.

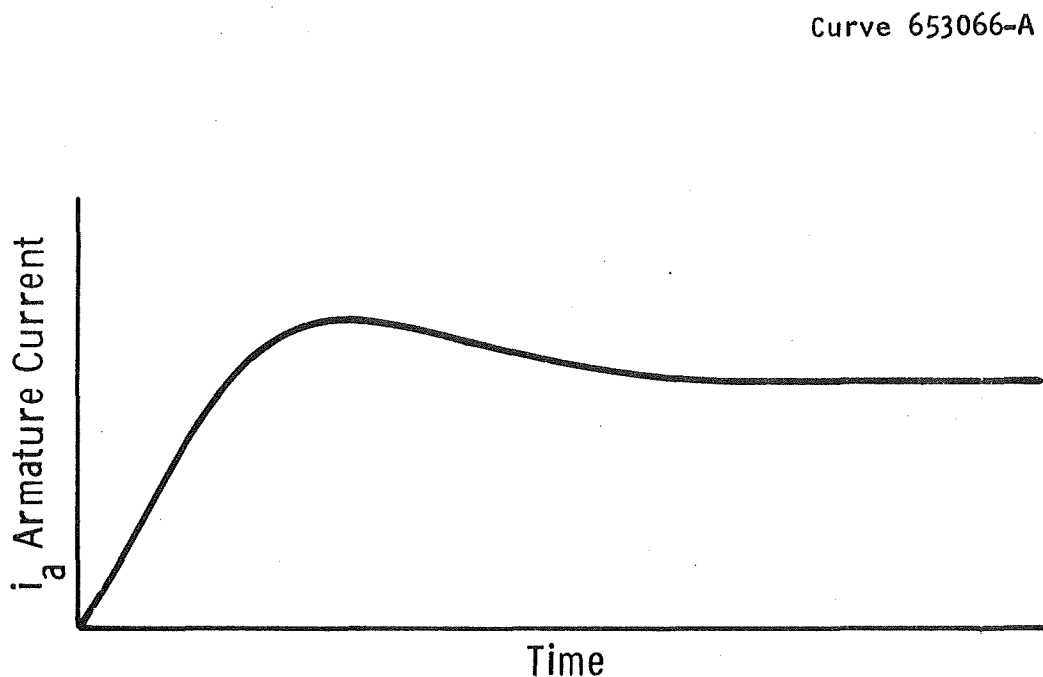


Fig. 2.3-4—Illustrating transient characteristics of DC generator fault current.

A detailed discussion of the factors that affect this short circuit curve is given in Reference (3).

Basically, the slow decay of current after the maximum is determined mostly by the field time constant and takes so long that it can be safely ignored relative to expected breaker opening times. The initial current build up depends on the armature time constant, T_a , and is given by,

$$T_a = \frac{L_a}{r'_d}$$

L_a = the unsaturated armature inductance

r'_d = the transient generator resistance.

The value of L_a varies with generator speed, kW rating, voltage, and whether or not a compensating winding is used. Typical values of L_a given in Reference (4) and tabulated in Table 2.3-3 range from 100 to 10,000 microhenries for generators in the range of 150 to 1000 kW and 300 to 600 volts.

A value of r'_d which gives 15 times rated current at short circuit has been assumed as a worst case based on discussions with generator designers.

The construction of synchronous converters is similar to dc generators and the same parameters have been assumed.

Table 2.3-2. Typical equivalent circuit parameters
of dc power supplies

	Power Rating kW	R _{source} mΩ	L _{source} μH	I _{short circuit} Amperes
Rectifiers 600 Volt	150	219	685	2,160
	300	63	206	7,200
	500	35	124	12,200
	750	24	83	18,200
	1000	17	62	24,400
Rectifiers 300 Volt	150	55	171	4,320
	300	16	51	14,400
	500	8.8	31	24,400
	750	6	21	36,400
	1000	4.4	15	48,800
Rotating Machine 600 Volt	150	160		3,750
	300	80		7,500
	500	48		12,500
	750	32		18,750
Rotating Machine 300 Volt	150	40		7,500
	300	20		15,000
	500	12		25,000
	750	8		37,500

Table 2.3-3. Typical generator inductance values

<u>Power Rating kW</u>	<u>Speed r/min</u>	<u>Voltage Volts</u>	<u>Compensating Winding</u>	<u>Armature Inductance mH</u>
150	200	250	No	3.00
200	3600	250	No	0.195
200	200	250	No	2.20
250	185	250	No	1.90
250	200	250	No	1.80
250	1780	250	No	0.323
250	3600	250	No	0.172
300	1200	250	No	0.253
300	200	250	No	1.50
300	150	250	No	1.60
375	1200	250	No	0.674
470	150	250	No	1.00
500	300	250	No	0.600
500	150	250	No	0.960
750	600	250	No	0.200
900	720	250	No	0.270
250	300	600	No	10.40
300	1200	345	Yes	0.39
500	400	600	Yes	0.86
750	720	250	Yes	0.10
500	900	250	Yes	0.10

2.4 Resistance and Inductance of Typical Cable Arrangements

In the coal mine the dc currents may be carried by trolley wires as large as 500 kcmil in parallel with copper feeder conductors varying from 211.6 kcmil to 1000 kcmil in section or aluminum conductors as large as 1590 kcmil. Current is also carried by means of the steel rails which vary from 40 lbs/yard to 85 lbs/yard. Separation between trolley and feeder wires and the rails is expected to vary from about 40 inches to 70 inches.

It is shown in Appendix 2 that the most arduous duty for the circuit breaker, i.e. the maximum energy dissipation requirement is not necessarily associated with the highest current condition. Greatest current always occurs with the source shorted at its output, however, if the cable has a significantly larger time constant than the source, more energy has to be dissipated for a short at the end of a specific length of cable than for a short of the source. As a worst case the maximum energy conditions were applied for the circuit breaker tests. Some tests were also run under more typical conditions.

2.4.1 Conductor Parameters for 300 Volt Mine System

For a typical 300 volt mine system, the lowest resistance will occur using the largest cables. From the mine surveys summarized in Table 2.2-1 this will include a 1000 kcmil copper feeder and a 400 kcmil copper trolley wire in parallel. The highest inductance will occur when the largest rail 85 lbs/yard is used with a maximum spacing between conductor and rail of 70 inches. These parameters are used to calculate worst case cable impedance characteristics as follows.

Referring to Figure 2.4-1, the copper conductor and two rails are assumed to be replaced by equivalent single conductors. The resistance of the 1400 kcmil copper conductor is estimated to be 0.00755 ohms/1000 ft and the resistance of the steel conductor representing the rail is estimated as 0.0063 ohms/1000 ft.

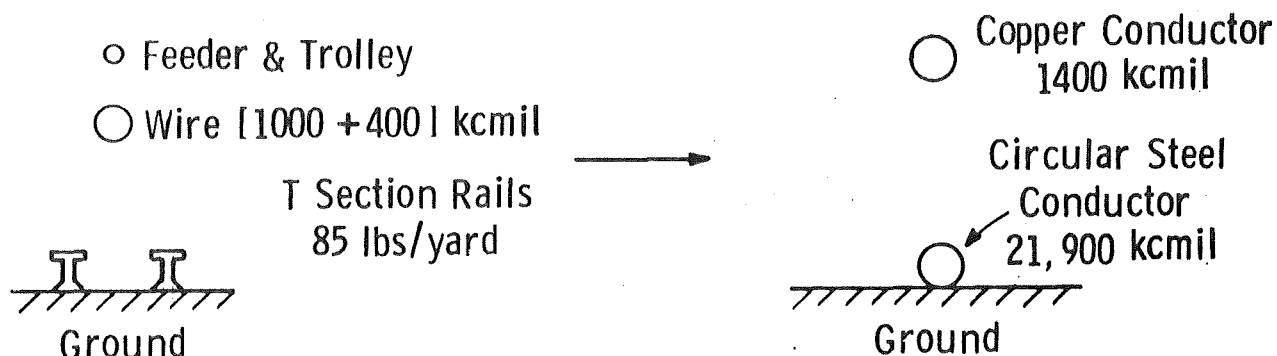


Fig. 2.4-1—Assumed representation of feeder and trolley wires and rails for calculation of impedance

To determine the wiring inductance, a possible difficulty exists because of the effects of the iron rail which by virtue of its permeability may exhibit a substantial self-inductance. Also, because the iron is capable of being saturated by the current, its inductance and ac resistance is non-linear. This non-linear effect is discussed in Appendix 4 and it is concluded that in calculating the inductance associated with fault currents it is permissible to neglect the effects of rail self-inductance, and consider only the cable loop inductance.

To determine the wiring loop inductance in a worst case 300 volt system, the two circular conductors and ground plane shown in Figure 2.4-1 are assumed. The loop inductance is then calculated from

$$^*L_{\text{loop}} = 0.1404 \log_{10} \frac{4h}{d} + 0.015 \mu\text{h per foot}$$

where h is the height of trolley and feeder wire above the rails and ground, namely 70 inches, and d is the maximum diameter of the equivalent feeder and trolley wire, namely 1.185 inches.

* Radio Engineers Handbook - Terman

Thus the calculations yield,

$$L_{\text{loop}} = 0.347 \text{ mH per 1000 ft of mine}$$

$$R_{\text{loop}} = 0.01385 \, \Omega \text{ per 1000 ft of mine}$$

and Cable Time Constant = 25 milliseconds

2.4.2 Conductor Parameters for 600 Volt Mine System

In this case the effective conductor representing the trolley and feeder wires has a diameter of 0.845", an area of 711.6 kcmil, and a resistance of 0.0149 ohms per 1000 ft.

Thus, the calculations yield,

$$L_{\text{loop}} = 0.368 \text{ mH per 1000 ft of mine}$$

$$R_{\text{loop}} = 0.0212 \, \Omega \text{ per 1000 ft of mine}$$

and Cable Time Constant = 17.4 milliseconds.

Summary of Mine Conductor Characteristics

A summary of the results for 600 volt and 300 volt cables is given in Table 2.4-1.

Table 2.4-1. Summary of calculated mine system parameters representing worst case for circuit breaker

	<u>600 Volt System</u>	<u>300 Volt System</u>
Resistance - ohms/1000 ft of mine	0.0212	0.01385
Inductance - millihenrys/1000 ft of mine	0.368	0.347
Time constant - milliseconds	17.4	25

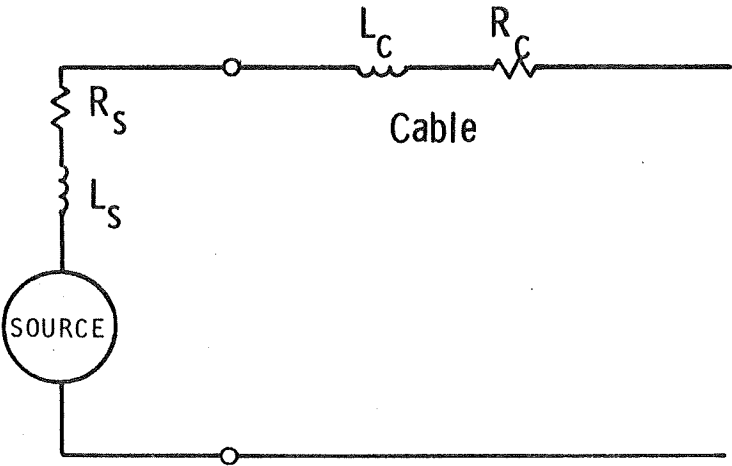
2.5 Complete Mine System Parameters Including Cable and Power Supplies

For precise calculation of circuit breaker duty, the inductance and resistance of the appropriate source or parallel sources must be added to the conductor parameters. The source can have an especially significant effect if the mine dc power is obtained from rotating machines. Assuming a maximum rotating power unit rating of 500 kW, and maximum rectifier rating of 1000 kW the mine circuit can then be represented as shown below in Figure 2.5-1 for worst case fault current analysis.

In terms of circuit breaker performance it is useful to know the variations of inductance with prospective fault current. It is to be noted, however, that the actual energy dissipation requirements of the circuit breaker are also affected by its speed of response as discussed in Appendices 1 and 2. Tables 2.5-1 and 2.5-2 illustrate typical parameters developed from the data in Figure 2.5-1.

Table 2.5-1. Variations of current and inductance for 300 volt mine system

Prospective Fault Current	<u>500 kW Generator</u>		<u>1000 kW Rectifier</u>	
	Total Inductance	Length of Mine	Total Inductance	Length of Mine
Amperes	mH	Feet	mH	Feet
2,000	4.41	9964	3.65	10,512
4,000	2.53	4584	1.78	5,097
6,000	1.91	2743	1.15	3,292
8,000	1.59	1841	0.84	2,390
10,000	1.41	1299	0.65	1,848
12,000	1.28	938	0.53	1,487
14,000	1.19	680	0.44	1,229
16,000	1.12	487	0.37	1,036



		Source Parameters				Cable Parameters
		500 kw Generator	1000 kw Rectifier			
600 volts DC	L_s	860 μ H	62 μ H	L_c	368 μ H/1000 ft	
	R_s	48 m Ω	17 m Ω	R_c	21.2 m Ω /1000 ft	
300 volts DC	L_s	960 μ H	16 μ H	L_c	347 μ H/1000 ft	
	R_s	12 m Ω	4.4 m Ω	R_c	13.9 m Ω /1000 ft	

Fig. 2.5-1—Equivalent circuit parameters for evaluating worst case mine system characteristics

Table 2.5-2. Variations of current and inductance for 600 volt dc mine system

Prospective Fault Current	500 kW Generator		1000 kW Rectifier	
	Total Inductance	Length of Mine	Total Inductance	Length of Mine
Amperes	mH	Feet	mH	Feet
2,000	5.24	11,886	4.98	13,349
4,000	2.63	4,811	2.37	6,273
6,000	1.76	2,452	1.51	3,915
8,000	1.32	1,273	1.07	2,735
10,000	1.06	566	0.81	2,028
12,000	0.89	94	0.63	1,556

2.6 Effect of Multiple Parallel Substations

The parameters in Tables 2.5-1 and 2.5-2 were prepared on the assumption of a worst case cable configuration supplied from a single 500 kW generator or 1000 kW rectifier, whereas in practice a multiplicity of various substations is anticipated operating in parallel and connected via the mine cabling. The situation is shown in Figure 2.6-1.

Assuming the generator short circuit current capability is related to its kW rating as is true practically then the worst case faults will occur assuming the largest generators are paralleled.

If the power sources are rotating machines, it is shown in Appendix 5 that a total prospective current of I_F drawn from a single generator causes more system stored energy than if the current I_F is made up of smaller contributions from multiple sources. Therefore, if the circuit breaker is found to be satisfactory for I_F amperes from a single generator, it will be even more satisfactory for I_F amperes from multiple generators.

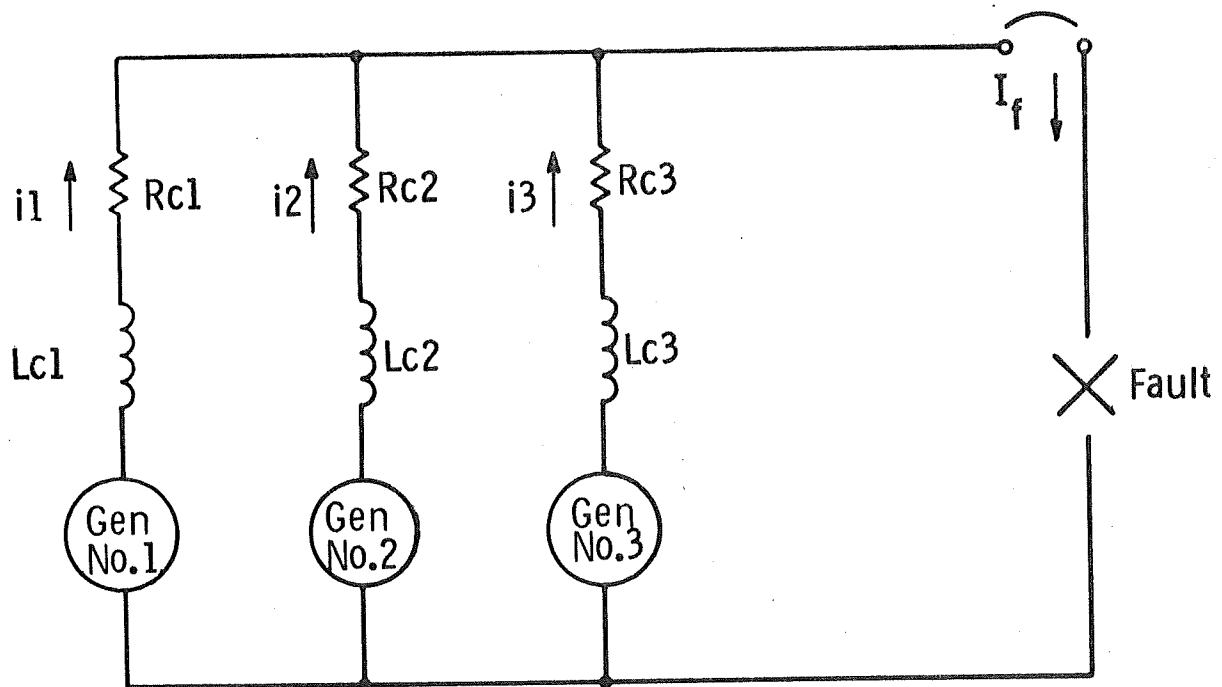


Fig. 2.6-1—Illustrating circuit for calculation of fault current with paralleled substations

For rectifier equipments the situation is not so straightforward because as shown in Appendix 2 there is a worst case stored energy condition which occurs when a fault is applied at about 460 ft or 220 ft from the 600 volt and 300 volt substations, respectively. In practice however, the distance between substations is expected to be 4000 ft or more and under these conditions the fault current and inductance are mainly controlled by the cable parameters which are fairly constant. Thus, for example, doubling the distance would double the cable inductance and halve the fault current so keeping constant the fault energy per ampere which varies as LI . Under these conditions a circuit breaker rated for a current I_F amperes from a single rectifier unit will also be satisfactory for a total of I_F amperes drawn from multiple parallel rectifiers.

2.7 Mine System Loads

The main power loading on the dc system consists of series field dc motors used in haulage vehicles. The ratings are various with a maximum rating totaling 800 horsepower being typical in a 50 ton locomotive. Transient currents are drawn by the motors during acceleration which is controlled by resistance starters. These transient currents must be passed by the system circuit breakers without causing spurious tripping to occur and on a nominal 600 volt, 800 hp system the initial starting current of 760 amps may reach a momentary peak of 2000 amps during acceleration. Motors are designed to produce full power down to about 83% of nominal system voltage and require approximately 3.55 amperes/hp at 250 volts and 1.77 amperes/hp at 500 volts.

2.8 Electrical System High Frequency Characteristics

Since our approach in developing a fault discriminating system involves the application of high frequency signals to the trolley and rail network, it is important to have data on the system inductance and resistance at frequencies between 1 kHz to 20 kHz. In particular since the rails may have appreciable self-inductance it is necessary that the ground connections are sufficiently low impedance to bypass this inductance.

Working in collaboration with the Lee Engineering Division of Consolidation Coal Co. a visit was made to the Ireland Creek Mine in February, 1973 with the intent of determining the high frequency characteristics of a 300 volt dc trolley and rail system. For tests, 3800 ft of main haulage way was available and as best could be determined all known parallel loads were disconnected. The power cables consisted of a 1,592 kcmil aluminum feeder and copper trolley wire of 500 kcmil, the height of which varied from about 5 ft to 7 ft.

Separate tests were made over lengths of 1400 ft, 2500 ft, and 3800 ft. The test circuit is shown in Figure 2.8-1.

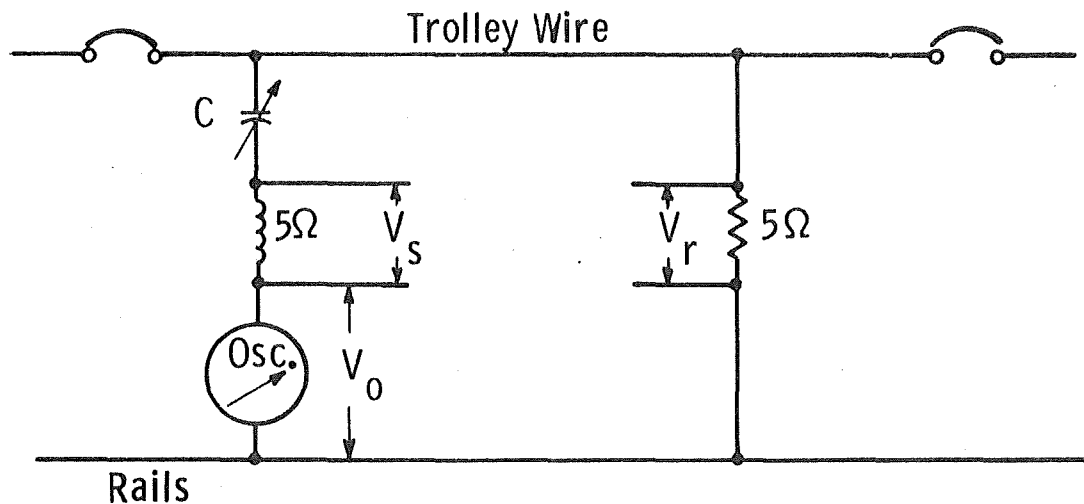


Fig. 2.8.1—Showing techniques for testing mine cable high frequency characteristics

The test technique was such that with a suitable capacitor C the oscillator frequency was adjusted for resonance. (Defined as voltage V_S in phase with the oscillator voltage V_O . At this point the values of C , f , V_O , and V_S were recorded. The results are given in Table 2.8-1.

Analysis of the test results show that although no loads were assumed to be connected, a slightly inductive load of between $55\ \Omega$ to $85\ \Omega$ appeared across the test cables in the vicinity of the oscillator section. This, however, did not affect the usefulness of the test data and the results are summarized as follow:

1. Up to 3.2 kHz and over a distance of 3800 ft the impedance of the rail and ground return was negligible compared to $30\ \Omega$ which is the level of illegitimate load it is hoped can be detected by a discriminating circuit breaker. At higher frequencies (up to 20 kHz) the results were less conclusive.

Table 2.8-1. Mine cable test data

Test 1 - Cable length 1400 ft

<u>Series Capacitance μf</u>	<u>Oscillator Frequency Hz</u>	<u>Peak to Peak Oscillator Voltage Volts</u>	<u>Peak to Peak Voltage Across 5 Ω Resistors</u>	
			<u>Sending Volts V_s</u>	<u>Receiving Volts V_r</u>
2.94	5,200	0.700	0.300	0.250
0.47	13,900	0.880	0.300	0.250

Test 2- Cable length 3800 ft

2.94	3,200	0.920	0.300	0.250
0.47	10,400	1.200	0.200	0.113
0.18	20,500	1.300	0.150	0.060
0.047	39,500	1.750	0.100	0.040

Test 3 - Cable length 2500 ft
plus 1300 ft dead cable

2.94	3,950	0.800	0.300	0.260
0.47	11,000	0.800	0.200	0.150
0.18	21,000	1.260	0.200	0.135
0.047	38,000	1.850	0.150	0.100

2. The effective cable inductance was
0.28 mH/1000 ft. (This compares favorably
with the worst case calculation of 0.35 mH/
1000 ft derived in Section 2.4-1.

2.9 High Frequency Characteristics of DC Power Supplies

No data could be found in the literature discussing the high frequency characteristics of mine power supplies, however, it is clear from measurements on series motors described in Section 4.7 that the effect of eddy currents in the machine iron paths is significant at frequencies of interest. Due to this effect the impedance is lower than would be expected (varying as frequency to the power of 0.67 instead of proportionally as would be true if the inductance remained constant). It is expected that similar effects occur in dc generators and the power source high frequency impedance values are generally assumed to be low, for example, a few ohms.

SECTION 3. DC CIRCUIT BREAKER FOR MINE APPLICATION

3.1 Candidate Circuit Breakers

Possible suppliers of circuit breakers that might perform satisfactorily were invited to comment on the feasibility of their circuit breakers for 600 volt dc use. Eighteen vendors were contacted in the USA, one in Japan, and one in England.

Information received from the foreign suppliers was positive but incomplete and only three of the domestic suppliers responded positively, namely General Electric, ITE Power Equipment, and Westinghouse Electric Corporation. A positive response was also received from Siemens Corporation Power Equipment, a German company, with marketing offices in New Jersey.

Open construction power circuit breakers made by Westinghouse and Siemens Corporation have proven performance for 600 volt dc operation, but are large and costly. The low voltage power circuit breakers made by General Electric are proven at 500 volts dc and probably would be satisfactory for 600 volt dc mine systems. From data made available to us, but as yet unpublished, it was known that the molded case circuit breakers made by Westinghouse Electric Corporation were satisfactory for some levels of 600 volt dc operation. It was reasoned that similar performance could be expected from molded case circuit breakers made by ITE and GE; therefore, candidates for 600 amps were selected from the range of molded case breakers made by these three companies. In case tests on these molded case circuit breakers failed to produce an acceptable unit, a lower current open construction breaker rated at 400 amps was also selected from Siemens Corporation. In all cases the circuit breakers were ac types having 2 or 3 poles and generally it was recommended that 3 poles be used in

series to interrupt 600 volt dc systems and 2 poles in series for 300 volts dc operation. A list of the original circuit breaker candidates is shown in Table 3.1-1.

3.2 Circuit Breaker Trip Settings for DC Operation

The types of circuit breakers to be tested were equipped with adjustable, instantaneous magnetic trip units; also on some breakers thermal trip elements were included. It was found by laboratory tests that for dc operation the instantaneous dc current at trip is about 1.3 times the ac rms trip current setting. A high current, low voltage ac power supply was used for setting the trip units of candidate circuit breakers. Subsequently, during high power testing it was determined that the arrangement of power cables in the vicinity of the circuit breaker could modify the trip setting and final adjustments were made on the high power test rig.

With three poles in series there are three magnetic trip adjustments that can be set and generally it was found that the circuit breaker response was slightly more rapid with all three poles set to the required trip value.

Measurements were made on the candidate circuit breakers to determine the speed of operation of the trip mechanisms. The time required for the contacts to part after trip current point has been reached was measured for each breaker. The measurement was made by applying a single short duration high current pulse to the circuit breaker. The time for contact parting varied from 7 to 8 milliseconds for three of the candidate types but was 14 milliseconds for the fourth unit. It is not immediately evident from the mechanical structure why one type is significantly slower in operation, but it is possibly caused by eddy currents in the magnetic assembly.

The operating speed of the breaker and also the breaker trip setting have an important effect on the amount of energy dissipated in the breaker during interruption. These factors are analyzed in detail in Appendix 1. Based on the relationships developed in Appendix 1, the

Table 3.1-1. Original list of candidate circuit breakers expected to interrupt
300 volts dc at up to 2500 amps and 600 volts dc at up to 1200 amps

<u>Manufacturer and Code</u>	<u>Approx. Size</u>	<u>Wt Lbs</u>	<u>Approx. Cost Dollars</u>	<u>Comments</u>
*General Electric Co. TJK636600	8.25" x 10.125" x 3.8"	16.5	295	Three pole molded case ac circuit breaker for 600 amps. Includes thermal and magnetic trip (adjustable between 3 and 10 per unit). For 600 volt dc use 3 poles in series, for 300 volts 2 poles in series.
*General Electric Co. THKMA 836600	8.25" x 15.5" x 5.5"	33.25	378	Three pole molded case ac circuit breaker for up to 1200 amps. Includes thermal and magnetic trip (adjustable between 3 and 10 per unit). For 600 volts dc use 3 poles in series, for 300 volts use 2 poles in series.
Siemens Corp. New Jersey 3WQ1010	24.8" x 14.8" x 8.2"	100	1145	An open construction breaker. Rated at 1000 amps continuous with 2 poles in series for 600 volts dc, 25,000 amps and 0.36 mh. Mechanical life 10 ⁴ make/break operations.
Siemens Corp. New Jersey 3WV1111-OEA40		187	3160	An open construction high speed (3 millisecs) current limiting circuit breaker with 1200 volts arc. Able to interrupt 31,000 amps. Mechanical life 10 ⁴ make/break operation.
*Siemens Corp. New Jersey 3WA2210-2DL00	15.4" x 8.4" x 9.5"	36.4	220 (**See Note Below)	An open construction 3 pole, 400 amp ac circuit breaker in a metal enclosure. Able to interrupt 600volts dc with 3 poles connected in series and 300 volts dc with 2 poles in series. Thermal and magnetic trip (set at 10 times rated).
*ITE Imperial KM2A600	15.5" x 9.0" x 4.56"	24	315	Two pole molded case ac breakers rated at 600 amps. Magnetic trip only. Normal minimum set at 1900 amps ac. Use 2 poles in series for 600 volts. 20% surcharge for special low calibration.

**
The manufacturer stated that this breaker is no longer available - Oct. 1973

Table 3.1-1 (continued)

	<u>Manufacturer and Code</u>	<u>Approx. Size</u>	<u>Wt Lbs</u>	<u>Approx. Cost Dollars</u>	<u>Comments</u>
3-4	*Westinghouse Electric Corp. Type MA	16" 8.25" 6.06"	35.2	294	Molded case circuit breaker rated up to 800 amps continuously. Magnetic trip only can be supplied adjustable over a 2:1 range. Can be supplied with window to view contacts. Three poles in series for 600 volts dc and 2 poles in series for 300 volts dc. A fused version "TRIPAK" is available that provides current limiting. In-house tests show single pole operation at 300 volt dc. Two hundred operations for 1650 amp and 3 operations at 4650 amps.
	*Westinghouse Electric Corp. Type NB		39.9	480	Molded case circuit breaker rated at 600-1200 amps continuously. Thermal and magnetic trip (adjustable over 2:1 range). For 600 volts dc use, 3 poles in series for 300 volts dc use 2 poles in series.
	Westinghouse Electric Corp. Type DB25	24" x 13" x 12"	110	1680	A 3 pole 600 volt ac circuit breaker for drawer mounting. Could be used for 600 volt dc by connecting 3 poles in series and 300 volts by using two poles in series. Using special arc chutes for dc application, type DBL version is available with fuses to provide current limiting.
	*Navy Breaker Type AQB A250	8.25" x 10.75" x 4.75"	26.4	254	A 3 pole molded case Navy type rated at 500 volts ac and 250 amps. Similar to 600 volt commercial units but different molding material and greater ruggedness. Also plug in connections.

*The circuit breakers were tested under simulated mine conditions

value of arc energy (J_{arc}) vs prospective current has been calculated for a typical 600 volt mine system with 18 millisec time constant. The following conditions were assumed; arc voltage of twice system voltage, trip settings of 1200 and 2000 amperes, and unlatching times of 7 and 14 milliseconds. These values are typical and correspond to the range of mine operating conditions. The results of the calculations are plotted on Figure 3.2-1. The effect of a rapid unlatching time in limiting the amount of energy to be dissipated by the breaker is quite evident. The lowering of the trip setting to limit the arc energy is less important and is most effective at low values of prospective current. Exact correlation of the calculated values of energy with the test data is difficult due to the perturbation of the arc voltage in actual operation.

3.3 Testing Candidate Circuit Breakers

3.3-1. Test Facility for High Power Tests

The facilities of the Westinghouse East Pittsburgh plant were used for the high power tests. Four dc generators were available in conjunction with a fairly wide range of inductance and resistance load banks and the generators could be operated either singly or in parallel as required. The rating of each dc generator was 1500 kW at 750 volts and the armature inductance and resistance were given as $L_a = 0.484$ mH and $R_a = 0.036 \Omega$, respectively.

An oscillograph was used in conjunction with suitable shunts to record the transient arc voltages and the system fault current.

An open construction, high power dc circuit breaker was used as a back up protection to open the circuit at a suitable time after the fault was applied.

3.3-2. Circuit Breaker Test Specification

From Section 2.5 and Appendix 2 worst case impedance conditions have been determined for 600 volt and 300 volt mine dc power systems and they are reproduced in Table 3.3-1.

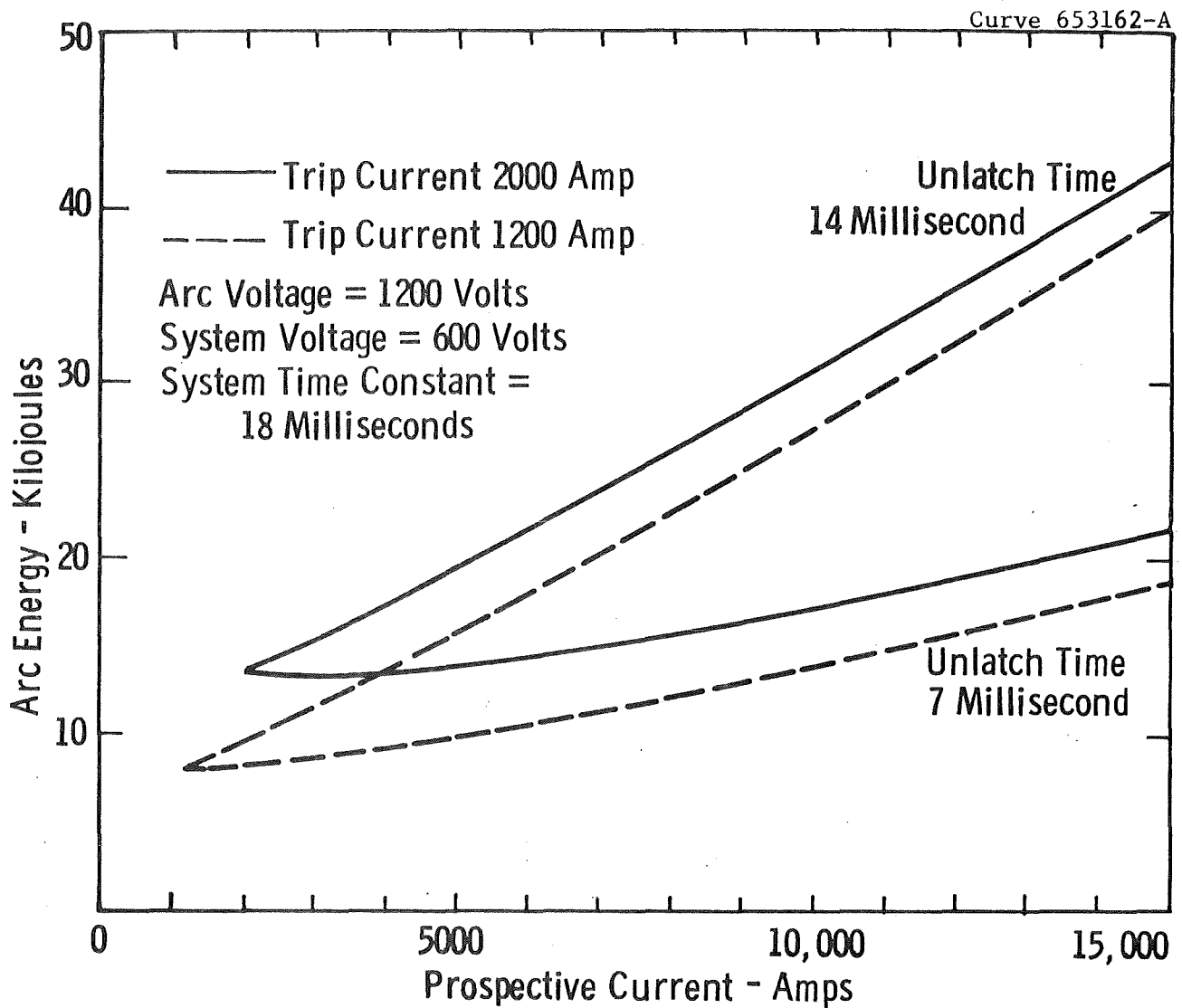


Fig. 3.2-1 —Arc energy vs prospective current for different breaker trip settings and unlatch times

Table 3.3-1. Worst case mine impedance parameters

<u>Power Source</u>	<u>Prospective Fault Amperes</u>	<u>Inductance mH</u>	<u>System Time Constant ms</u>	<u>kJ Energy Stored After 18 ms</u>
1000 kW Rect. 600 Volt	22,400	0.54	20	47.2
500 kW Gen. 600 Volt	12,500	0.86	18	27
1000 kW Rect. 300 Volt	40,000	0.092	12.3	43.6
500 kW Gen. 300 Volt	25,000	0.96	80	12.2

The kilojoules of stored energy in the system are given for a time of 18 milliseconds after an assumed fault is applied because this elapsed time is typical of the time to reach peak current in tests that were made of molded case circuit breakers with trip settings of 2000 amperes and 4000 amperes, respectively for the 600 volt and 300 volt dc systems.

Candidate circuit breakers for mine dc systems can be tested with circuit conditions similar to those in the above table; however, the conditions need not be identical provided the kilojoule capability of the breaker is compatible with the system stored energy and the operating speed of the circuit breaker. Molded case circuit breakers will operate in times of 18 milliseconds or less and should be tested to be capable of interrupting a 600 volt system with stored energy of about 48 kilojoules. Faster acting circuit breakers would not normally be required to dissipate as much stored energy as discussed previously in Section 3.2 and also in Appendix 1.

During testing of candidate circuit breakers a wide variety of tests were conducted from which a test procedure to determine adequacy has been prepared as shown in Table 3.3-2. It is considered that candidate circuit breakers should operate successfully at least twice at each test condition, also a further 30 operations for the condition marked by asterisks should be completed satisfactorily.

Table 3.3-2. Test conditions for candidate mine circuit breakers for 600 volt and 300 volt operation

<u>Circuit Breaker Trip Setting</u>	<u>Source Voltage Volts</u>	<u>Prospective Fault Current Amperes</u>	<u>Fault Inductance mH</u>	<u>Fault Time Constant ms</u>	<u>kJ Energy Stored After 18 msecs</u>
2000 amperes	600	24,200	1.0	40.3	38
2000 amperes	600	24,000	0.24	9.6	49
2000 amperes	*630	11,200	1.0	17.8	25
Shunt trip	600	1,400	19	44	18.6 (at trip)
Shunt trip	600	600	23.4	23.4	4.2 (at trip)
4000	300	27,200	0.12	10.9	28
4000	*300	19,500	0.88	57	12.2
4000	300	11,700	0.88	34.4	9.9
Shunt trip	300	1,100	23.7	87	14.3 (at trip)

It is noted that in the test program relatively low current, high inductance tests are called for. These are particularly important as it was found during testing that some circuit breakers would perform satisfactorily at high currents but failed to sustain high arc voltage and interrupt at low currents.

3.4 Circuit Breaker Descriptions

Circuit breakers from four different manufacturers were tested and, in order to distinguish between the various types, a code name has been allocated, such as Manufacturer A abbreviated to Mnfr A followed by a number representing the maximum steady state current rating of that circuit breaker frame size. For example, Mnfr D 1200 indicates a breaker made by Manufacturer D in which the maximum recommended continuous current rating of the frame size is 1200 amps.

3.5 First High Power Test Series On Candidate Circuit Breakers

The overall objectives of the program were to determine the adequacy of circuit breakers to interrupt 600 volts dc and 300 volts dc as applicable to a mine electrical system; however, for this first test program, effort was applied to the 600 volt system since less information was available concerning the performance of probable 600 volt dc circuit breakers. From analysis of typical mine electrical systems as given in Section 2.5 a range of load impedance conditions was obtained.

Four different types of circuit breakers were available for test and three models of one type were tested. Each circuit breaker was of molded case construction with three poles designed primarily for 600 volt, 3 phase, ac operation. Each was capable of at least 600 amps continuous current rating and each was offered by the manufacturer as being capable of interrupting 250 volt dc.

The four different types of circuit breakers tested in the initial 600 volt test series are described briefly in the table below.

<u>Type</u>	<u>Approx Wt</u>	<u>Approx (OEM) Cost</u>
Mnfr A 600	17 lbs	\$295
Mnfr A 1200	33 lbs	\$378
Mnfr D 800	35 lbs	\$294
Mnfr D 1200	40 lbs	\$480

Each breaker has an instantaneous trip associated with each pole, however, only a single trip was used in these tests, the other trips being set to a high position. For low current interruption tests below the instantaneous magnetic trip setting, a shunt trip coil was used.

Tests were conducted at 600 volts dc with various current and inductance levels, and in general the high current tests, i.e. above 1500 amperes reflected a load time constant of about 17.6 milliseconds which is similar to the mine cabling value. For lower currents, greater

inductance was used. The maximum necessary setting for the magnetic trip was deemed to be 2000 amps, however, an overcurrent test with the setting at 4000 amps was made to try to determine any weak points in the circuit breakers.

To achieve the greatest arc voltage the three poles of the breaker were series connected. This was done as shown below with current entering at the stationary contact on Pole 1 and leaving on the moving contact of Pole 3. Pole 1 is considered to be that on the left hand side of the circuit breaker when viewed from the front. No. 3 pole is on the right side of the breaker. It is noted that this method of interconnection imposes a voltage stress of approximately twice a single pole arc voltage between the moving contacts of poles 2 and 3 but the method is simple to implement practically.

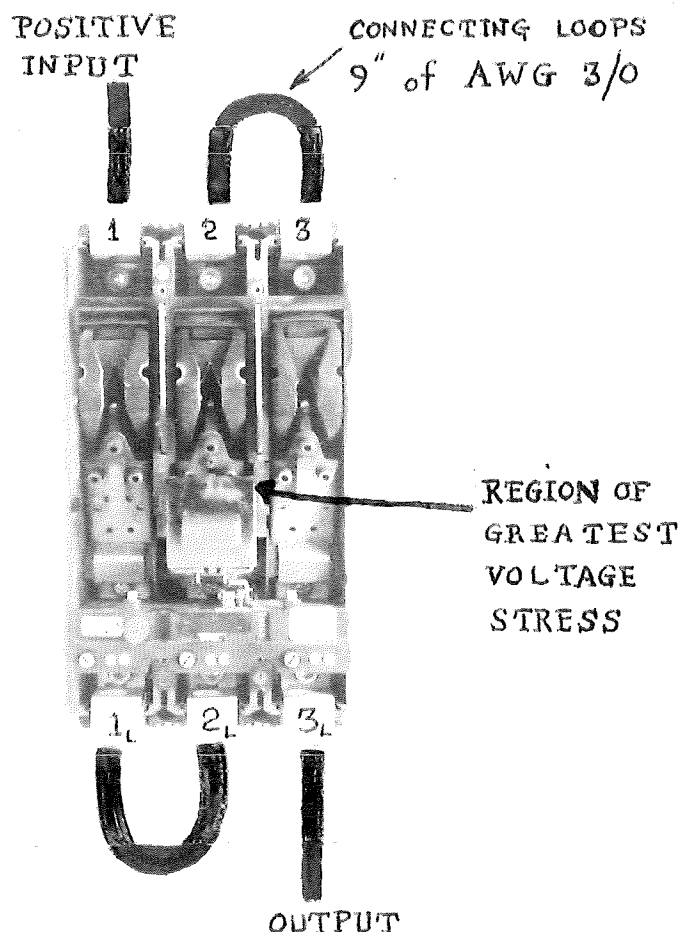


Fig. 3.5-1. Interconnection of poles for high current tests

During tests oscillograph recordings were made of the dc current, the arc voltages across each pole, and also the total arc voltage. The source impedance conditions were checked by recording a bolted fault characteristic just prior to testing the circuit breaker.

Tests were made of the circuit breaker total contact resistance before and after each test but no significant changes were observed in any of the circuit breaker's contact resistance during any of the tests.

The results of the tests are summarized below and the order of the results is chronological. In most instances the power was derived from two 1500 kW, 750 volt generators operating in parallel although in some of the low current tests, only a single 1500 kW generator was used.

Test 1. Breaker Type Mnfr A 600

<u>Magnetic Trip Setting Amperes</u>	<u>Prospective Fault Current Amperes</u>	<u>Peak Let Through Current Amperes</u>	<u>Fault Inductance Millihenrys</u>	<u>No. of Operations</u>
2000	5,400	3660	2.0	2
2000	7,300	4200	1.45	2
2000	9,300	5200	1.21	2
2000	11,200	5780	1.03	6
4000	11,500	7500	1.03	2
Shunt Trip	620	620	22	3
Shunt Trip	1,030	1030	22	1
*Shunt Trip	1,030	1030	22	1
*Shunt Trip	1,340	1340	22	2

* In these tests the circuit breaker failed to interrupt due to low arc voltage which is thought to be caused by the fact that the current is not high enough to force the arc into the arc chute. The back-up breaker, which was set to operate about 200 millisecs after the shunt trip, cleared the circuit and prevented damage to the breaker under test.

Conclusions

This circuit breaker operated satisfactorily at the higher current settings but at low current and high inductance the arc voltage was marginal. At the conclusion of testing, the circuit breaker was in good operating condition. Some modifications are necessary to make this breaker acceptable for 600 volt dc mine application. At this time the required modifications are not clearly evident.

Test 2. Breaker Type Mnfr A 1200

<u>Magnetic Trip Setting Amperes</u>	<u>Prospective Fault Current Amperes</u>	<u>Peak Let Through Current Amperes</u>	<u>Fault Inductance Millihenrys</u>	<u>No. of Operations</u>
2000	5,400	4150	2.0	2
2000	7,300	5200	1.45	2
2000	9,300	6600	1.21	2
2000	11,200	7300	1.03	6
Shunt Trip	590	590	20	4
Shunt Trip	1,030	1030	20	1
Shunt Trip	1,200	1200	20	1
Shunt Trip	1,400	1400	19	2
*4000	11,300	8200	1.03	2

* This is an overcurrent condition and in one of the operations a restrike of the arc occurred after the circuit was interrupted, however, the ensuing increase of current was only about 1300 amps and the circuit breaker forced the current to zero again and interruption was satisfactory.

Conclusions

The circuit breaker operated satisfactorily over the complete range of tests and at the conclusion of tests it appeared to be in good operating condition.

Test 3. Breaker Type Mnfr D 800

<u>Magnetic Trip Setting Amperes</u>	<u>Prospective Fault Current Amperes</u>	<u>Peak Let Through Current Amperes</u>	<u>Fault Inductance Millihenrys</u>	<u>No. of Operations</u>
2000	11,200	6650	1.03	12
Shunt Trip	600	600	20	4
Shunt Trip	1,150	1150	9.4	1
Shunt Trip	1,150	1150	21	1
Shunt Trip	1,380	1380	20	1
Shunt Trip	1,520	1520	21	1
4000	11,200	7700	1.03	2

Before carrying out the 4000 amp overcurrent checks, a small piece of 1/32" micarta was cemented in position to give an additional barrier between the handle mechanism and the right hand pole (i.e. between poles 2 and 3). It was noticed that some slight arcing deposits had appeared where the cover and base butt together at this point.

Conclusions

The circuit breaker operated satisfactorily over the normal range of tests, however, a possible weak point was determined,* and a remedy implemented such that the breaker operated satisfactorily in the overcurrent test. At the conclusion of tests, the circuit breaker appeared in good condition.

* Subsequent tests with a modified interconnection of the poles indicate that this is not in fact a weak point.

Test 4. Breaker Type Mnfr D 1200

Some difficulty was experienced with this breaker in that an internal arc developed between poles during the overcurrent test condition and also in the low current, high inductance test condition. This was in spite of the fact that very good interruption was achieved under other test conditions. Two additional breakers of this type were tested to confirm the failure modes and the results which are listed in chronological sequence indicate at what point changes were made.

<u>Magnetic Trip Setting Amperes</u>	<u>Prospective Fault Current Amperes</u>	<u>Peak Let Through Current Amperes</u>	<u>Fault Inductance Millihenrys</u>	<u>No. of Operations</u>
2000	2,810	2500	4.84	1
2000	5,400	4000	2.0	2
2000	7,300	4760	1.45	2
2000	9,300	5720	1.21	2
2000	11,200	6200	1.03	6
*4000	11,200	8000	1.03	2

*Unit failed at this point due to internal arc between handle mechanism and pole 3. A simple insulating paper barrier was installed and the test repeated, but unit failed again. A new breaker was acquired and this failed in a similar manner but at low current as listed below (**). A further frame was tested but it too failed in an identical manner, this time at 1390 amps as indicated below (***).

**Shunt Trip	1,340	1340	22 mh	1
Shunt Trip	620	620	14.5	2
Shunt Trip	620	620	20.0	1
Shunt Trip	980	980	21.5	2
***Shunt Trip	1,390	1390	21.5	1

Conclusions

The insulating barriers between poles 2 and 3 of this breaker are inadequate to permit pole interconnections as was done in this test series. It was verified later that a minor change would overcome this deficiency and make the breaker suitable for 600 volt dc.

3.6 Second High Power Test Series On Candidate Circuit Breakers

A second series of tests on candidate circuit breakers for 300 volt and 600 volt dc mine systems were made. The objective was to test different circuit breakers and also to determine the effectiveness of modifications^{*} introduced as a result of the first series of tests.

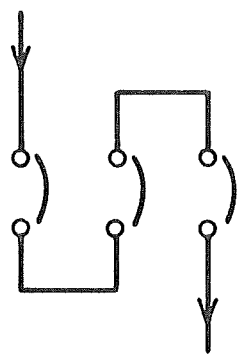
Because of dielectric stress factors noted in the earlier series of tests and the effects of the method of pole interconnection, a different interconnection was used in some of the tests. This different interconnection causes current to flow in the same direction in each pole. It requires slightly longer interconnecting cables and has been referred to as a "long pole" interconnection (LP) in contrast to the "short pole" interconnection (SP) used in the first test series. The two techniques are illustrated in Figure 3.6-1.

It was established that at 600 volts dc the long pole interconnection gave a larger interrupt capability even though the peak let-through current was greater for this connection. It was also found that in a marginal operating condition the breaker performs more reliably in an upright mounting position.

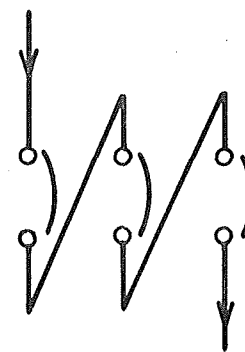
It was determined that the per unit arc voltage (discussed in Appendix 3) is generally greater in the 300 volt system. This is to be expected since the applied volts per pole is lower, for example, $300/2$ compared to $600/3$. Thus, breaker performance is more positive in the 300 volt system. Per unit arc voltage listed in the tabulated data is defined as the ratio of total circuit breaker arc voltage to the system supply voltage. Since the actual arc voltage of the circuit breaker perturbates significantly an equivalent steady arc voltage was calculated which if developed across the circuit would drive the current to zero in the same time that the actual arc voltage did.

^{*}The modification which included additional isolation between poles is shown in drawing No. 1257C59 at the end of this report.

Dwg. 6208A94



Short Pole
Connection SP



Long Pole
Connection LP

NOTE: 3 poles in series for 600 volts dc
2 poles in series for 300 volts dc

Fig. 3.6-1—Illustrating different circuit breaker
pole interconnection

A possible dielectric problem was discovered in regard to isolation of the shunt trip assembly and some flashovers were found to develop between the shunt trip assembly (normally at ground potential) and the nearest main pole. Breakers for mine operation are not always used with shunt trips; however, they will be necessary for a discriminating circuit breaker and some extra care is required in isolating the shunt trip assembly for dc operation.

A brief discussion and tabulation of test results of each circuit breaker now follows.

Mnfr A 1200

Summary

This type of breaker was tested satisfactorily at 600 volts dc in the first test series. In this second test series the maximum fault current level was increased until a dielectric failure occurred (flashover between poles 2 and 3). Failure occurred interrupting 10,400 amps in 1 mH using the short pole connection, however, using a long pole connection the breaker was satisfactory at 13,400 amps in 1 mH.

600 Volt Tests

The results are tabulated in Table 3.6-1.

The differences in peak let-through current caused by different pole connections are observed by comparing, for example, test Nos. (10 and 14), (11 and 15), (12 and 16), and (13 and 17). Typically the long pole interconnection causes the peak let-through current in this circuit breaker to be increased about 14%; however, despite this, the long pole interconnection permitted larger system faults to be satisfactorily interrupted. It is noted that in a marginal situation (test 17) the circuit breaker failed when tested in an inverted position (test 18).

Table 3.6-1

TABULATION OF DC CIRCUIT BREAKER TESTS CONDUCTED IN FEB. 1973

SYSTEM VOLTAGE= 600

BREAKER TYPE MNFR A 1200

A	B	C	D	E	F	G	H	COMMENTS	
TRIP CURR AMPS	PROSP CURR AMPS	IND MH	TRACE NO	LET THRU AMPS	ARC TIME MS	PU ARC VOLTS	LOAD TC MS		
2000	11900	1.00	1	7900	11	1.90	19.8	OK	SP
2000	8900	1.00	2	7900	11	1.81	14.8	OK	SP
600	600	23.40	3	600	21	1.69	23.4	OK	SHUNT TRIP LP
600	600	23.40	4	600	19	1.80	23.4	OK	" "
305	305	23.40	5	305	13	1.50	11.9	OK	" "
600	600	23.40	6	600	21	1.69	23.4	OK	" SP
2000	13500	.24	7	11600	5	1.56	5.4	OK	" "
2000	22800	.24	8	16500	8	1.52	9.1	OK	" "
2000	24000	.24	9	17200	6	1.83	9.6	OK	" "
2000	24000	1.00	10	10400	999	1.00	40.0	FAILED - FLASH OVER BETWEEN 2+3	
2000	13800	1.00	11	9700	14	1.84	23.0	OK	LP
2000	16500	1.00	12	10000	24	1.43	27.5	OK	"
2000	19000	1.00	13	11200	25	1.49	31.7	OK	"
2000	24200	1.00	14	13400	31	1.48	40.3	OK	"
2000	14000	1.00	15	8300	18	1.51	23.3	OK	SP
2000	16600	1.00	16	9250	18	1.61	27.7	OK	"
2000	19000	1.00	17	9700	22	1.51	31.7	OK	"
2000	19000	1.00	18	9700	999	1.00	31.7	UNIT INVERTED - FAILED FLASH OVER BETWEEN 2+3	
2000	14200	1.00	22	9250	30	1.26	23.7	OK	CABLES CROSSED IN FRONT
2000	14200	1.00	23	9250	28	1.29	23.7	OK	CABLES CROSSED AT REAR
4000	14200	1.00	24	10500	27	1.35	23.7	OK	CHANGED TRIP SETTING

300 Volt Tests

The results are tabulated in Table 3.6-2.

It is noted that as in the 600 volt tests the long pole connection permits a greater let-through current. This is thought to be due to the fact that the short pole connections may modify the magnetic trip unit characteristics. The per unit arc voltage was very satisfactory in these tests.

Table 3.6-2

TABULATION OF DC CIRCUIT BREAKER TESTS CONDUCTED IN FEB. 1973

SYSTEM VOLTAGE= 300

BREAKER TYPE MNFR A 1200

A	B	C	D	E	F	G	H			
TRIP CURR AMPS	PROSP CURR AMPS	IND MH	TRACE NO	LET THRU AMPS	ARC TIME MS	PU ARC VOLTS	LOAD TC MS	COMMENTS		
500	500	24.00	19	500	23	2.29	40.0	OK	Shunt Trip	SP
1060	1060	24.00	20	1060	48	2.31	84.8	OK	Shunt Trip	SP
4000	12600	.88	25	7100	13	2.34	37.0	OK		SP
4000	25300	.19	26	15600	6	2.36	16.0	OK		SP
4000	27600	.22	27	16200	7	2.42	20.2	OK		SP
4000	19500	.88	28	8200	16	2.30	57.2	OK		SP
4000	19500	.88	29	9500	19	2.24	57.2	OK		SP

Mnfr B 600

The breaker submitted by this manufacturer was 2 pole for 600 volt rating. Based on our earlier tests it was considered that the arc voltage produced by two poles would be inadequate for 600 volt dc thus only 300 volt tests were carried out. Even at 300 volts the breaker was found to develop insufficient arc voltage under certain load conditions. Further tests carried out in the third test series with a different type of arc chute failed to make this breaker satisfactory. The tests conducted in the second series are tabulated below in Table 3.6-3.

Table 3.6-3.

TABULATION OF DC CIRCUIT BREAKER TESTS CONDUCTED IN FEB. 1973

SYSTEM VOLTAGE= 300

BREAKER TYPE MNFR B600

A	B	C	D	E	F	G	H	COMMENTS
TRIP CURR AMPS	PROSP CURR AMPS	IND MH	TRACE NO	LET THRU AMPS	ARC TIME MS	PU ARC VOLTS	LOAD TC MS	LP INTERCONNECTION THROUGHOUT
4000	12500	.96	1	6500	36	1.36	40.0	INTERRUPTED BUT ONE POLE LOST ARC VOLTAGE
4000	12500	.96	2	6800	999	1.00	40.0	FAILED - BOTH ARCS WERE LOW
497	497	25.00	3	497	26	2.14	41.4	OK
497	497	25.00	4	497	26	2.14	41.4	OK
1060	1060	23.00	5	1060	96	1.44	81.3	DIFFICULT INTERRUPT LOW ARC VOLTS.
1060	1060	23.00	6	1060	108	1.36	81.3	" " " "
2260	2260	23.00	7	2260	110	2.13	173.3	OK

Mnfr C 400**

This circuit breaker has a maximum continuous current rating of only 400 amps. This is inadequate based on the contract specification which requires 600 amps at 600 volts and 1200 amps at 300 volts. Higher current ratings could be obtained in open construction circuit breakers, however, the costs far exceed those of molded case types as may be seen in Table 3.1-1.

Because the arc chute construction of this breaker differs significantly from that of molded case circuit breakers, it was evaluated for its interrupt capabilities.

The test breaker was a 3 pole, 400 amp, 600 volt ac type of open construction and 3 poles were connected in series for the 600 volt dc tests. The magnetic trip was set at 4000 amps, but we made adjustments to set one pole at 2000 amps. The poles are not mechanically linked and it was found during tests that the adjusted pole tripped about 10 milliseconds before the other two.

On interruption, a substantial amount of arcing debris was ejected through the top of the arc chutes, however, the arc performance was very good and stable. The results are tabulated below:

Table 3.6-4

Tabulation of DC Circuit Breaker Tests Conducted in Feb. 1973

System Voltage = 600

Breaker Type Mnfr C 400

A	B	C	D	E	F	G	H	
Trip Curr Amps	Prosp Curr Amps	IND MH	Trace No	Let Thru Amps	Arc Time MS	PU Arc Volts	Load TC MS	Comments LP Interconnection Throughout
2900	14800	1.0	1	7400	15	1.60	24.7	OK
2900	14800	1.0	2	7400	17	1.50	24.7	OK
2900	20500	1.0	3	8600	14	1.83	34.2	OK
2900	3000	12.0	5	3000	51	1.75	60.0	OK

Although the interrupt capabilities of this circuit breaker were found to be very satisfactory, further tests were not carried out because satisfactory performance was also found with readily available molded case circuit breakers.

**
The manufacturer stated that this breaker is no longer available - Oct. 1973

Mnfr D 1200

This type of breaker had shown predictable dielectric failure in the first test series. To eliminate this failure, 0.125" thick Micarta plates (2.2" x 3.5") were cemented in position between poles 1 and 2 and 2 and 3. This modification, which was to improve the dielectric strength, was found to be completely satisfactory in conjunction with the long pole interconnection. A modified drawing of it is given in Dwg. No. 1257C59 at the end of this report.

Results of the 600 volt tests are tabulated in Table 3.6-5.

The circuit breaker performed satisfactorily throughout the 600 volt tests. It is noted that the peak let-through current permitted by this breaker is significantly less than that of breaker type Mnfr A 1200, for example, compare results of trace No. 9 (Mnfr A 1200) and No. 21 (Mnfr D 1200). This is thought to be caused by the more rapid action of the magnetic trip unit and agrees with separate measurements made of trip time in our laboratory, for example, Mnfr A 1200 took about 14 milliseconds to trip in contrast to the 8 milliseconds required for Mnfr D 1200.

It was determined that some further slight improvement of speed of response could be obtained by setting all three shunt trips at the same value, for example, compare trace numbers (15 and 16) and (19 and 20).

The tabulated results of 300 volt tests are given in Table 3.6-6. The performance was generally satisfactory.

Table 3.6-5

TABULATION OF DC CIRCUIT BREAKER TESTS CONDUCTED IN FEB. 1973

SYSTEM VOLTAGE= 600

BREAKER TYPE MNFR D 1200

A	B	C	D	E	F	G	H	COMMENTS	
TRIP CURR AMPS	PROSP CURR AMPS	IND MH	TRACE NO	LET THRU AMPS	ARC TIME MS	PU ARC VOLTS	LOAD TC MS	LP INTERCONNECTION THROUGHOUT	
1500	1500	23.00	1	1500	89	1.27	57.5	OK	- SHUNT TRIP
1500	1500	23.00	2	1500	105	1.19	57.5	OK	- SLOW
1500	1500	23.00	3	1500	60	1.54	57.5	OK	
1500	1500	23.00	4	1500	56	1.61	57.5	OK	
1350	1350	23.00	5	1350	60	1.46	51.7	OK	
1800	14800	1.00	6	6500	9	2.00	24.7	OK	
1800	2500	1.00	7	2100	6	1.26	4.2	OK	
1800	1900	1.00	8	1900	5	1.26	3.2	OK	
1800	14800	1.00	11	7100	11	1.85	24.7	OK	
1800	20500	1.00	12	8200	10	2.18	34.2	OK	
1800	25500	1.00	13	8400	13	1.92	42.5	OK	
1800	24800	.24	14	15100	6	1.73	9.9	OK	
2100	14300	1.00	15	6900	10	1.93	23.8	OK	
2100	14300	1.00	16	6300	8	2.10	23.8	OK	ALL THREE TRIPS SET SAME
2100	14300	1.00	17	6300	10	1.85	23.8	OK	
2100	14300	1.00	18	6400	9	1.98	23.8	OK	
2100	26000	.24	19	15100	8	1.50	10.4	OK	
2100	26000	.24	20	14600	7	1.58	10.4	OK	ALL THREE TRIPS SET SAME
2100	26000	.24	21	15100	6	1.74	10.4	OK	
2100	26000	.24	22	15000	6	1.74	10.4	OK	
2100	26000	.24	23	15000	6	1.74	10.4	OK	
2100	26000	.24	24	15000	8	1.50	10.4	OK	
1360	1360	23.70	25	1360	54	1.58	53.7	OK	SHUNT TRIP
1360	1360	23.70	26	1360	88	1.24	53.7	OK	" "
1360	1360	23.70	27	1360	68	1.39	53.7	OK	" "
1360	1360	23.70	28	1360	63	1.45	53.7	OK	" "
1360	1360	23.70	29	1360	60	1.49	53.7	OK	" "
1360	1360	23.70	30	1360	63	1.45	53.7	OK	" "

Table 3.6-6

TABULATION OF DC CIRCUIT BREAKER TESTS CONDUCTED IN FEB. 1973

SYSTEM VOLTAGE= 300

BREAKER TYPE MNFR D 1200

A	B	C	D	E	F	G	H	COMMENTS	
TRIP CURR AMPS	PROSP CURR AMPS	IND MH	TRACE NO	LET THRU AMPS	ARC TIME MS	PU ARC VOLTS	LOAD TC MS		
5100	11700	.88	31	7400	11	2.67	34.3	OK	SP
5100	11700	.88	32	7400	13	2.37	34.3	OK	SP
5100	19500	.88	33	8650	18	2.20	57.2	OK	SP
5100	19500	.88	34	8650	29	1.67	57.2	OK	SP
5100	27200	.12	35	15100	9	1.43	10.9	OK	SP
5100	27200	.12	36	15100	9	1.43	10.9	OK	SP
538	538	23.70	37	538	30	1.98	42.5	OK	Shunt Trip LP
538	538	23.70	38	538	29	2.02	42.5	OK	Shunt Trip LP
538	538	23.70	39	538	37	1.72	42.5	OK	Shunt Trip LP
538	538	23.70	40	538	29	2.02	42.5	OK	Shunt Trip LP
1100	1100	23.70	41	1100	68	1.84	86.9	OK	Shunt Trip LP
1100	1100	23.70	42	1100	72	1.78	86.9	OK	Shunt Trip LP
1100	1100	23.70	43	1100	65	1.90	86.9	OK	Shunt Trip LP
1100	1100	23.70	44	1100	71	1.79	86.9	OK	Shunt Trip LP
2160	2160	23.70	45	2160	123	1.95	170.6	OK	Shunt Trip LP
2160	2160	23.70	46	2160	120	1.98	170.6	OK	Shunt Trip LP

Mnfr D AQB250

This breaker was a 3 pole molded case, Navy type AQB-A250 rated at 500 volts ac and 250 amps. In general, the main difference between breakers of this type and similar rating commercial units is in the greater ruggedness of the Navy types and the different molding material.

Tests were carried out at 600 volts dc on this breaker with 3 poles connected in series in order to determine whether any significant differences could be found in the arcing characteristics; none were determined.

In setting up this unit for tests, a readily available commercial type, shunt trip coil was installed to facilitate low current tests, however, on the first test a flashover occurred from this coil to the adjacent breaker main pole and only tests using the normal magnetic trip could be carried out.

The results are tabulated below.

Table 3.6-7

TABULATION OF DC CIRCUIT BREAKER TESTS CONDUCTED IN FEB. 1973

SYSTEM VOLTAGE= 600

BREAKER TYPE MNFR D NAVY TYPE AQB-A250

A	B	C	D	E	F	G	H	
TRIP CURR AMPS	PROSP CURR AMPS	IND MH	TRACE NO	LET THRU AMPS	ARC TIME MS	PU ARC VOLTS	LOAD TC MS	COMMENTS LP INTERCONNECTION THROUGHOUT
900	1330	23.70	3	1130	32	2.01	52.5	OK
900	1330	23.70	4	1080	46	1.58	52.5	OK
900	1330	23.70	5	1110	55	1.45	52.5	OK
900	1330	23.70	6	1100	65	1.34	52.5	OK
900	1330	23.70	7	1100	60	1.39	52.5	OK
900	1330	23.70	8	1100	60	1.39	52.5	OK
900	1580	23.70	9	1200	78	1.31	62.4	POOR INTERRUPT DUE TO LOSS OF ARC VOLTS

3.7 Third High Power Test Series

A third series of tests was carried out to complete the high power testing and endurance testing of the selected breakers. Final analysis of test results shows that three types of molded case breakers performed satisfactorily under conditions simulating the mine electrical system. Discussion of the third test series continues as follows:-

Mnfr D 800

This breaker type was previously found satisfactory using three poles at 600 volts dc and this final test evaluation was using two poles and 300 volts dc. The results of the 300 volt test program which includes traces Nos. 94 through 110 were satisfactory and are given in Table 3.7-1.

A deliberate attempt to find the maximum single operation capability was made in traces Nos. 111, 112, and 113 in which interruption of 3860 amps in 15.5 mH was attempted. Tests Nos. 111 and 112 were satisfactory but in No. 113 the back-up breaker interrupted. It is concluded that this level of power which causes about 75 kilojoules dissipation per pole in each operation is close to the ultimate capability of this type of breaker.

3.8 Endurance Tests on Selected Molded Case Circuit Breakers Satisfactory for 300 Volt and 600 Volt DC Mine Use

From tests at various voltage and inductance conditions three types of molded case circuit breakers have been found capable of interrupting currents such as many occur in mine dc electrical systems. To determine the electrical ruggedness and failure modes of these selected breakers they were operated repeatedly until failure occurred.

The test procedure was more arduous than would be expected in practice. The breakers were operated fairly rapidly (at about 3 minute intervals) and the voltage and currents were representative of severe operating conditions.

Table 3.7-1

TABULATION OF DC CIRCUIT BREAKER TESTS CONDUCTED IN MARCH, 1973

SYSTEM VOLTAGE= 300

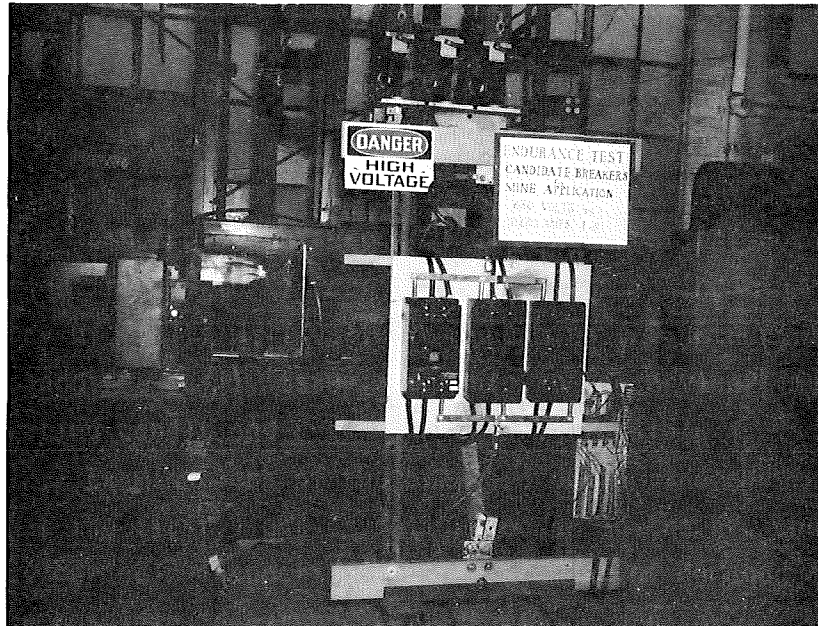
BREAKER TYPE MNFR D 800

A	B	C	D	E	F	G	H		COMMENTS
TRIP CURR AMPS	PROSP CURR AMPS	IND MH	TRACE NO	LET THRU AMPS	ARC TIME MS	PU ARC VOLTS	LOAD TC MS		
470	470	23.70	94	470	27	1.94	37.1	OK	
470	470	23.70	95	470	31	1.77	37.1	OK	
470	470	23.70	96	470	23	2.17	37.1	OK	
470	470	23.70	97	470	23	2.17	37.1	OK	
950	950	23.70	98	950	78	1.55	75.0	OK	Back Up Operated Same Time AS Breaker
950	950	23.70	99	950	48	2.12	75.0	OK	
950	950	23.70	100	950	48	2.12	75.0	OK	
950	950	23.70	101	950	57	1.88	75.0	OK	
1570	1760	23.70	102	1570	83	2.09	139.0	OK	
1760	1760	23.70	103	1760	112	1.81	139.0	OK	
1740	1740	23.70	104	1740	80	2.27	137.5	OK	
3870	11000	.88	105	6330	13	2.16	32.3	OK	
3870	11000	.88	106	6300	16	1.89	32.3	OK	
3870	19800	.88	107	6900	13	2.39	58.1	OK	
3870	19800	.88	108	6900	13	2.39	58.1	OK	
3870	27600	.12	109	13000	10	1.32	11.0	OK	
3870	27600	.12	110	12800	8	1.44	11.0	OK	
3350	3860	15.50	111	3350	138	1.87	199.4	Flame but extinguished	OK
3860	3860	15.50	112	3860	230	1.46	199.4	Flame but extinguished	OK
3860	3860	15.50	113	3860	999	1.01	199.4	Failed to interrupt. Flame self extinguishing. Would not reclose	

The number of high current fault interruptions obtained before failure varied from 68 to 97 for the three types. Since the severity and frequency of faults will vary from one mine to another, the number of faults cannot be easily translated into an in-service life, although if the operating conditions are known this is feasible as indicated in Section 3.12. Examinations of the breakers during the endurance test revealed that the first signs of failure occur in the arc chutes of the breaker. By periodic inspection and replacement of damaged arc chutes, it should be possible to extend the life of the breaker.

In order to reduce the time required for endurance tests, the three candidate breaker types were mounted on a test stand and wired in parallel. During tests they were operated sequentially and this procedure not only enabled the breakers to be tested for current interruption at 3 minute intervals, but also during the off period subjected the circuit breaker to a dielectric stress caused by the opening of a parallel breaker. After 55 rapid shots on each breaker it was noted that in the area of the arc chutes significant temperature rise had occurred on the outside of the breakers and a fan was added to the test assembly to provide cooling before the tests continued.

A picture of the test assembly is shown below.



On the left is mounted a circuit breaker described as Mnfr A 1200, at center a breaker type Mnfr D 1200 and at right type Mnfr D 800. Each breaker has its poles connected and in series such that current flow is the same way in each pole.

The endurance tests were conducted at 630 volts dc (5% higher than normal 600 volts) and with a fault impedance to provide nominally 11,000 amperes in 1 mH. Each breaker operated successfully 55 times at this level. Subsequently, to hasten failure, the level of fault was changed to 10,500 amps in 2 mH.

A summary of the endurance test data is tabulated in Table 3.8-2.

Comments on Endurance Tests

The failure modes of the three breakers were all different; however, it is noted that the total energy absorbed by each before failure was similar. This energy absorption factor may provide a criteria for determining life in a given application. It is probable that periodic inspection and replacement of the arc chutes would enable longer life to be obtained since a gradual deterioration of arc voltage was noted during tests as shown in the oscillograph recordings.

Endurance tests were carried out at 630 volts only since it is considered that this voltage is much more exacting on the circuit breakers than would be a 2 pole, 300 volt test.

At the conclusion of tests the main current carrying contacts of the breakers appeared to be in satisfactory condition.

A more complete history of the interrupting conditions for each test breaker is given in the following tables and figures.

Table 3.8-2

<u>Breaker Type</u>	<u>Total No. of Interruptions</u>	<u>*Total Energy Absorbed k Joules</u>	<u>Failure Mode</u>	<u>Comments</u>
Mnfr A 1200	68	4161	Poor interrupt breaker could not be reclosed.	As the number of interruptions increased the arc voltage gradually reduced and the arc chutes showed wear. The arc plates had molten metal particles deposited on them.
Mnfr D 1200	97	4181	Failed to interrupt flashover between poles 1 and 2.	As testing proceeded, the interruption was less positive and the arc chutes showed wear. An external flashover to the test bus work occurred on shot 71 but only slight damage was caused to breaker connector. External bus was insulated and tests continued.
Mnfr D 800	94	3780	Breaker interrupted but considered failed due to excessive smoke emission.	This breaker was new at start of endurance tests. Eventually flame and smoke occurred due to thin paper barrier (2 thickness of 1/32") over top of arc chutes. Breaker arc chutes showed wear.

* Approx. calculated as $\Sigma (\text{Arc Volts} \times \text{Arcing Time} \times \text{Peak Current}/2)$

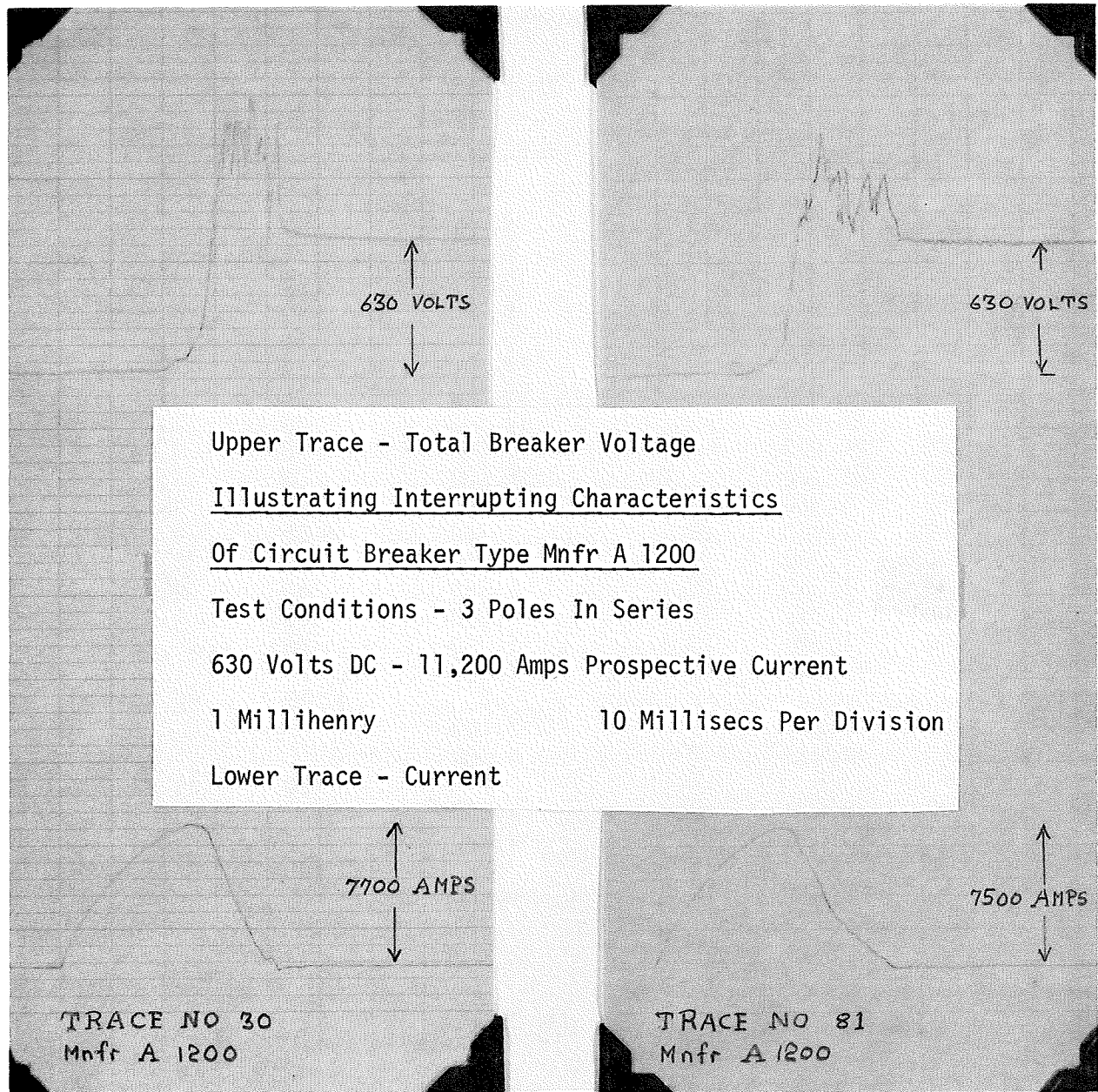
Endurance Test Data
Mnfr A 1200

Trace No.	SYSTEM PARAMETERS			Peak Let-Thru Current Amperes	Arcing Time mS	P.U. Arc Voltage	Approx Energy Absorbed k Joules
	Voltage Volts	Current Amperes	Inductance mH				
19	300	500	24	500	23	2.29	4
20	300	1,060	24	1,060	48	2.31	17.6
25	300	12,600	0.88	7,100	13	2.34	32.4
26	300	25,300	0.19	15,600	6	2.36	33.1
27	300	27,600	0.22	16,200	7	2.42	41.2
28	300	19,500	0.88	8,200	16	2.30	45.3
29	300	19,500	0.88	9,500	19	2.24	60.6
22	600	14,200	1.0	9,250	30	1.26	105
23	600	14,200	1.0	9,250	28	1.29	100
24	600	14,200	1.0	10,500	27	1.35	115
30	630	11,200	1.0	7,600	13	*18	*60
Thru	↓	↓	↓	↓	21		
84	630	11,200	1.0	7,600			
85	630	10,500	2.0	6,000	28	1.43	76
86	630	10,500	2.0	6,000	37.5	1.27	90
** 87	630	10,500	2.0	6,000	69	1.08	141

* Average Values

TOTAL ENERGY ABSORBED AT FAILURE = 4161 kilojoules

** At Trace No. 87 interruption was slow and the breaker could not subsequently be reclosed.



Illustrating Arc Voltage Change During Endurance Test

Endurance Test Data
Mnfr D 1200

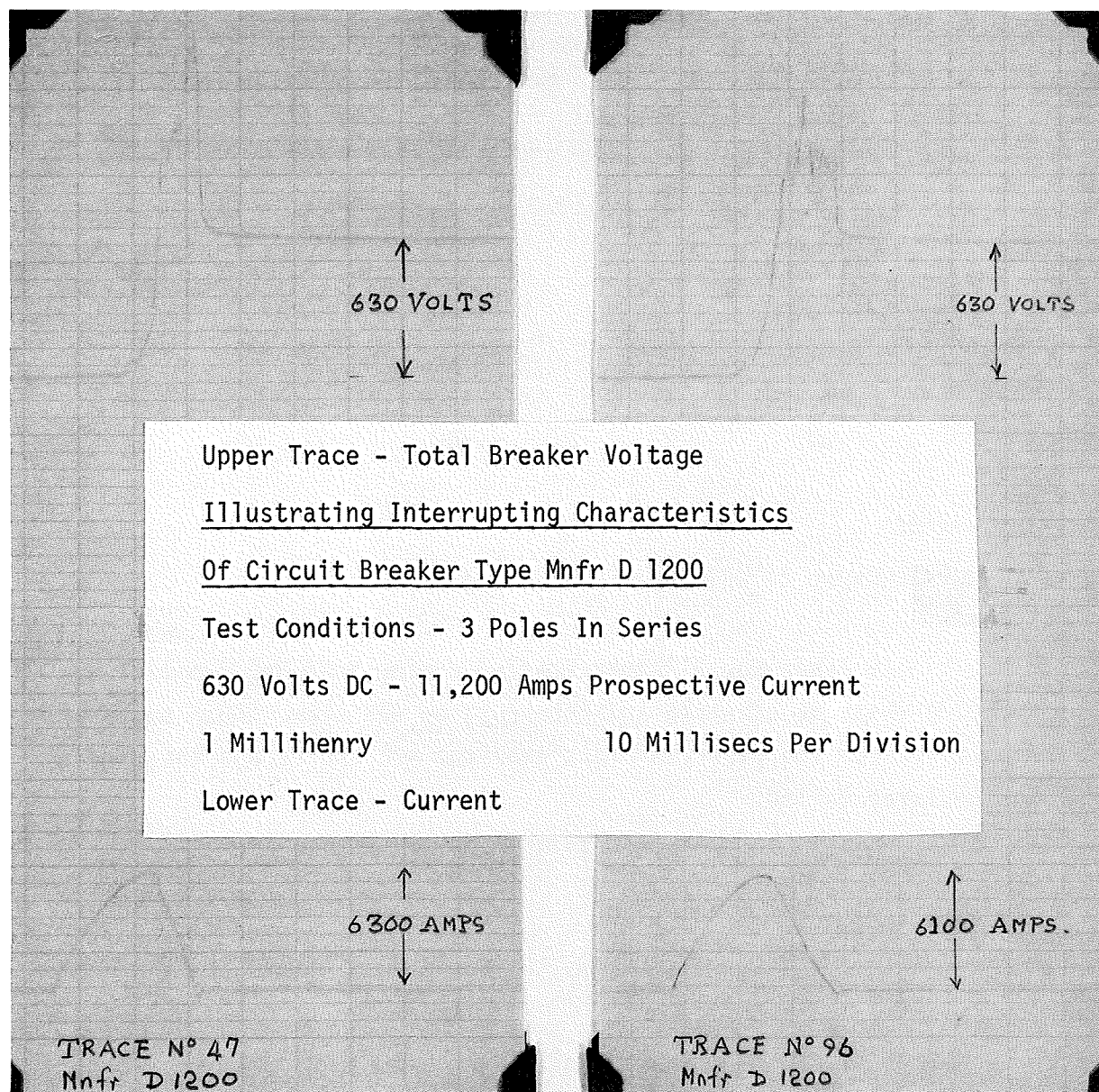
Trace No.	SYSTEM PARAMETERS			Peak Let-Thru Current Amperes	Arcing Time mS	P.U. Arc Voltage	Approx Energy Absorbed k Joules
	Voltage Volts	Current Amperes	Inductance mH				
15	600	14,300	1.0	6,900	10	1.93	40
16	600	14,300	1.0	6,300	8	2.10	32
17	600	14,300	1.0	6,300	10	1.85	35
18	600	14,300	1.0	6,400	9	1.98	34
19	600	26,000	.24	15,100	8	1.5	54
20	600	26,000	.24	14,600	7	1.58	48
21	600	26,000	.24	15,100	6	1.74	47
22	600	26,000	.24	15,100	6	1.74	47
23	600	26,000	.24	15,000	6	1.74	47
24	600	26,000	.24	15,000	8	1.5	54
25	600	1,360	23.7	1,360	54	1.58	35
26	600	1,360	23.7	1,360	88	1.24	44
27	600	1,360	23.7	1,360	68	1.34	38
28	600	1,360	23.7	1,360	63	1.45	37
29	600	1,360	23.7	1,360	60	1.49	36
30	600	1,360	23.7	1,360	63	1.45	37
47	630	11,200	1	6,100	9	*12	36
Thru	↓	↓	↓	↓	15		*36
102	630	11,200	1	6,100			
103	630	10,500	2	4,600	*20	*1.53	*44
Thru	↓	↓	↓	↓			
115	630	10,500	2	4,600			
116	630	10,500	2	4,600	*35	*1.22	*62
Thru	↓	↓	↓	↓			
129	630	10,500	2	4,600			

* Average Values

TOTAL ENERGY ABSORBED AT FAILURE = 4181 kilojoules

At Trace No. 102 an external flash occurred between pole No. 3 and the incoming positive bus. Interruption was slow and caused an additional 60 kilojoules in arc. The bus was insulated and tests continued. Interruption was slow in No. 108 due to temporary reduction of arc voltage. From Traces No. 116 onward interruption was slower still, typically 35 milliseecs until in 129 a flashover occurred between poles 1 and 2. Subsequently the breaker could not be reclosed.

Trace Nos. 47 and 96 are included and show the effects of arc voltage changes during test.



Illustrating Arc Voltage Change During Endurance Test

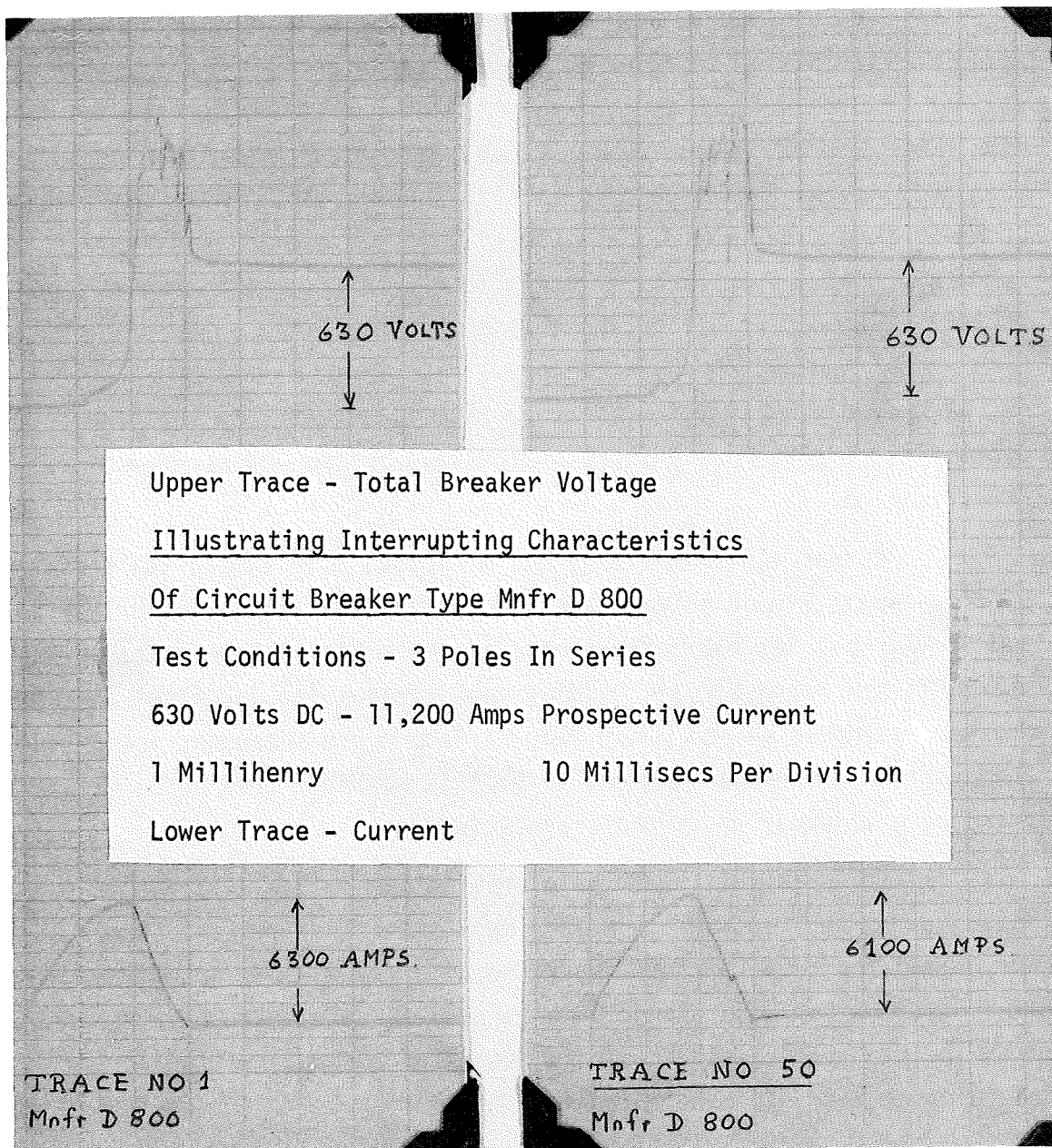
Endurance Test Data
Mnfr D 800

Trace No.	SYSTEM PARAMETERS			Peak Let-Thru Current Amperes	Arcing Time mS	P.U. Arc Voltage	Approx Energy Absorbed k Joules
	Voltage Volts	Current Amperes	Inductance mH				
1	630	11,200	1	6,200	11		
Thru	↓	↓	↓	↓	↓ *12	*1.59	*38
55	630	11,200	1	6,200	13		
56	630	10,500	2	4,600	20		
Thru	↓	↓	↓	↓	↓ *20	1.53	*44
93	630	10,500	2	4,600	21		

*
Average Values

TOTAL ENERGY ABSORBED AT FAILURE = 3762 kilojoules

At Trace No. 91 smoke started coming from No. 2 pole. At No. 93 a restrike occurred and interruption was slow. Much smoke was emanating from the paper barriers over the arc chutes and the breaker was declared failed.



Illustrating Arc Voltage Change During Endurance Test

3.9 Molded Case Circuit Breaker Transient Current Rating

The continuous rating of molded case ac circuit breakers is partly determined by temperature rise criteria of the connectors as defined in Underwriters Laboratories Standard UL 489. In general, the continuous current rating must not cause a temperature rise of greater than 50°C at the breaker terminals. This corresponds under worst case conditions to a maximum temperature of 100°C at the connector and to a temperature at the contacts of about 125°C. The contact temperature is thought to represent a limiting feature and practical engineering judgement indicates that for satisfactory life, limits of 150-200°C should not be exceeded. Actual temperature rise is affected by the size of the connecting conductors and these are defined in the Underwriters' specification.

Curves and formulae given in Section 3.10 enable the transient loading capability of molded case circuit breakers to be determined in such a way that the temperature rise at the contacts is comparable to that obtained in continuous loading applications for which the circuit breaker rating is normally defined. If the circuit breaker incorporates a conventional thermal overload trip it is possible that nuisance tripping will occur under these conditions.

It is thought that these application curves will result in satisfactory service life; however, exhaustive life tests to prove this are beyond the scope of the present work. As a further practical guide it is recommended that connections be periodically checked to ensure that the stresses caused by cyclic expansion and contraction do not cause connections to become loose.

3.10 Circuit Breaker Current Rating for Mine Application

Tests have been made to confirm the short duration load current rating of the acceptable molded case circuit breakers. In the haulage system, the breaker is normally subjected to very high currents (above the nominal nameplate rating) for short periods of time. For example,

a breaker connected between the trolley wire and dc substation passes a high current during the time a haulage locomotive is passing through the section energized by that particular substation. Since the peak currents are several times greater than the rated current of the breaker, it is important to know the safe limits for these higher currents. Safe current vs time ratings were predicted from a theoretical analysis of the factors affecting the breaker performance and tests were then made of the actual breaker performance. The data has been converted into application curves which enable the user to select the proper circuit breaker for use in any dc mine application.

A possible repetitive temperature, current, and time relationship is shown in Figure 3.10-1.

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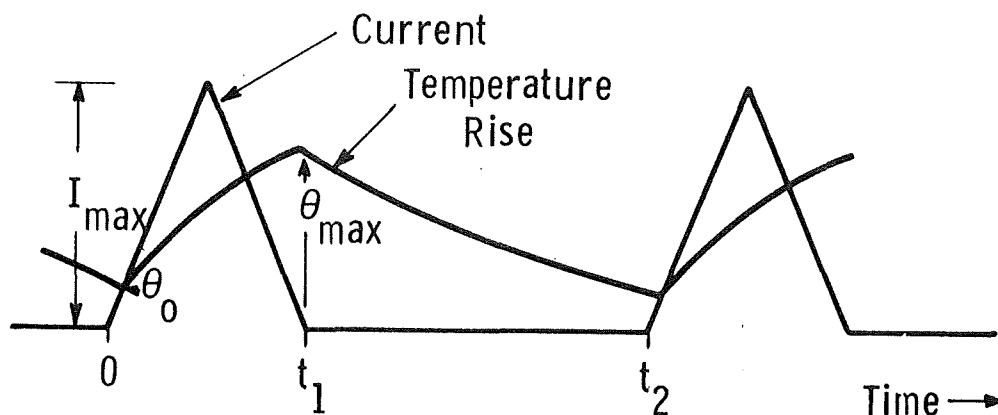


Fig. 3-10-1—Illustrating possible transient loading and temperature rise of circuit breaker (typically $t_1 = 10$ minutes, $t_2 = 40$ minutes)

Referring to Figure 3.10-1, the rms current carried by the circuit breaker is given by $\frac{I_{\max}}{\sqrt{3}} \sqrt{\frac{t_1}{t_2}}$. However, because of the temperature perturbations caused by fairly long intervals between pulses it is not safe to assume this rms current can equal the breaker continuous current rating as normally defined by the manufacturer. A more detailed calculation is necessary which includes the effects of the circuit breaker thermal time constant. To obtain the value of the thermal time constant, direct current tests were made on the 800 ampere frame circuit breaker described as Mnfr D 800. The poles were interconnected as for 600 volt operation using two 300 kcmil copper conductors in parallel. From these tests, shown in Figure 3.10-2, it was determined that the temperature rise of the contacts and connecting studs could be reasonably well defined for time duration pulses of 60 minutes or less by the relationships

$$\Theta = 62 \times \left(\frac{I_{\text{RMS}}}{800} \right)^2 [1 - e^{-t/35}]$$

where t is the time in minutes and Θ is the temperature rise in °C of both contact and connector. It is recognized that this is only approximate since there is a long time constant effect which eventually increases the temperature of the contact to about 13°C above the connector at rated current. For the short pulse approximation the thermal time constant of the circuit breaker is about 35 minutes and similar values of time constant are considered applicable for the other two types of circuit breakers, namely Mnfr A 1200 and Mnfr D 1200.

Calculations for Pulse Loads

A sketch of the probable temperature and current variations is shown in Figure 3.10-1. For analysis the following definitions are applied.

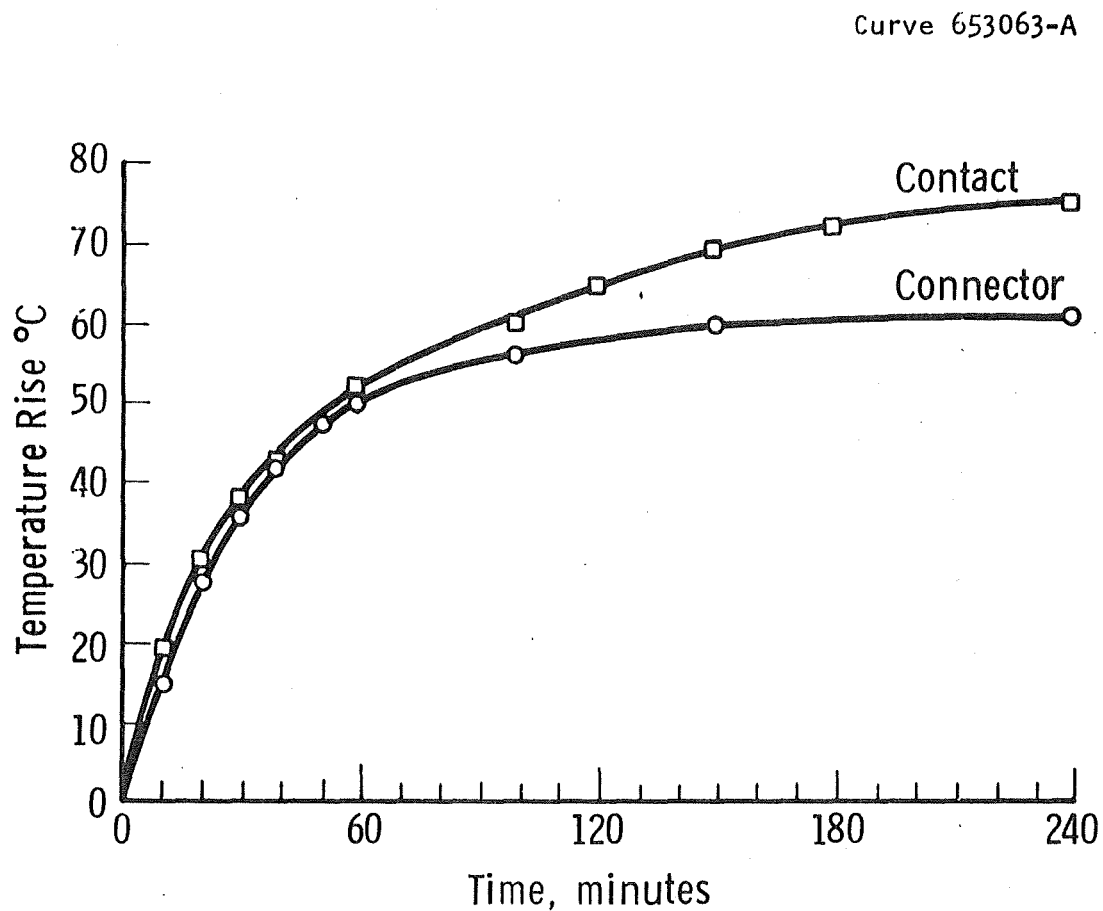


Fig. 3.10-2—Illustrating temperature rise of center pole fixed contact and load side connector for breaker type Mnfr D 800. Each pole carrying 800 amperes dc. Connections between poles and power supply was two parallel conductors of 300 kcmil copper cable, 4 ft long.

Let

- θ = Breaker instantaneous temperature rise
- $\theta_{\max}$ = Maximum breaker temperature rise
- θ_0 = Initial breaker temperature rise
- θ_d = Maximum breaker temperature rise permitted for continuous rated operation
- t_1 = Current conduction time
- t_2 = Cycle repetition time
- I_{rated} = Breaker continuous current rating specified by manufacturer
- $I_{t_1 \text{rms}}$ = rms value of load current over time t_1 [For example, $I_{t_1 \text{rms}} = I_{\max} / \sqrt{3}$ for triangular wave]
- T = Breaker thermal time constant [typically 35 minutes]

During the period 0 to t_1 the breaker heats up and from t_1 to t_2 it cools. There will be an equilibrium condition after a few cycles of operation in which the maximum temperature rise $\theta_{\max}$ just reduces to the initial value θ_0 in time $(t_2 - t_1)$, and from this condition the transient rating can be calculated.

To simplify the calculations, a practical assumption is made that time t_1 is less than the thermal time constant of the circuit breaker. Also, it is assumed that temperature rise varies only as the square of the current, i.e. the changes of resistivity which occur with temperature and also the change of cooling with temperature are neglected. This is a reasonable assumption since these two factors tend to have counteracting effects.

For these conditions the equations determining temperature are from time 0 to t_1

$$\theta = \theta_0 e^{-t/T} + \left(\frac{I_{t_1 \text{ rms}}}{I_{\text{rated}}} \right)^2 \cdot \theta_d [1 - e^{-t/T}] \quad (1)$$

and at equilibrium $\theta = \theta_{\text{max}}$ for $t = t_1$

From time t_1 to t_2 we have

$$\theta = \theta_{\text{max}} e^{-(t - t_1)/T} \quad (2)$$

and at equilibrium $\theta = \theta_0$ for $t = t_2$

Combining these two equations we obtain an equilibrium condition such that if θ_{max} just equals the design permitted value θ_d then

$$I_{\text{rated}} = I_{t_1 \text{ rms}} \sqrt{\frac{(1 - e^{-t_1/T})}{(1 - e^{-t_2/T})}} \quad (3)$$

Equation 3 can be used to determine the required circuit breaker for any pulse load rating and is illustrated in Figure 3.10-3.

As an example, assume the circuit breaker has a current rating of 800 amps and a triangular pulse of current is applied over a 7.5 minute period with a total period of 20 minutes. From Figure 3.10-3 the factor $I_{t_1 \text{ rms}}/I_{\text{rated}}$ equals 1.5. Since the pulse of current is triangular its peak is $\sqrt{3} \times 800 \times 1.5$, i.e. 2080 amps, therefore the calculated pulse pattern permitted is as shown in Figure 3.10-4.

It is calculated that the maximum temperature rise in this condition will be similar to that for a continuous current of 800 amps.

Measurements made on the circuit breaker type Mnfr D 800 with the pulse pattern of Figure 3.10-4 resulted in a maximum temperature rise of 84°C and the initial temperature rise θ_0 was 52°C.

As an additional check on the application curves of Figure 3.10-3 a rectangular pulse load of 1200 amps was applied for a

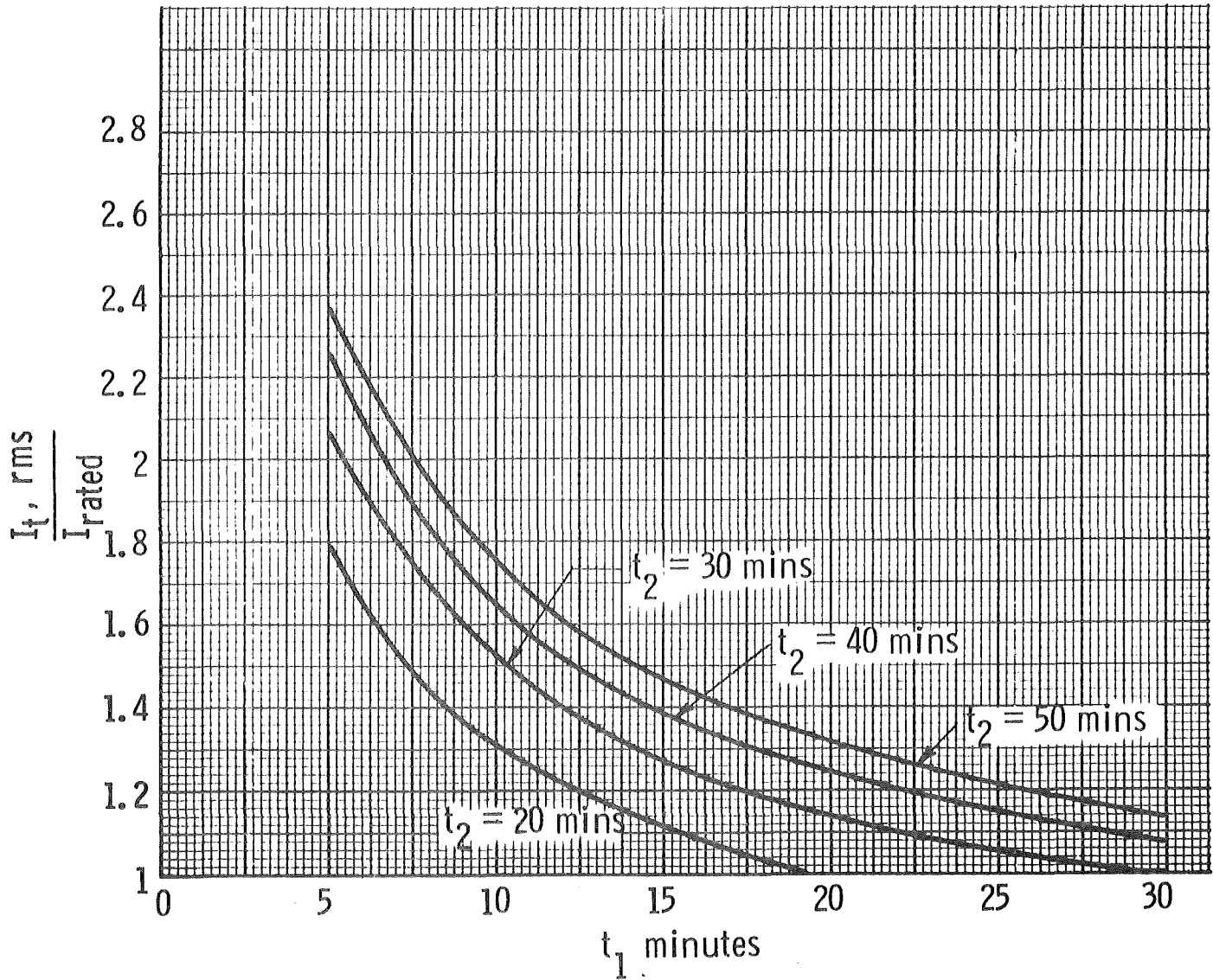


Fig. 3.10-3—Transient current rating for circuit breakers with 35 minute thermal time constant [Conduction time t_1 - Cycle time t_2 - No other loading]

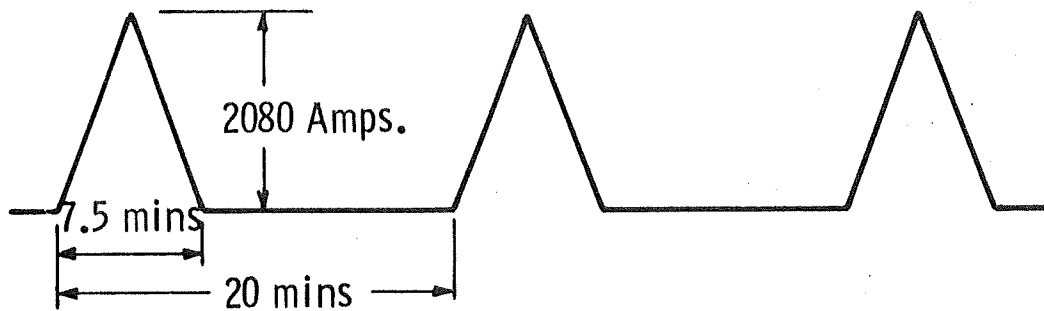


Fig. 3.10-4—Example of pulsed circuit breaker load

period of 7.5 minutes with a cycle time of $t_2 = 20$ minutes; in this case the measured temperature rise of the contact at equilibrium was 84°C and Θ_0 was 57°C . Similarly a rectangular pulse load of 1660 amps for 5 minutes with a cycle time of 30 minutes produced a temperature rise at the contact of 89°C .

It is noted that these temperature rise values are somewhat higher than the normal maximum temperature rise for steady current which is 75°C , however, they are considered acceptable for ambient temperatures up to 50°C .

If the circuit breaker is subjected to a steady load, as well as pulse load, the transient loading capability will be reduced. For example, for continuous loads of half or less of the circuit breaker rating, the pulse current rating will be as shown in Figure 3.10-5. For other conditions where the steady loading is I_2 amperes, the pulse load capability can be calculated from

$$\frac{I_{t_1 \text{ rms}}}{I_{\text{rated}}} = \sqrt{\frac{(1 - e^{-t_2/T}) - \left(\frac{I_2}{I_{\text{rated}}}\right)^2 (e^{-t_1/T} - e^{-t_2/T})}{(1 - e^{-t_1/T})}}$$

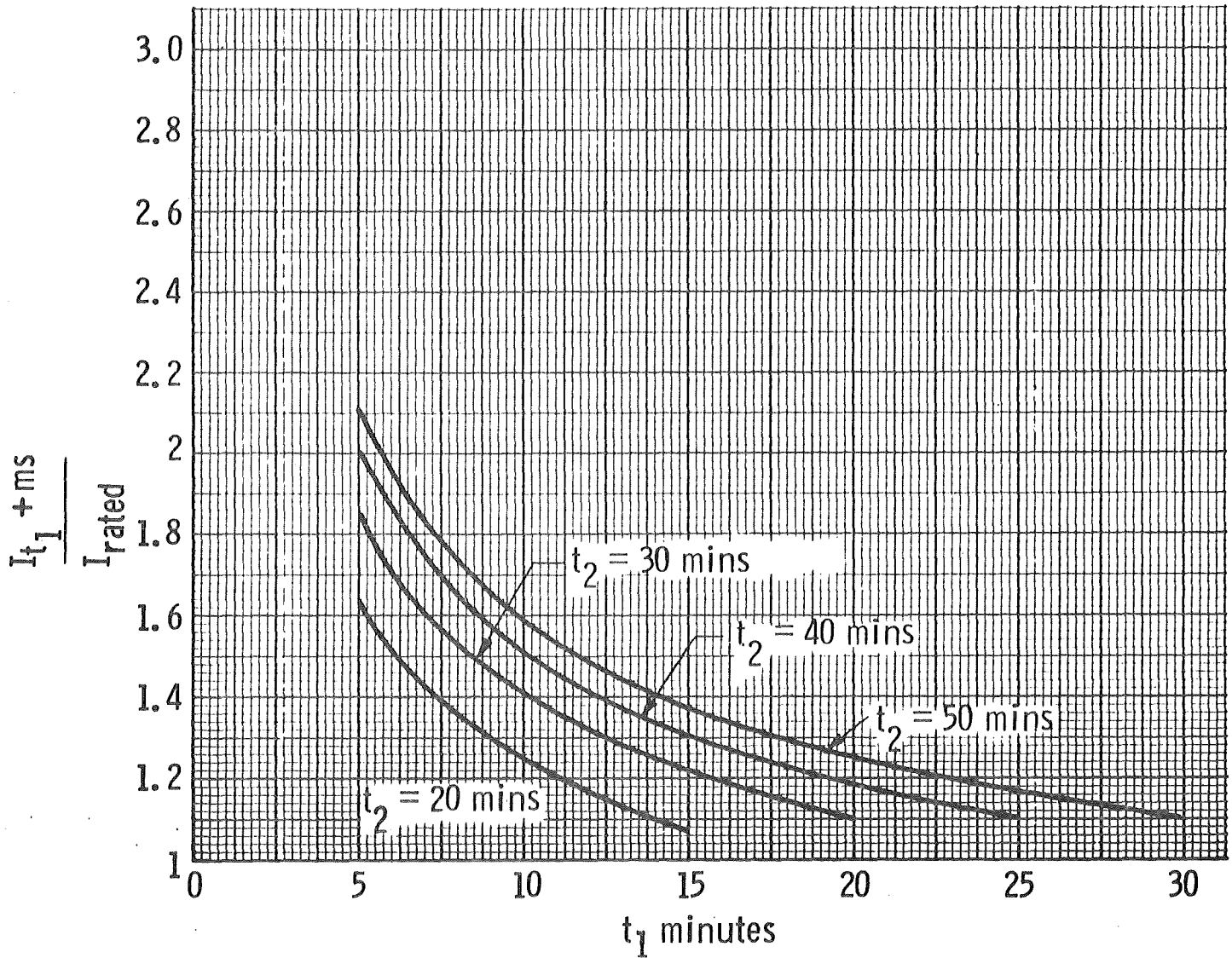


Fig. 3.10-5-Transient current rating for circuit breakers with 35 minute thermal time constant [conduction time t_1 - cycle time t_2 - normal continuous loading of half-rated]

3.11 Circuit Breaker Shunt Trip Requirements

It was found during high power tests that the conventional shunt trip coil and microswitch assembly used routinely for ac circuit breakers was a weak point that could cause the high voltage arc to flashover to ground during interruption of high dc currents. This weakness is caused by exposed soldered connections on the microswitch and is readily overcome in a discriminating circuit breaker design (discussed in Section 4.2) which eliminates the microswitch. In this design the circuit breaker is operated by means of a well insulated shunt trip coil energized by a momentary pulse of current from a charged capacitor. The range of dc voltage and capacitance necessary to operate a 120 volt ac shunt trip coil at ambient temperatures of 25°C was determined from a coil supplied by manufacturer D and is given in Table 3.11-1.

Table 3.11-1. Minimum dc voltage required on charged capacitor to operate 120 volt ac shunt trip coil of resistance 21 Ω

Capacitance	μ F	70	270	440	620	1000	1500
Voltage	Volts	120	50	40	35	30	28

3.12 The Selected Circuit Breakers and Application Guidelines

The following circuit breakers were tested and found adequate to meet the interrupting conditions prevailing in dc mines with voltages varying from 300 to 600 volts and power supplies ranging from up to 1000 kW rectifier units and up to 500 kW generators.

Manufacturer A 1200

This is a 3 pole molded case construction ac circuit breaker made by General Electric Co. It comes in a frame size known as the K1200 line and is available up to 1200 amps maximum rating. The particular type tested satisfactorily was THKMA 836600 rated at 600 amps. The weight was 33.3 lbs and the cost was \$378.

Manufacturer D 800

This is a 3 pole molded case construction ac circuit breaker made by the Westinghouse Electric Corporation. It comes in a frame size known as type MA and is available up to 800 amps maximum rating. The particular type tested satisfactorily was MA800. The weight was 35 lbs and the cost was \$294.

Manufacturer D 1200

This is a 3 pole molded case construction ac circuit breaker made by the Westinghouse Electric Corporation. It comes in a frame size known as type NB and is available up to 1200 amps maximum rating. The particular type tested was an NB1200. The weight was 39.9 lbs and the cost was \$480.

Application Guidelines for DC Mine Use

The following application guidelines for use of molded case circuit breakers on dc power systems are drawn up based on the results of both high and low power tests:

1. For 600 volt operation connect 3 poles in series so that current flows in the same way in each pole in order, i.e. join poles 1 and 2 and poles 2 and 3.
2. For 300 volt operation use the two outer poles of the circuit breaker with current flowing the same way in each pole.
3. Set the magnetic trips with interconnecting cables between poles laid out as in the actual application. Use the lowest value of trip setting possible consistent with freedom from nuisance tripping. Do not exceed 2000 amp trip settings for 600 volt, 3 pole operation or 4000 amp trip setting for 300 volt, 2 pole operation.

4. Mount in an upright position.
Leave an adequate space 6" - 12" or use insulation between circuit breaker connectors and the enclosure to prevent ejected arc plasma causing a ground arcing flashover.
5. From the tables in Section 3.10 choose a steady-state current rating adequate to handle the transient load demands. (Until long term life data has been accumulated it is recommended that the calculated circuit breaker rating required be increased somewhat over that obtained from the tables, say by about 10%.)
6. Periodically check that the circuit breaker connections remain tight and that the arc chutes are in good condition. Replace the arc chutes if it is known that the total energy absorbed is greater than about 800 kilojoules per pole. Depending upon the application, this will correspond to about 50 or more high fault current interruptions.

If the load inductance is L henrys, and current is I amperes and there are P poles in series, then No. of Operations before arc chute replacement $\approx 800 \times P \times 10^3 / (L \times I^2)$.

For example, a load of 2.4 mH and 4000 amperes could be interrupted by a 3 pole circuit breaker about 60 times before maintenance.

In the limit, the number of operations should not exceed those given by Underwriters' specifications for molded case circuit breakers as tabulated in the following.

Table 3.12-1. Underwriters' requirements for
switching molded case circuit breakers

<u>Frame Size in Amperes</u>	<u>Number of Cycles of Operation With Current</u>	<u>Without Current</u>	<u>Total</u>
600	1000	5000	6000
800	500	3000	3500
1200	500	2000	2500

SECTION 4. DISCRIMINATING CIRCUIT BREAKER

4.1 Introduction

The discriminating circuit breaker, abbreviated to DISCB, is required to detect the presence of illegitimate loads such as could be caused by fallen cables or leaky insulators and interrupt power to these unwanted loads when certain maximum values are exceeded. The detectable value, typically 30 amperes for a 600 volt system, is much less than the normal legitimate load current. It is not possible to guarantee that fire risk is zero with this illegitimate load trip value, however, it is clearly very much less probable and far safer than conventional trip units which only operate at currents about 60 times as large. The DISCB must be capable of passing the full range of legitimate load currents without false tripping, also it must be capable of interrupting high overloads such as could be caused by bolted fault conditions. To meet these objectives the DISCB is equipped with a conventional instantaneous magnetic trip unit set typically at 1800 amps and a shunt trip unit which is activated by commands from electronic sensing circuits which detect when an illegitimate load impedance of $20\ \Omega$ or less is present. This is the lowest sensitivity. Depending on where the illegitimate load is located it may be possible to detect $30\ \Omega$ or greater.

In some mine installations it may be undesirable to shut down the complete mine dc power system when an illegitimate load occurs and to achieve selective protection for this situation a system concept is envisaged which uses appropriately spaced circuit breakers capable of isolating faulty sections or branches. Different installations will require individual design; however, the control units for different systems are the same. Appropriate selectivity of the DISCB's can be obtained by adjustment of trip settings and inverse time delays. Where

selective protection is required it is necessary to use more than one oscillator and control unit to retain integrity of protection for the remaining sections.

To prevent oscillators from appearing as illegitimate loads either suitably spaced "dead blocks" or pulsed operation of the oscillators is necessary. It is anticipated that for 600 volt systems "dead block operation" in which the mine wiring is split into electrically separate systems will be feasible and most simple to implement.

4.2 Operating Principles of Discriminating Circuit Breakers

The system diagram in Figure 4.2-1 shows the DISCB concept.

To detect the presence of illegitimate loads, a low power sinusoidal oscillator is used to apply a 3 kHz ac voltage to the trolley wires and feeders. The basic concept is similar to that described in CERCHAR PUBLICATION No. 1306 of January, 1963 and that suggested in Bureau of Mines request for proposal No. H0122058. It was selected after extensive analysis of alternate techniques. The frequency of 3 kHz was selected so as to give good signal transmission over 5000 ft as discussed in practical tests on a mine system (Section 2.8).

The ac currents from the oscillator are coupled into the trolley cables and feeders by means of a blocking capacitor, suppression choke, and damping resistor. The function of the latter being to control ac currents which may flow in the oscillator as a result of line voltage transients caused by normal loads.

In the event of an illegitimate load a 3 kHz current will flow through the detector transformer (which is tuned to resonate at 3 kHz) and when a certain preset level is exceeded the electronic controls of the DISCB cause the circuit breaker to operate by means of a voltage applied to the shunt trip coil.

Since the mine cable has inductance it will resonate at some point along its length with the coupling capacitor and the design is arranged so that at this point an illegitimate load impedance of 30 Ω

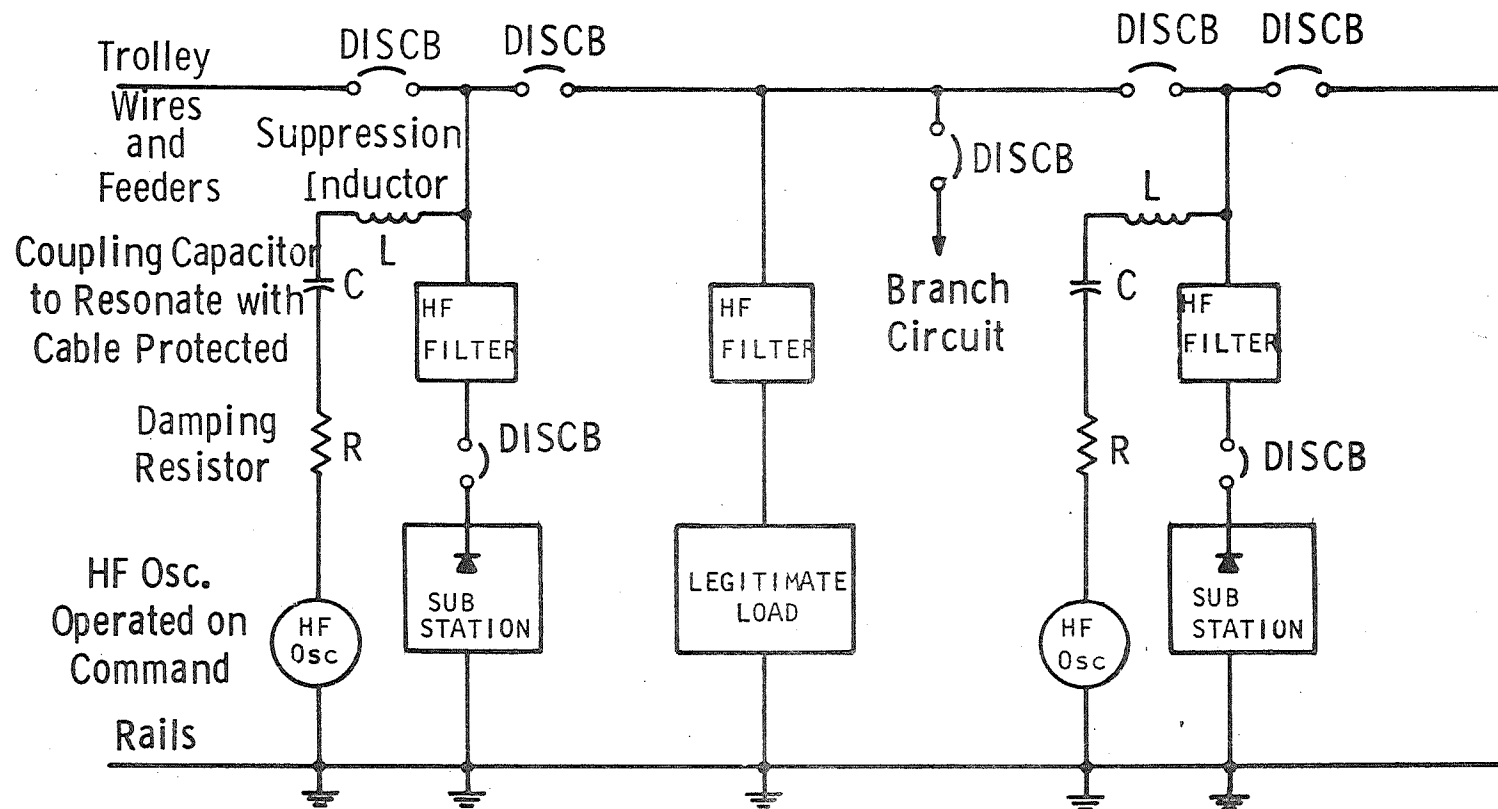


Figure 4.2-1—Illustrating systems concept for applying discriminating circuit breaker DISCB

can be detected. For a fault at the oscillator where capacitance reactance is dominant or at the end of the cable where inductive reactance is dominant the detectable illegitimate load is about 20 Ω .

To prevent legitimate loads and power substations from providing paths through which the 3 kHz ac currents could flow the impedance of these paths must be greater than 30 Ω at 3 kHz and the total parallel impedance of the legitimate loads would desirably be greater than about 100 Ω . Depending on individual characteristics of the legitimate loads, additional ac filters may be necessary to achieve the required impedance level.

A circuit presentation and calculation of signal currents as a function of fault resistance is shown in Figure 4.2-2. Resonance occurs at a cable length of 2500 ft and the protected length is 6400 ft. Maximum and minimum currents in the detector are shown as a function of fault resistance.

4.3 Components of Discriminating Circuit Breaker

The elements required for a discriminating circuit breaker system are summarized as follows:

- a. Power Circuit Breaker - The breaker is equipped with instantaneous magnetic trip and also a shunt trip coil. In the circuit breaker assembly is included a current transformer to detect the 3 kHz ac signals.

- b. Discriminating Circuit Breaker Control Unit

This unit contains the electronic circuits necessary to process data from the current transformer in the circuit breaker enclosure and transmit appropriate signals to the shunt trip coil.

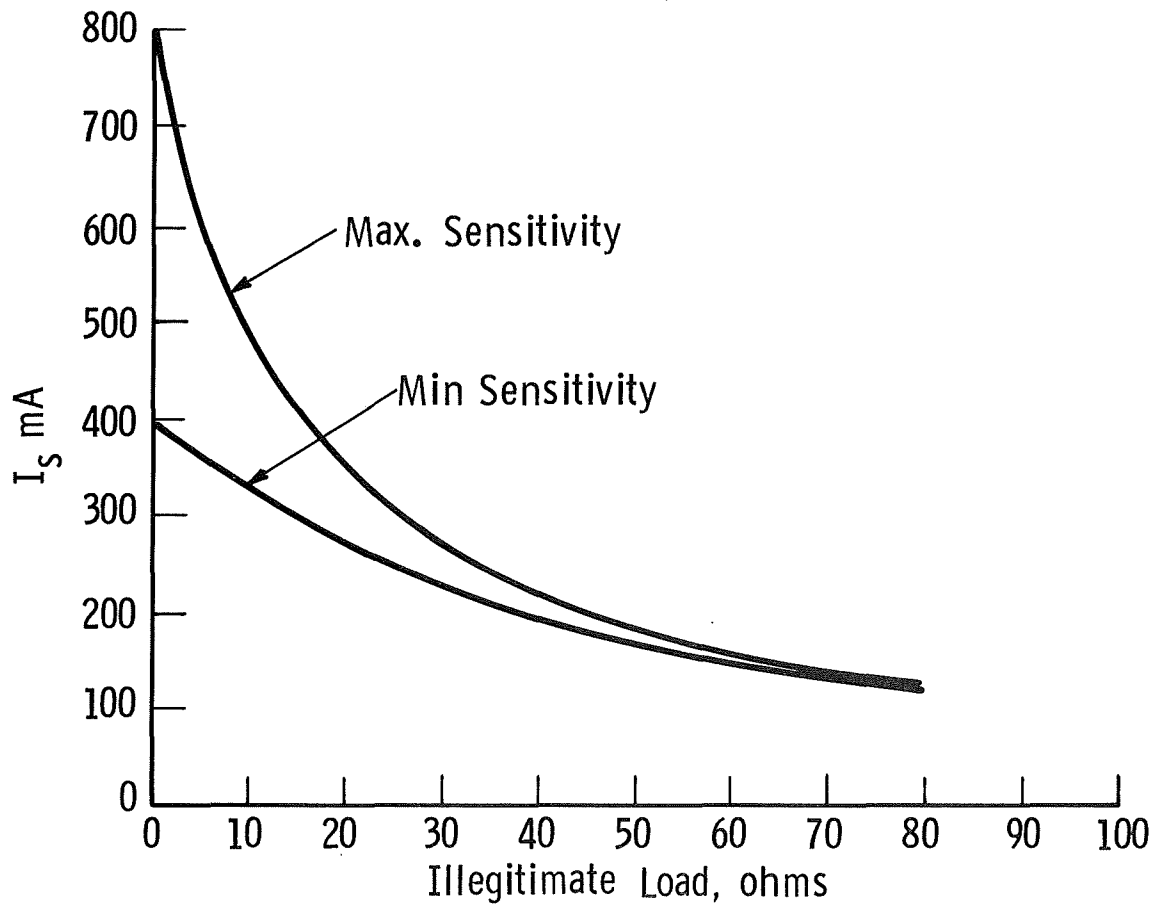
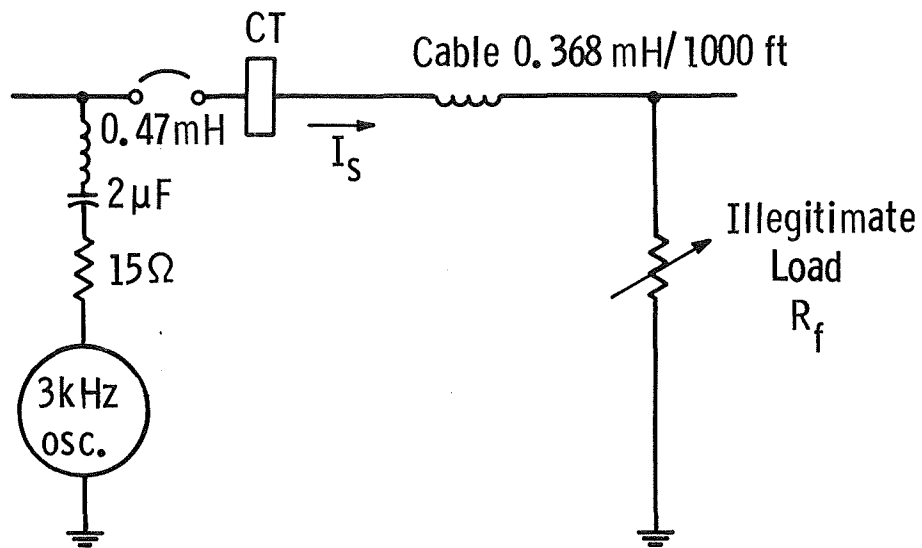


Fig. 4.2-2—Calculated signal current I_s as a function of illegitimate load (12 Volt Oscillator)

- c. High Frequency Oscillator - The oscillator generates a 15 volt sinusoidal voltage and applies it through a coupling capacitor, suppression inductor and resistor to the trolley wire and feeder cables.
- d. AC Filters for Legitimate Loads - These may be either passive or active filters to raise the impedance at 3 kHz of the legitimate loads or substations. Their size and complexity depends on individual mine applications and in some installations they may be unnecessary.

A detailed discussion of these system components follows in the ensuing sections.

4.4 Power Circuit Breaker

Power circuit breakers that can be used to interrupt power on both 600 volt and 300 volt dc systems are listed in Section 3.12. For a prototype 600 volt unit a Westinghouse type MA breaker rated for commercial use at 800 amps was selected with the instantaneous trip set at 1540 amps ac. Three poles are connected in series by two parallel 300 kcmil cables. The breaker and the air cored current transformer are mounted in a Nema type 12 enclosure measuring 36" x 24" x 10".

Details of the air cored current transformer used to detect 3 kHz ac signals are given in Spec Sheet DCB-CTI in Appendix 6 and a photograph of the circuit breaker assembly is given in Figure 4.4-1.

4.5 Discriminating Circuit Breaker Control Unit

A complete circuit schematic of the prototype DISCB control unit is given in Figure 4.5-1. Power to operate the unit is drawn from the 600 volt feeder cable via a 2400 Ω dropping resistor such that continuous operation over the range of 350 to 700 volts is possible. An input rectifier bridge permits the unit to operate with either positive or negative potential on the trolley wires. The total power

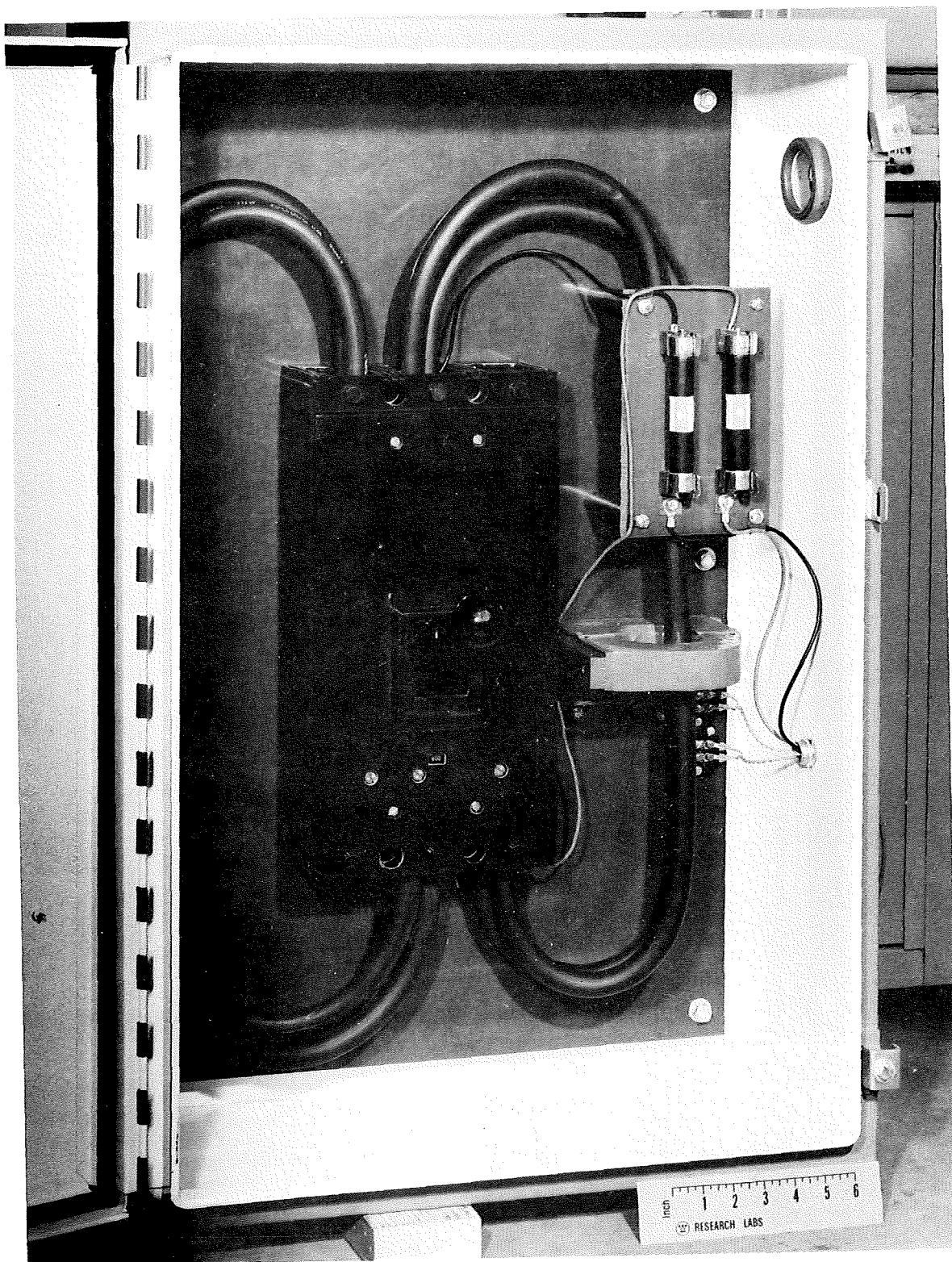
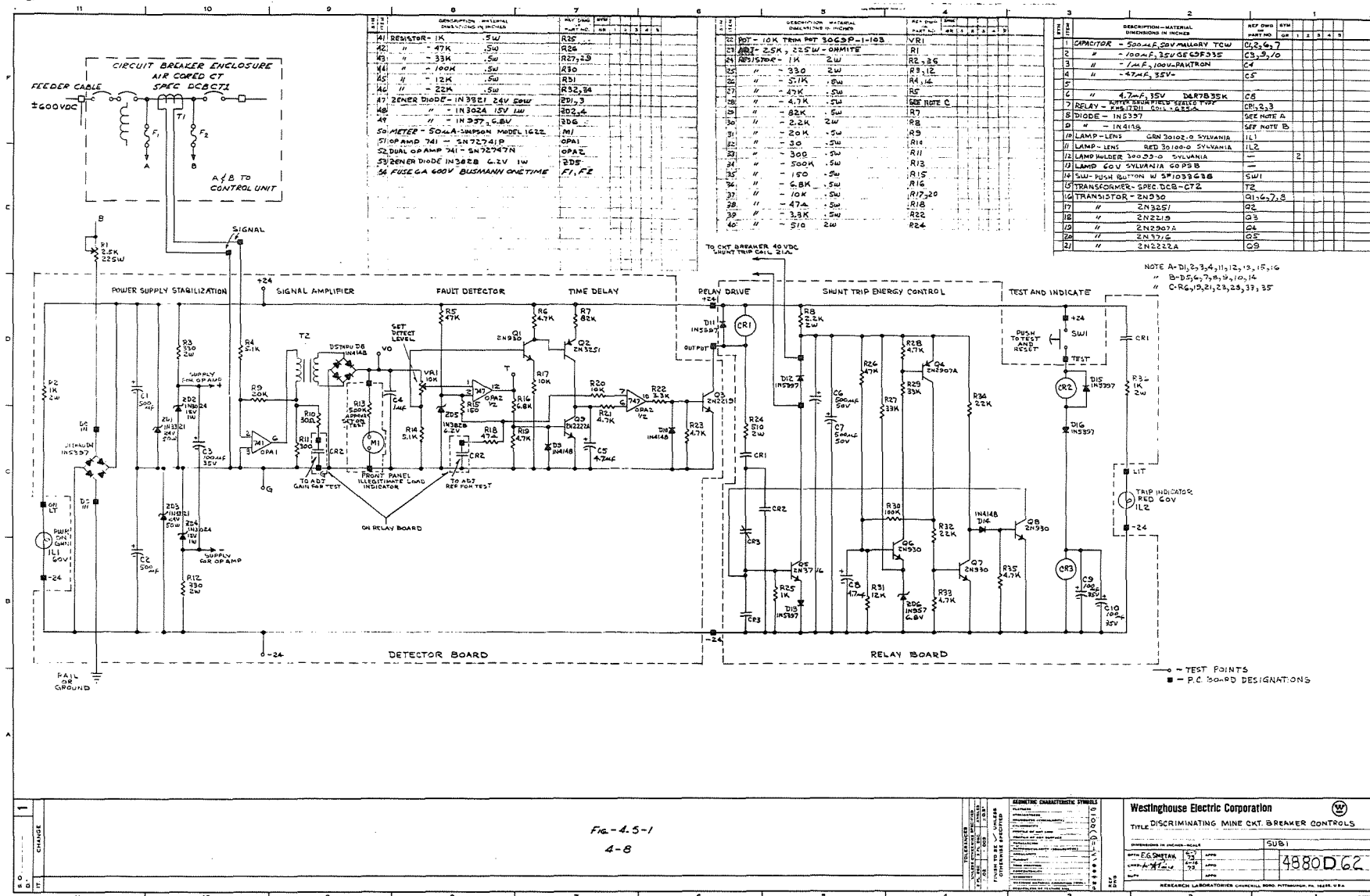


Fig. 4.4-1. Photograph of circuit breaker assembly



consumption is 138 watts at 160 volts. The minimum loading on the dc supply is 60 ma with one lamp lit and 130 mA with the circuit tripped and both lamps lit. The 24 volt zener diodes and 500 μ F smoothing capacitors ensure that stabilized, transient-free ± 24 volt power is available for the control circuits.

A block diagram presentation of the control unit is shown in Figure 4.5-2.

Dwg. 6209A01

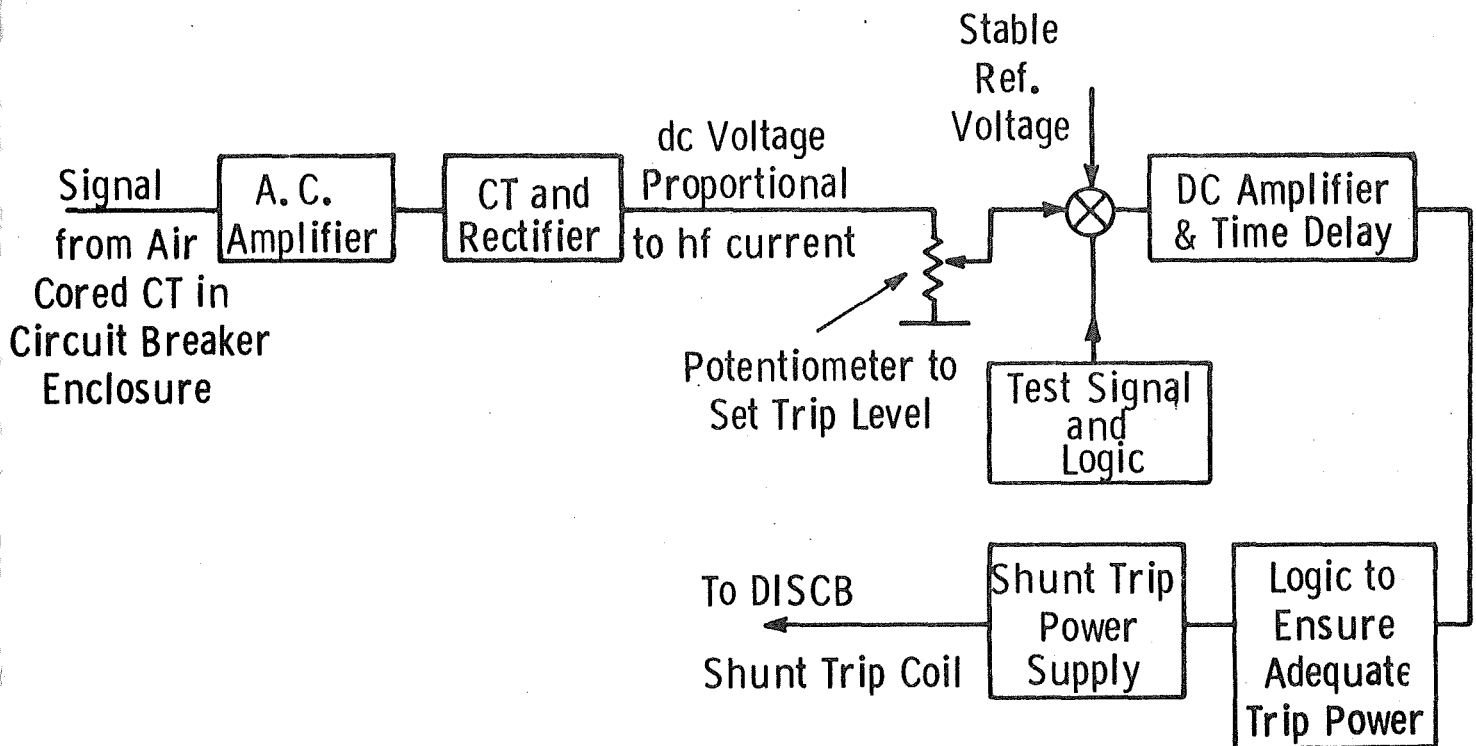


Fig. 4.5-2—Block diagram of DISCB control unit

Referring to Figure 4.5-2 a dc voltage is obtained from the ac amplifier, current transformer and rectifier which is practically drift free. This voltage which indicates the amount of high frequency ac current in the feeder cable is fairly linear up to 30 volts dc with a rate of 4 volts dc per 100 mA ac. An adjustable fraction of this voltage sets the trip level and it is compared with a 6.2 volt reference zener diode. When the reference voltage is exceeded a trip signal is initiated and passed through a time delay circuit before activating the main circuit breaker. The time delay characteristics are readily modified by changing the value of R6 and the result for a breadboard unit is shown as a function of illegitimate load resistance in Figure 4.5-3.

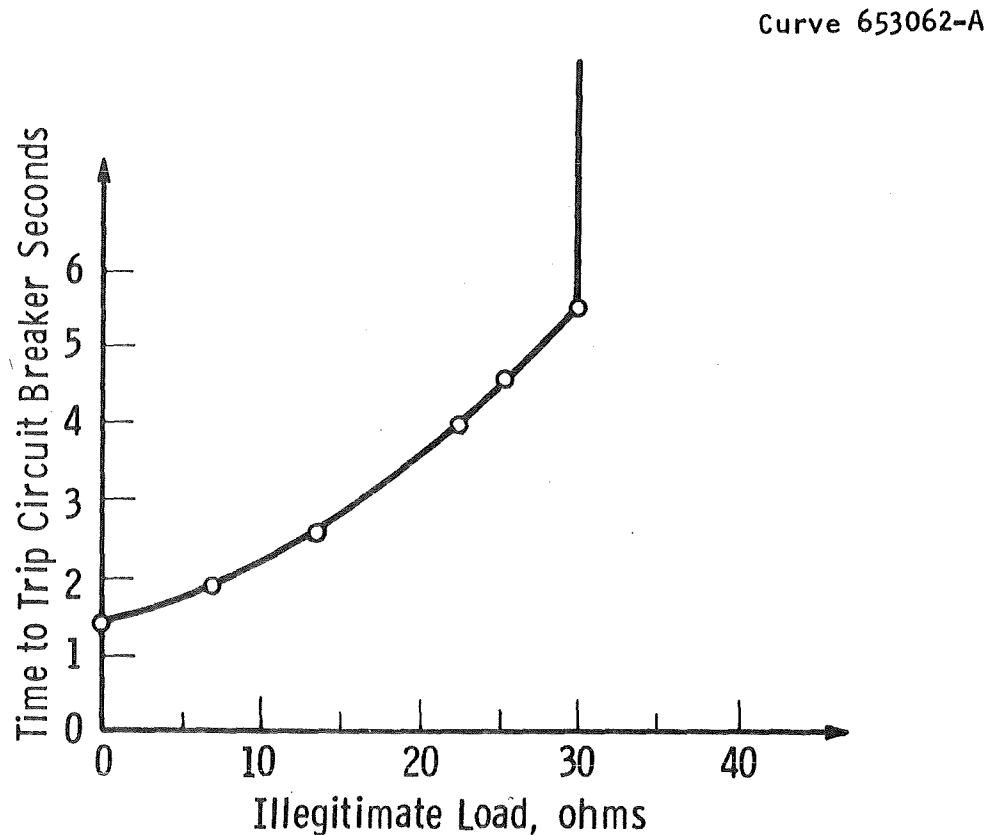


Fig. 4.5-3—Illustrating circuit breaker operating delay with illegitimate load

The degree of freedom from nuisance tripping with this level of time delay can only be satisfactorily resolved by field tests; however, the rapid automatic reset feature of the time delay circuit which eliminates memory of previous trip signals is expected to be valuable in this regard.

The shunt trip power supply is derived from a 1000 μ F capacitor which by means of a logic control is guaranteed to be charged to not less than 38 volts. When the breaker is to be tripped, the capacitors are rapidly discharged through the shunt trip coil. Circuitry is provided to recharge the capacitors and pulse the shunt trip coil about once every five seconds as long as a trip condition exists. It is shown in Section 3.11 that 38 volts is a value satisfactory for operating the circuit breaker. Because the shunt trip power supply is operated by short duration pulses rather than continuously it is not necessary to include in the circuit breaker the usual microswitch assembly which isolates current from the shunt trip coil to prevent overheating when the breaker opens. This feature helps to improve the overall dielectric strength of the breaker as noted in Section 3.6.

To monitor the state of the DISCB the following features are included in the DISCB control unit.

1. A green light (IL1) indicates power is available when lit
2. A red light (IL2) is activated if the circuit breaker is tripped
3. A meter (M1) displays the amount of illegitimate load current passing through the circuit breaker
4. A reset and test button (SW-1) is included to reset the controls after the circuit breaker has been tripped by an illegitimate load.

In order that the integrity of the complete discriminating scheme can be checked without interfering with normal operation the reset and test button also operates in the control circuits to achieve the following:

- a. The circuit breaker shunt trip coil is isolated.
- b. The trip reference level is reduced and the sensitivity of the control is increased so that the small dc current drawn by the control unit is "seen" as an illegitimate load. After a short delay the trip indicator light operates. The reset test button thus checks out all aspects of the control scheme except the main circuit breaker shunt trip coil.

To achieve a high level of noise immunity, relays are used in the logic control circuits. Printed circuit boards are used for the low power controls.

The control unit is housed in the same Nema type 12 enclosure as the 3 kHz oscillator and a photograph of the complete assembly is given in Figure 4.5-3.

A detailed description of the logic circuitry operation is given in Appendix 7.

4.6 3 kHz Power Oscillator

The function of the power oscillator is to inject a suitable ac voltage onto the mine dc trolley wires and feeder cables. A value of 15 volts and 15 watts was selected as a compromise between the desire for a high ac signal to transient voltage ratio, which requires a high voltage output and the need for a low power demand which requires a low voltage output. The final assessment of this compromise can only be critically evaluated from practical system tests.

The output voltage is required to be sinusoidal so that any filters required for isolating legitimate loads can be effectively tuned. The oscillator must also be capable of operating into a shorted output. A further requirement is that the oscillator be safe against high voltage transients applied from the trolley wires. A complete

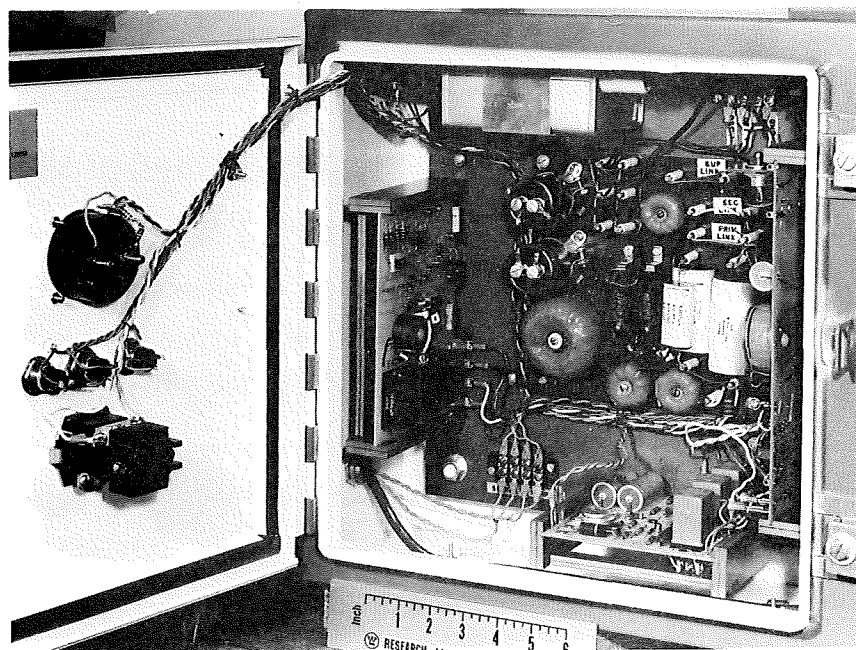
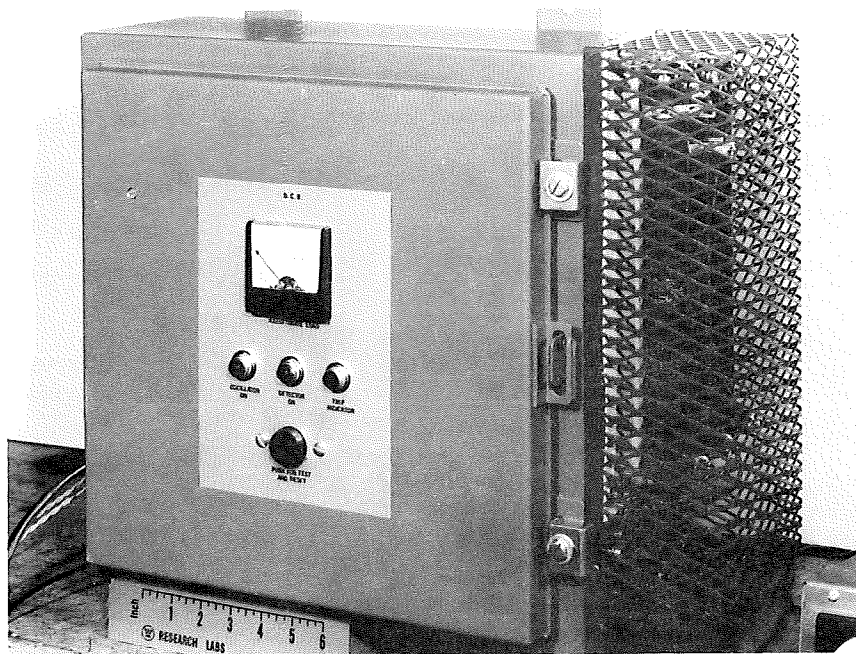


Fig. 4.5-3. Photograph of control unit for discriminating circuit breaker

schematic drawing is given in Figure 4.6-1 and details of the transformers and chokes are given in Appendix 6.

A block diagram illustrating the prototype oscillator operation is shown in Figure 4.6-2. Note that the power transistors are well isolated from possible line voltage transients by the ac filter.

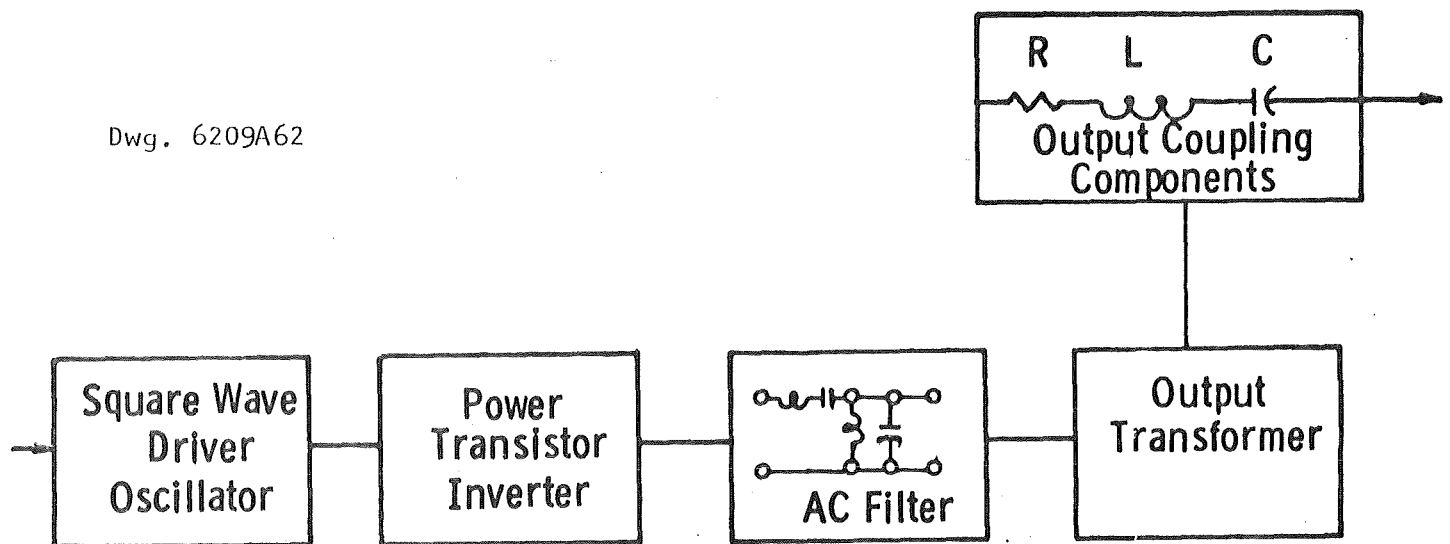
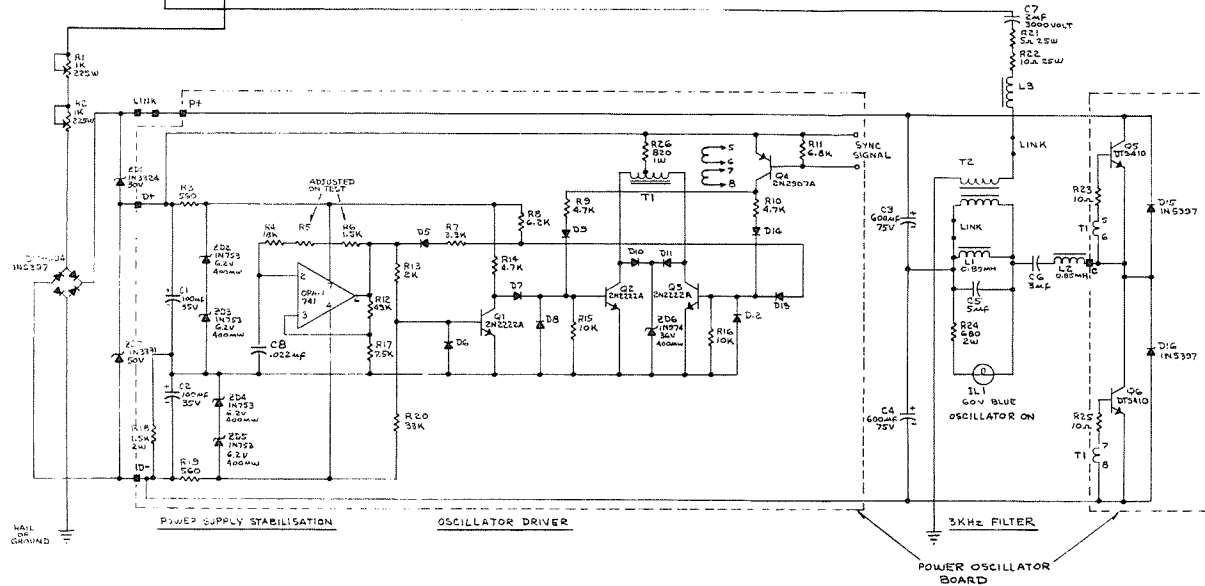


Fig. 4.6-2 —Representation of signal oscillator

Tests over a temperature range of 0°C to 50°C indicated a change of less than 1% in the oscillator output frequency and this level of accuracy is more than adequate to ensure proper operation of any tuned circuits that might be incorporated in the mine system.

Output voltage regulation curves for the prototype unit are shown in Figure 4.6-3 for reactive and resistive loads which correspond to different illegitimate load conditions on the mine dc system.

Power supplies for the power oscillator and driver stages are obtained from the nominal 600 volt feeder cables and are then stabilized at 80 volts and +25 volts for the driver and power stages respectively. Large smoothing capacitors ensure these power supplies are free from possible power supply transients.

[illegible]

—○TR1 - TEST POINTS
■ - PC BOARD DESIGNATIONS

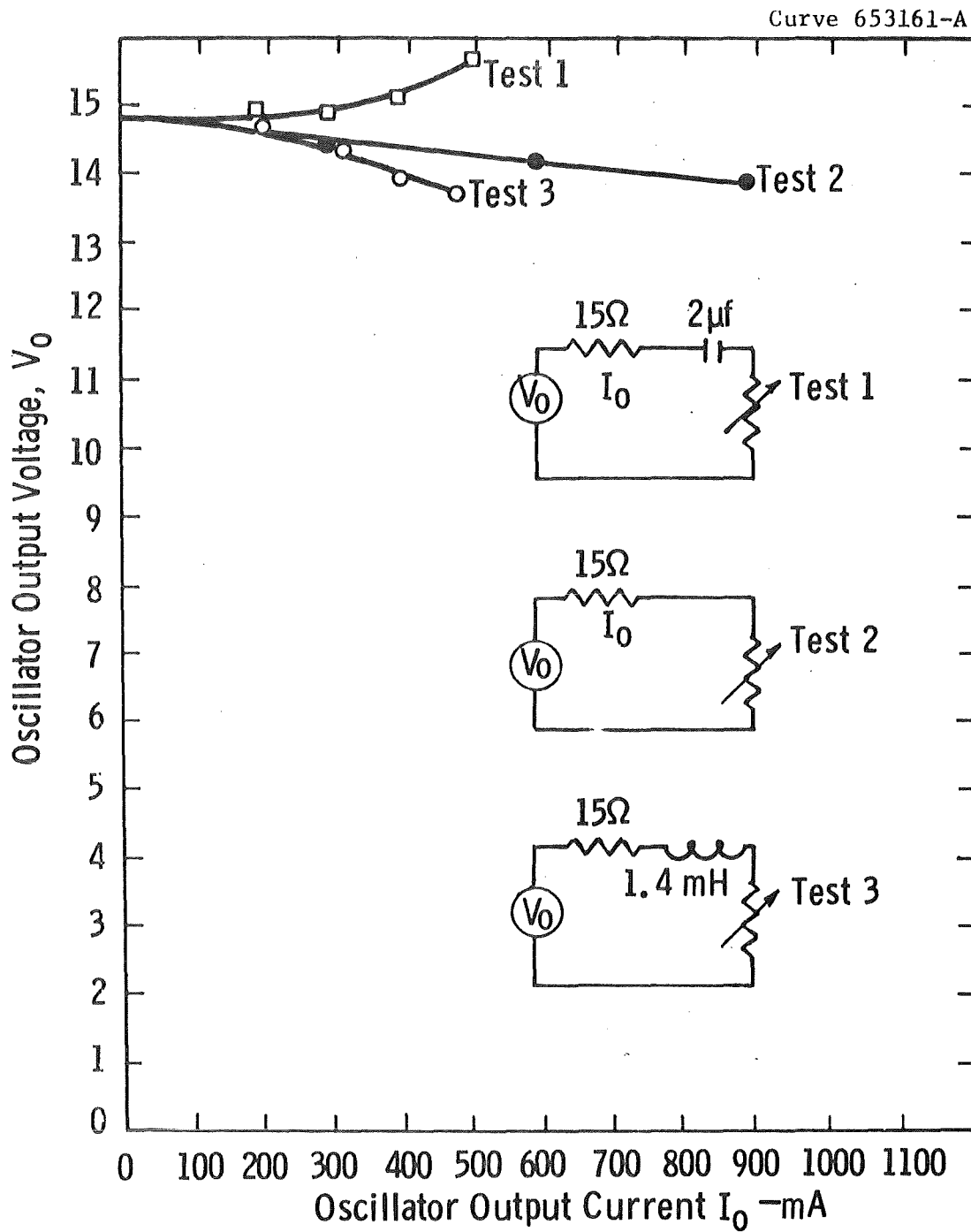


Fig. 4.6-3—Power oscillator regulation curves for simulated mine load conditions

The minimum dc current required for correct operation of the oscillator circuits depends on its ac output loading. From tests the range of current required was determined as 90 mA dc with an open circuited output and 200 mA dc with a shorted output of the oscillator. The 1600 Ω ballast dropping resistor which draws this current from the dc supply is such that operation over the range of input voltage from 400 volts to 700 volts is feasible. Total power consumption at 600 volts is 195 watts. It was considered that because the oscillator will normally be located close to the substation the low input voltage capability need not be quite as good as for the detector circuits which operate down to 350 volts.

4.7 AC Filters for Legitimate Loads

In some mine dc power systems it will be necessary to include isolating filters in series with legitimate loads to raise their impedance above the value of detectable illegitimate loads. Each system must be evaluated individually; however, some improvement of the high frequency impedance of the haulage motors can be obtained by means of relatively small tuning capacitors connected across each motor. Approximate impedance value of dc motors at 3000 Hz are given in the table.

Table 4.7-1. Approximate 3000 Hz impedance of dc motors used in coal mines as function of horsepower

	<u>Impedance</u> <u>Untuned</u>	<u>At 3000 Hz</u> <u>Tuned</u>	<u>Tuning Capacitor</u>
600 Volt Motors	<u>12,600 ohms</u> hp rating	<u>25,200 ohms</u> hp rating	0.0037 μ F per hp
300 Volt Motors	<u>3,150 ohms</u> hp rating	<u>6,300 ohms</u> hp rating	0.0148 μ F per hp

The size of the tuning capacitor in Table 4.7-1 was estimated from empirical relationships determined for series dc motors which

showed that the effective inductance of mine haulage motors can be approximated by,

$L_a \approx 190/\text{hp} \text{ -- } \text{mH}$ for 300 volt motors

$L_a \approx 760/\text{hp} \text{ -- } \text{mH}$ for 600 volt motors.

In the event that the total impedance of the legitimate load system is less than 100Ω , it may be necessary (depending on threshold detect level and freedom from nuisance tripping required) to raise the impedance by means of parallel tuned filters such as shown in Figure 4.7-2.

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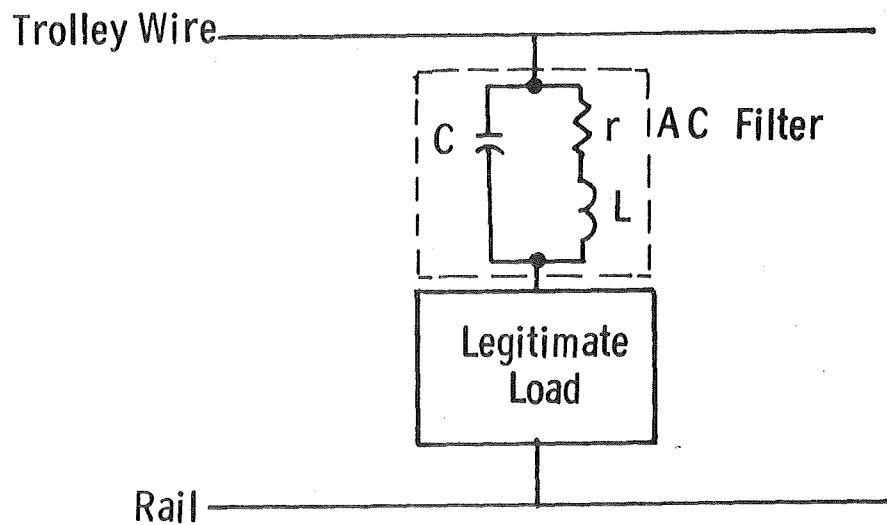


Fig. 4.7-2—Illustrating use of AC filter to raise impedance of legitimate load

Design of the ac filters would be reasonably straightforward, however, at the higher power levels the following factors are relevant and their consideration will facilitate design.

1. Proximity and skin effects are of first order importance and must be controlled in the inductor design. The effects can be limited

by using either Litz wires or copper foil with suitable spacing between turns.

2. Inductors should be air cored and kept a suitable distance from conducting surfaces to prevent reduction of Q ($Q = \omega L/r$)
3. Practical Q factors in the range of 20 to 80 are obtainable with care in inductor design, however, assuming a frequency tolerance of 3000 Hz $\pm 1\%$ the Q should not exceed 50 and would desirably be less, say about 25 in order that adequate bandwidth is maintained despite tolerances. [Note -- because the effective ac resistance of the inductor is controlled by skin effects the variation of copper dc winding resistance with temperature does not noticeably effect the Q factor.]

It is estimated that for small loads such as pumps the application of ac tuned filters will be straightforward and simple to implement. For the high power loads and substations the filter may be quite large due to the coil size as an example will show.

Assume an inductor is to be designed to meet the following conditions:

Q of the coil is 25

DC current rating is 1800 amps (corresponds to a 600 volt 1000 hp motor)

Operating frequency f_o is 3 kHz

Required impedance over the bandwidth of f_o/Q Hz is not to be less than 100 ohms, thus the impedance at resonance is 140 ohms.

From the assumptions the coil inductance L is determined from

$$L = 140/Q \times \omega_0 \text{ where } \omega_0 = 2\pi \times 3000$$

$$L = 297 \mu\text{H}$$

Inductor VA rating at 60 Hz

$$= (1800)^2 \times 377 \times 297 \times 10^{-6}$$

$$= 362 \text{ kVA}$$

It is determined empirically that the weight of 60 Hz reactors is given by

$$Wt_{(60 \text{ Hz reactor})} = 24 \left(\frac{\text{kVA rating}}{2} \right)^{0.75} \text{ lbs}$$

from which the reactor and hence approximate filter weight is determined as 1190 lbs.

The weight of a similar impedance reactor and filter at the substations is reduced because of the more favorable rms current rating at the substation.

Recognizing the practical difficulties of incorporating this size of filter in the mine system, a different filtering technique was sought and a new approach described as an active impedance multiplier is thought to be practical.

New HF Filter Design Concept

The aim of the HF filter is to prevent high frequency currents from being drawn into the legitimate load despite its low impedance. By using an auxiliary oscillator to supply the legitimate load with high frequency currents in response to the demand of the high frequency voltage on the trolley wire only a small current is drawn from the

trolley wires and thus the motor is seen as a high impedance. The principle is simply illustrated in Figure 4.7-3.

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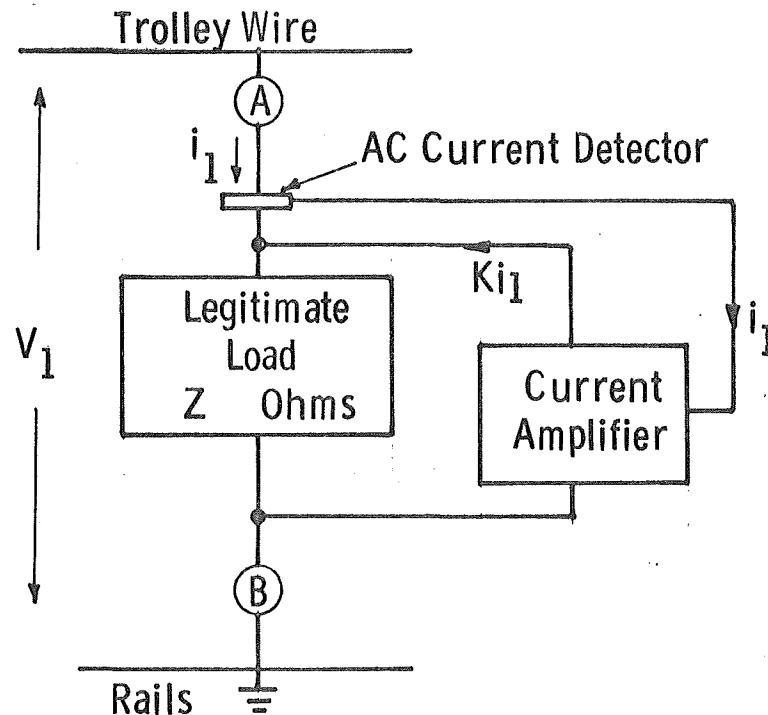


Fig. 4.7-3 - Illustrating means for raising impedance of legitimate load with amplifier

Referring to the Figure 4.7-3, it is required to raise the effective impedance seen between the terminals A and B.

A current detector (typically a tuned air cored current transformer) feeds a signal to a current forcing amplifier (typically a low power transistor amplifier) such that the ac current fed into the motor is the sum of i_1 and Ki_1 . Thus, with the amplifier connected, the voltage V_1 across the terminals is $(i_1 + Ki_1)Z$ and the apparent impedance across A and B is given by

$$Z_a = \frac{V_1}{i_1} = \frac{(i_1 + Ki_1)Z}{i_1} = (1 + K) Z$$

Thus, the apparent impedance seen by the source outside the terminals, namely the high frequency oscillator, is increased by the factor $(1 + K)$.

All the design variables of the amplifier have not been fully investigated at this time, however, some simple measurements using readily available equipment show that the approach is technically feasible and the apparent impedance of a 20 ohm motor was increased to 200 ohms by a simple amplifier rated at about 50 watts. A patent disclosure on this system has been prepared and a copy is given in Appendix 8.

Although the success of this invention is not crucial to the discriminating circuit breaker concept, its realization would make its application much simpler and lower cost. Work to continue with development of this invention has been funded under continuation of contract H0122058.

SECTION 5. SOLID STATE SWITCHES

5.1 Introduction

Protection and interruption of dc power circuits can be performed by solid-state switching devices. At the current and voltage levels existing in coal mine electrical systems the device most applicable in a solid-state dc circuit breaker is a thyristor (also called silicon controlled rectifier). The thyristor is a well proven power handling device and has found extensive use in a variety of industrial power conversion and control applications.

Despite the excellent performance capabilities offered, solid-state switches and circuit breakers have not yet become widely used in electrical power systems. The higher cost of the solid-state equipment as compared to conventional electromechanical protective devices has limited application to a few selected areas, primarily in ac power systems and in lower power contactors, motor starters, and relays.

As a candidate protective device for dc mine electrical systems the solid-state switch has several features worthy of further consideration. Its major advantages are: a much faster interruption which reduces the energy into a fault, completely arc-free operation, and virtually unlimited life due to the absence of moving parts and contacts. Its primary disadvantage is higher initial cost. The following section will discuss the performance, application and economic factors related to the possible use of solid-state switches in coal mine electrical systems.

5.2 Solid State DC Circuit Breaker

The basic solid-state circuit breaker, as shown in Figure 5.2-1, consists of the main switching device, a commutating circuit, sensing

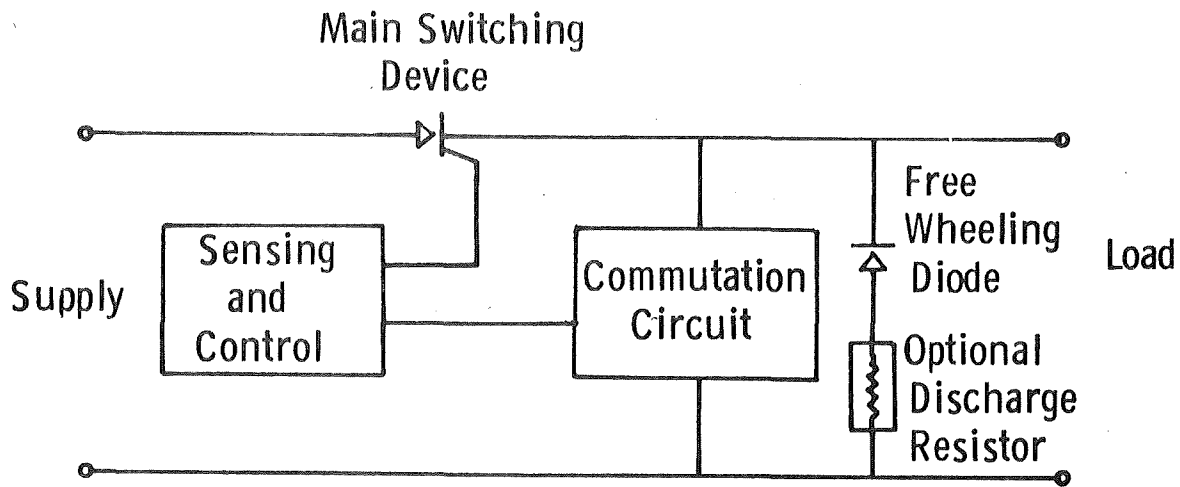


Fig. 5. 2-1—Basic solid-state circuit breaker

and control circuit, and a free-wheeling diode. The main switching device, which may be either a single thyristor or several thyristors in parallel, is switched on by a signal from the sensing and control circuitry and is switched off by a pulse obtained from the commutating circuit. A "free-wheeling" diode provides a path for inductive load currents to decay when the main switch is opened. A resistor in series with this diode can be used to more rapidly dissipate the energy stored in either cable or load inductance.

A simple solid-state breaker, as shown above, can perform the basic function of normal circuit opening and closing and current interruption in event of a fault. In a critical protection application; however, additional features must be added to increase safety and reliability of protection. Since the solid-state devices permit a small leakage current to flow when they are "off" a bleeder resistor must be added across the output to ensure that the voltage on the output circuit is held below a value that would be dangerous to personnel. To ensure that the power circuit is safe for maintenance or repair, a mechanical

disconnect should be used ahead of the solid-state switch. Since solid-state power devices normally fail to a shorted rather than open condition, it would also be desirable to provide for automatic opening of the power circuit in event of failure of the switching device. This is accomplished by a series fuse and a "crow-bar" circuit which causes the fuse to blow if the main switch fails to switch off when signaled to do so.

The energy stored by the source and feed cable inductance which is normally dissipated in the arc of a conventional breaker, must be absorbed elsewhere when a solid-state breaker is used. A dissipative element may be placed in parallel with the main switching device or across the supply terminals as shown by the transient suppressor in Figure 5.2-2.

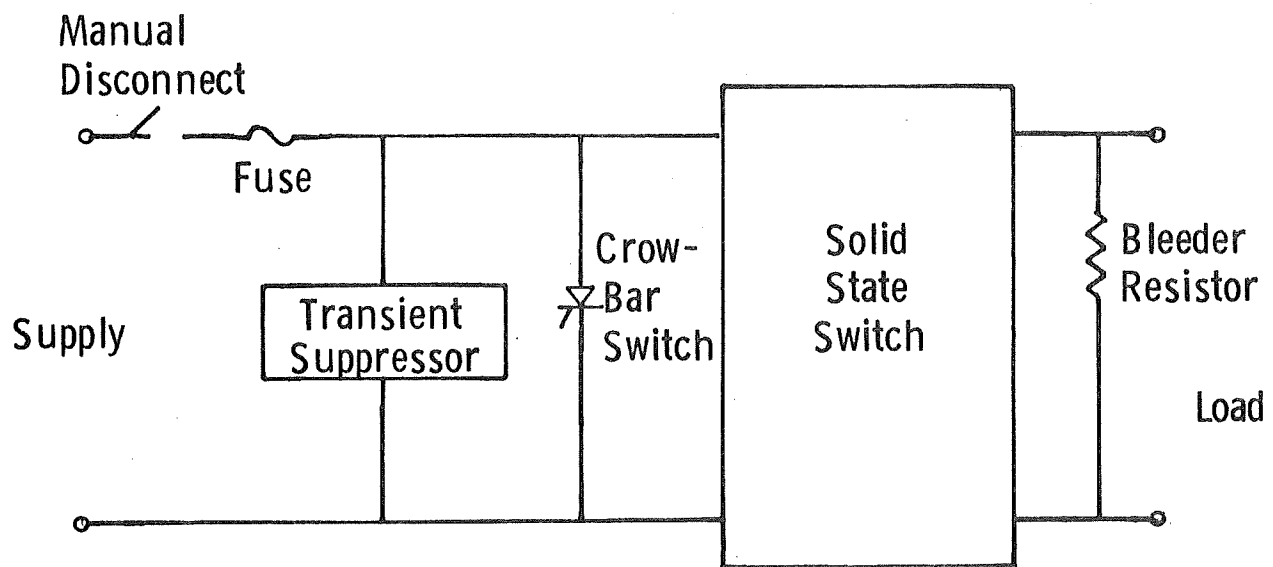


Fig. 5. 2-2—Auxiliary features desirable in a solid-state switch for mine application

5.3 Primary Design Considerations

Reliable operation of the solid-state circuit breaker depends primarily upon proper engineering application of the main power switching device and the design of its commutation and protective circuitry. The main thyristor rating must be chosen to withstand the worst case operating conditions imposed by the dc power system. Adequate safety margins must be allowed on voltage, current, and thermal ratings. In addition, the rate of voltage and current rise permitted in the circuit must be maintained within the limits specified for the device.

The commutating circuit used to switch the main device off must be designed to commute the highest peak value of fault current expected. The worst case fault current can, however, be controlled and limited to values much less than the available short circuit current by appropriate design of the circuit breaker. Since the system voltage may vary over a wide range, it is also important to ensure that the commutation capability is maintained despite the voltage variations.

The sensing and control circuitry for the solid-state breaker must reliably detect overcurrents produced by a fault condition and must respond rapidly in providing the signals which cause the main power switch to be turned off. This requires that the current sensing circuitry be designed to measure the instantaneous value of the dc current passing through the breaker and that the trip value of current be accurately set and maintained under all service conditions. The control circuitry must also be insensitive to electrical transients and noise on the power lines. Finally, the control circuit must have provision for easily checking the operation and calibration of the breaker and for ensuring that any failure of the power devices produces a fail-safe or opened condition.

5.4 Solid-State Breaker Design Example

Keeping the above mentioned considerations in mind, let us examine a specific design for a solid-state circuit breaker. In this example, only the more significant design aspects will be considered

and detailed circuitry for performing all internal functions will not be presented.

The specifications for the breaker are assumed to be the worst case conditions found in our evaluation of mine dc electrical systems. Tabulated below are the more important design requirements for a breaker operating in a system supplied from a 600 volt, 500 kW supply.

Voltage rating - 600 volts, nominal; range of steady state variations assumed to be 400 volts to 700 volts.

Current rating - 600 amp continuous rating; short time rating based on triangular current envelope having a peak current of 1500 amperes and total duration of 5 minutes.

Available fault current - 12,500 amperes

Source impedance - 0.86 mH inductance; 0.048 ohms resistance.

For the above conditions the main power switching device must be capable of handling 600 amperes continuously and the 1500 ampere peak triangular currents. This latter current condition corresponds to an average current of 750 amperes and an rms current of 865 amperes during the 5 minute load period.

Several manufacturers offer devices applicable at the current and voltage levels needed for this type of service. In selecting devices; however, one is confronted with a number of technical and economic trade-offs. For example, the higher current devices have a long turn-off time, and therefore, require a considerably larger commutating circuit. Fast switching devices, which permit smaller commutating components are not available in the highest current ratings; therefore, two or more devices must be paralleled to obtain the needed switch rating. Not only must the differences of the cost of the devices be taken into account, but also the relative costs of the required commutating circuitry must be considered.

To obtain a rough estimate of the cost, and performance that could be obtained for a mine application let us examine the simplified design in Figure 5.4-1 and develop the pertinent information for the major components of the circuit.

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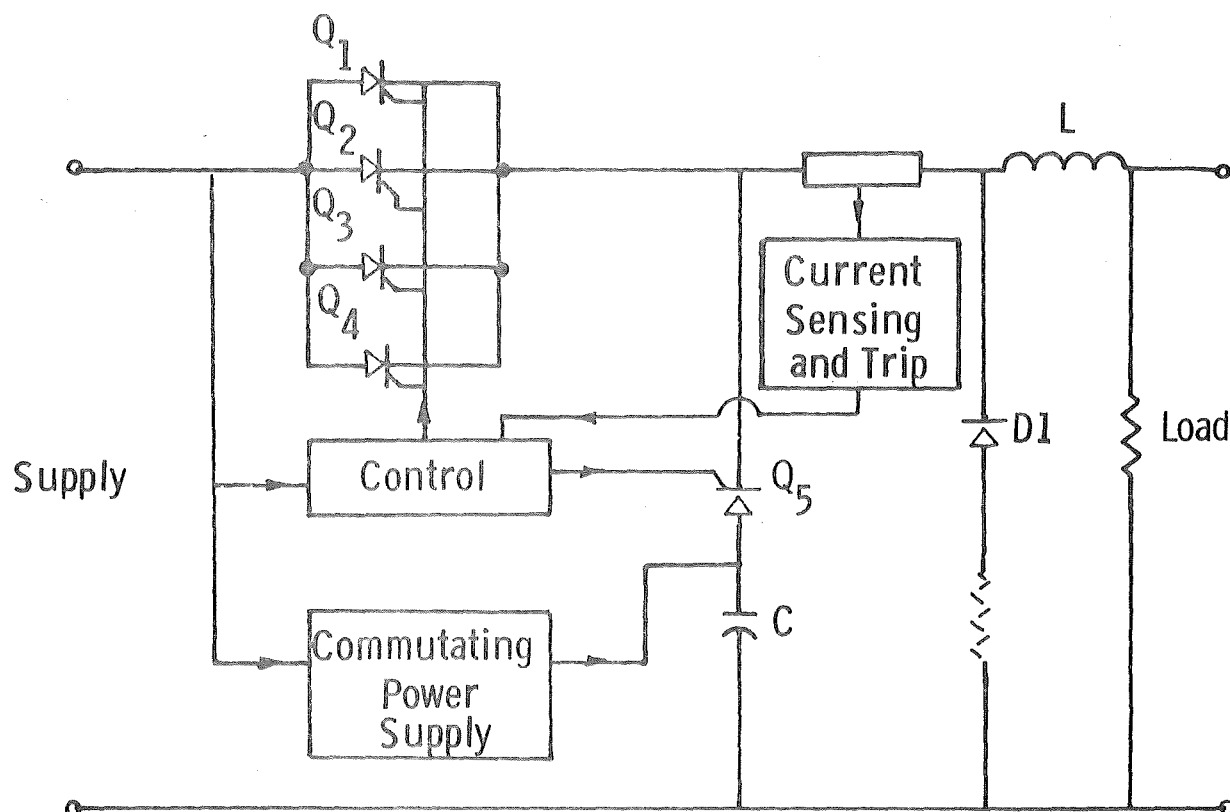


Fig. 5. 4-1—Simplified circuit for solid-state breaker

Thyristors Q1, Q2, Q3, and Q4 are paralleled fast switching thyristors. Thyristor Q5 applies the commutation pulse from capacitor C to the main switching devices. The commutating capacitor C is assumed to be charged from a separate power supply which is powered from the main 600 volt line. Inductor L is inserted to limit the rate of current build up into the fault on the load side. Diode D1 provides a path for

inductive energy stored in the load circuit to be discharged when the switch opens.

At the nominal rated current of 600 amperes, each thyristor carries 150 amperes. The power dissipation in each device for this condition is approximately 200 watts. For the peak current condition of 1500 amperes the power dissipation during the five minute load interval will be about 300 watts per device.

The thermal characteristics of suitable thyristors are typically; a maximum permissible junction temperature of 125°C and a thermal resistance from the device junction to the heat sink of about $0.04^{\circ}\text{C/watt}$. Under the worst condition of dissipation, 300 watts, the average temperature rise of the junction will be 12°C above the heat sink temperature. Assuming a maximum ambient temperature of 50°C , the maximum allowable heat sink thermal resistance is $63^{\circ}\text{C}/300$ watts or $0.21^{\circ}\text{C/watt}$. Heat sinks having thermal resistances of 0.2°C/watt and lower can be obtained using either natural or forced air convection cooling. The use of a blower for cooling the devices would permit a significant reduction in the heat sink volume; however, for a mine environment a blower may be unacceptable due to the probable need for air filters and their maintenance.

Since the 1500 ampere load is a cyclic load repeating at relatively long intervals, the peak temperature rise of the thyristors can be reduced by mounting them to a block of metal to provide a long thermal time constant. For example, if the device is in good thermal contact with a 2 pound block of aluminum, the aluminum will absorb 560 watt-minutes of dissipation for a temperature rise of 40°C . The most satisfactory thermal design for a solid-state mine circuit breaker may be one which uses a substantial enclosure on which the devices are mounted. The external surface would contain sufficient fins to maintain the sink temperature under normal load conditions at no more than 40°C above ambient. The mass of the enclosure would be designed to absorb the peak power dissipation with a temperature rise of only

a few degrees. As a final safety feature for preventing failure due to thermal problems, the switch can be made self-protecting by using a temperature sensor on the device or heat-sink to cause the circuit breaker to open if a preselected temperature limit is exceeded. In summary, a reasonable number of parallel devices can provide adequate current ratings for mine applications and adequate cooling can be obtained by natural or forced convection. Due to the nature of the mine environment and the load cycle applied to the breaker special consideration must be given in the packaging to reduce the effects of dust and dirt on heat transfer and to obtain optimum cooling during the repeated peak load conditions.

The second important factor in the design of a static breaker is ensuring adequate commutation capability turn-off under fault conditions. We shall not attempt to describe the variety of commutation circuits or the specific details of their design; but will consider only the major factors affecting the operation of a solid-state breaker. To force the conducting thyristors to the off condition requires that their current be forced to zero for a sufficient time to allow them to recover their blocking characteristics. This is normally accomplished by using a charged capacitor to momentarily supply the load and apply a reverse voltage to the thyristor. The capacitance required depends on the magnitude of current to be switched off, the recovery time of the particular thyristor used, and the commutating capacitor voltages. A very rough approximation of the commutating capacitance required is given by:

$$C = \frac{t I}{E_C - E} \text{ (}\mu\text{fd)}$$

where t = turn-off time in microseconds

I = current to be turned off

E = supply voltage

E_C = commutating capacitor voltage

For the breaker rating we have considered the capacitance required would be at least 100 μ fd assuming a turn-off time of 30 μ sec, a current of 2000 amperes, a supply voltage of 600 volts, and a capacitor voltage of 1200 volts.

For best performance the maximum permitted fault current should be held to the lowest practical value compatible with the operation of the electrical system. By limiting the peak fault current the size of the commutating capacitor is minimized and the thermal stress on the device is reduced. If the breaker is at some distance from either the fault or source, line inductance limits the rate-of-rise of current. If a fault occurs near a breaker installed at or near the source, the natural rate-of-rise of current may be excessively high and, in this case, a small value of inductance built into the breaker can be used to limit the current rise to a value compatible with the commutating circuit design.

5.5 Expected Performance of Solid-State Breakers

The major performance advantage of the solid-state breaker for a mine application is its speed of interruption and the resultant ability to reduce the energy supplied to a fault. For high current arcing faults, this reduction of energy lessens the possibility of starting a fire or damaging equipment. The energy delivered to an arcing fault is a function of the current and time and to a non-arcing fault a function of the square of the current and time. With a solid-state breaker both the magnitude of fault current and the time duration of the fault current are reduced.

To compare solid-state vs conventional breakers, let us examine their expected operation in a system. The initial rate-of-rise of current into a low impedance fault is determined by the system inductance and resistance. Assume both types of circuit breakers are set to trip at 2000 amperes. The approximate current vs time profile for the two breakers is shown in Figure 5.5-1.

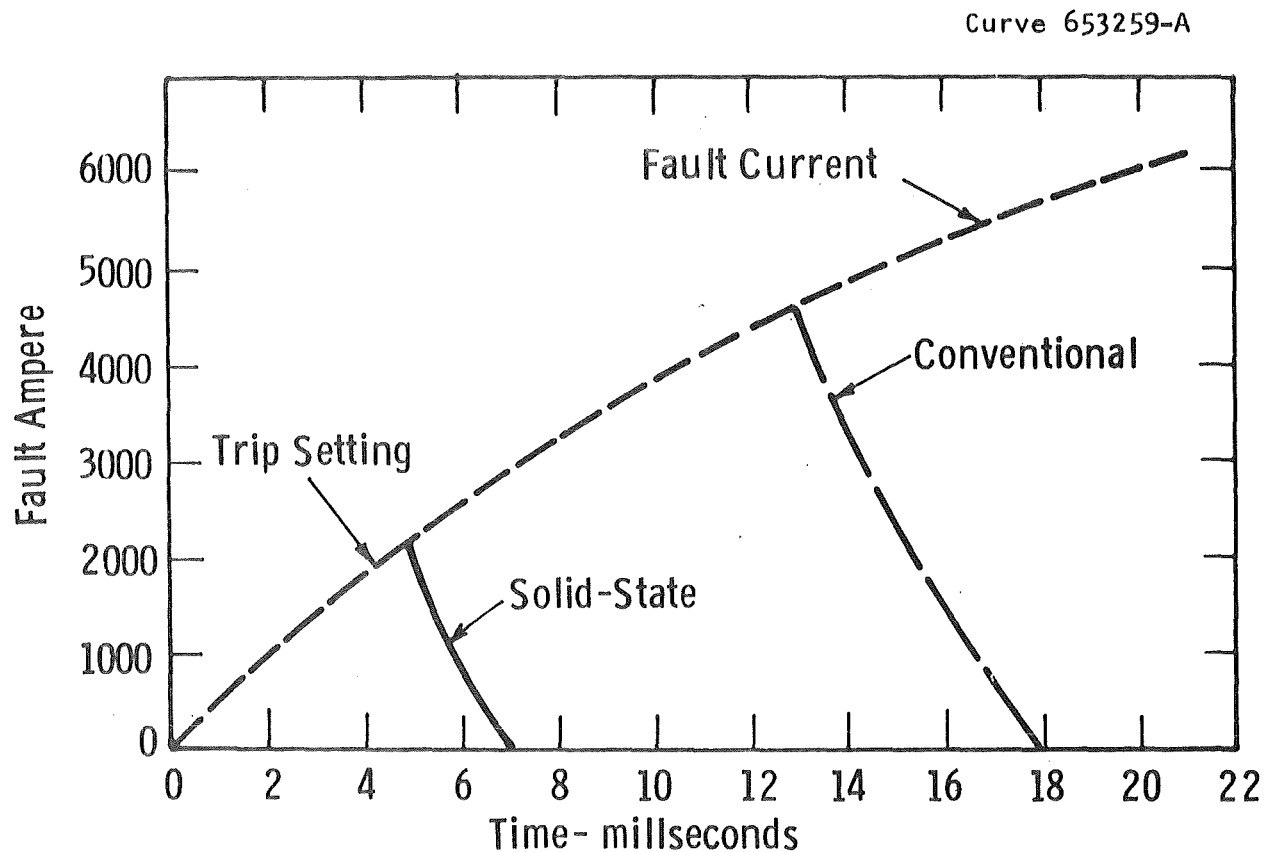


Fig. 5.5-1—Current vs time interrupting characteristic for conventional and solid-state breakers

Note that as soon as the trip setting is reached the solid state device is caused to be non-conducting very rapidly, thus interrupting power to the load within a fraction of a millisecond. The actual fault current may; however, last for several milliseconds due to energy stored in the load circuit. Since the mechanical breaker is much slower at developing arc voltage after the trip setting has been reached, the current into the fault not only lasts longer, but also rises to a considerably higher value. The actual decay of current once interruption has started depends upon the means provided in the interrupting device for absorbing the stored energy. In the conventional

breaker, the arc dissipates the stored energy and thus determines the rate of current decay. In the solid-state breaker, the stored energy due to the source and supply cables can be absorbed by non-linear resistive elements connected across the input terminals. Energy stored in the load and load cables can be absorbed by a resistor in series with the free-wheeling diode path. The current decay and the transient voltage to which the solid-state breaker is subjected will depend on the specific values chosen for the dissipative elements.

With the solid-state circuit breaker the current-time product (I.t) can be made considerably less than that obtained with a conventional breaker and, thus, reduce the energy supplied to a fault.

5.6 Cost

The present cost of a solid-state circuit breaker will be considerably higher than an equivalent rating electromechanical breaker. Since high power solid-state breakers are not being produced in any quantity or in standard types, the selling price of such a device is not easily determined. A very rough estimate can, however, be made of the component costs for a solid-state breaker. The tabulation below gives the approximate component costs for a 600 volt, 600 ampere continuous (1500 ampere peak) rating breaker.

Main thyristors (4 thyristors)	\$ 800
Commutating circuit (capacitors and thyristors)	400
Free-wheeling diode circuit	120
Commutating power supply	30
Sensing and control circuits	60
Transient suppressors	180
Heat sink, case, hardware	<u>200</u>
Total	\$1790

Despite the expected higher costs for solid-state circuit breakers, their application may be warranted if it were shown that the potential reduction in fault energy significantly improved safety or reduced damage to the electrical system.

SECTION 6. TESTING PROTOTYPE DISCRIMINATING CIRCUIT BREAKER

The complete discriminating circuit breaker comprises two enclosures and photographs of the component parts are given in Section 4 in Figure 4.4-2 and Figure 4.5-3. One enclosure contains the circuit breaker current transformer and power supply fuses. The other enclosure contains the high frequency (3 kHz) oscillator and controls.

The prototype unit was built from sub-circuits which had been tested before assembly and the prototype tests were to determine overall system performance and temperature rise of the more sensitive components. A photograph of the prototype assembled for testing is shown in Figure 6.1.

6.1 Circuit Breaker Enclosure

The instantaneous magnetic trips of the type MA 800 circuit breaker were set to operate at 1540 amperes ac by means of a low voltage high current power supply. This value corresponds to a dc trip value of about 2000 amperes dc.

Temperature rise of the enclosure was determined with the circuit breaker carrying a continuous current of 600 amperes and under these conditions it was determined that the air at the top of the enclosure was 29°C rise above the ambient air. At the bottom of the enclosure a 9°C temperature rise was recorded. These values are considered proper and safe for mine operation where the ambient air temperature of the enclosure does not exceed about 30°C. Under these maximum temperature conditions the working environment for the circuit breaker in the enclosure will have an average temperature of about 50°C. This is compatible with its maximum industrial performance rating.

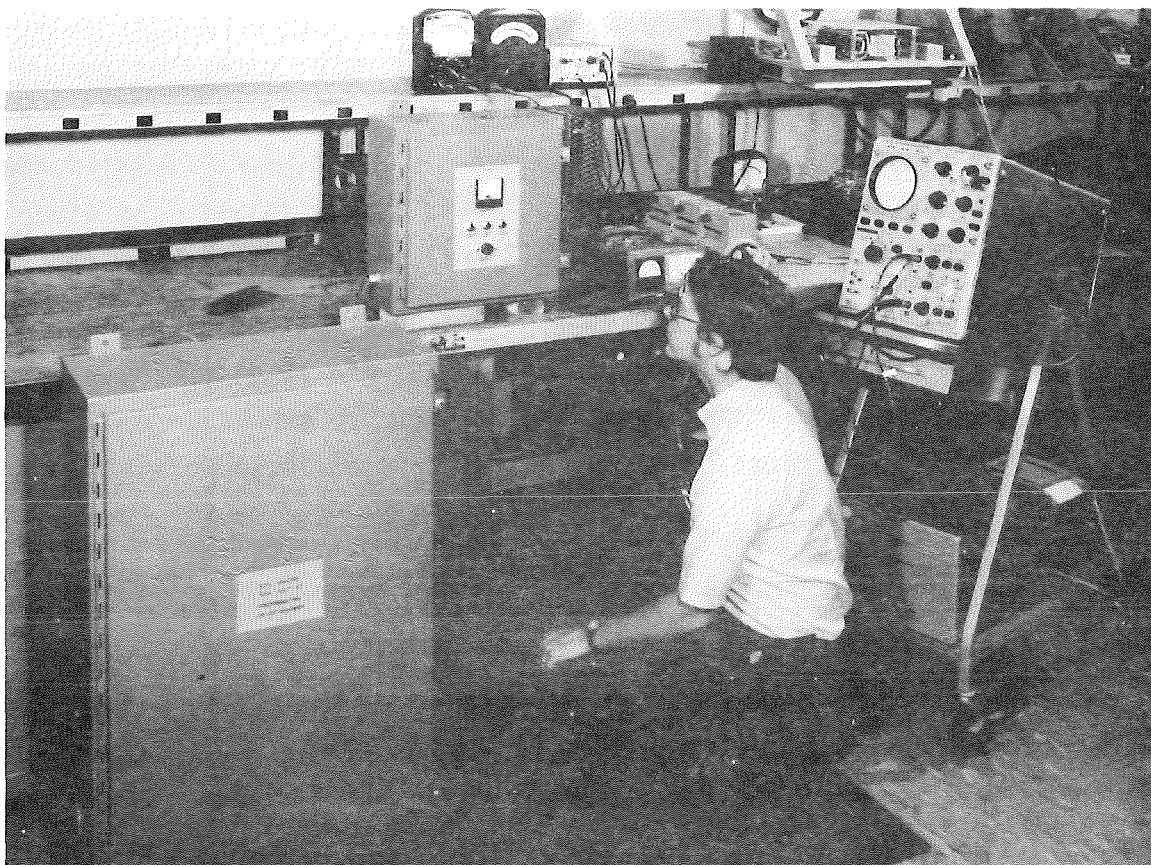


Fig. 6.1. Test arrangement for discriminating circuit breaker. Note: (The circuit breaker is housed in larger enclosure on the floor and control unit on the bench.)

6.2 Control Unit

The ballast resistors which control the current fed to the low power oscillator and control circuits were set at the design values of 1600 ohms and 2400 ohms, respectively. These values ensure that the oscillator will operate over the range of 400 to 700 volts dc and the control unit over the range of 350 to 700 volts dc.

After determining that the unit was functioning generally correctly and the self-check feature was operating, a measurement was made of total power requirements and dc current as a function of dc voltage. The results are shown in Table 6.2-1.

Table 6.2-1. Power consumption of discriminating circuit breaker control unit

Supply voltage	Volts dc	400	500	600	700
Supply current	Amperes dc	0.34	0.435	0.535	0.62
Power input to control unit	Watts	136	217	321	434

For these tests the interconnections of control unit and circuit breaker enclosure were as shown in Figure 6.2-1. To determine the temperature rise of the most critical parts of the control unit, thermocouples were mounted on the heat sinks of 50 volt zener diode ZD7 and 24 volt zener diode ZD1. A thermocouple was also mounted to record the temperature rise of the air at the top of the control unit enclosure. The results which are given in Table 6.2-2 were obtained under laboratory conditions with an ambient temperature of 25°C. They confirm that the unit will be satisfactory for operation in ambient temperatures of 30°C and with continuous voltages of up to 700 volts dc.

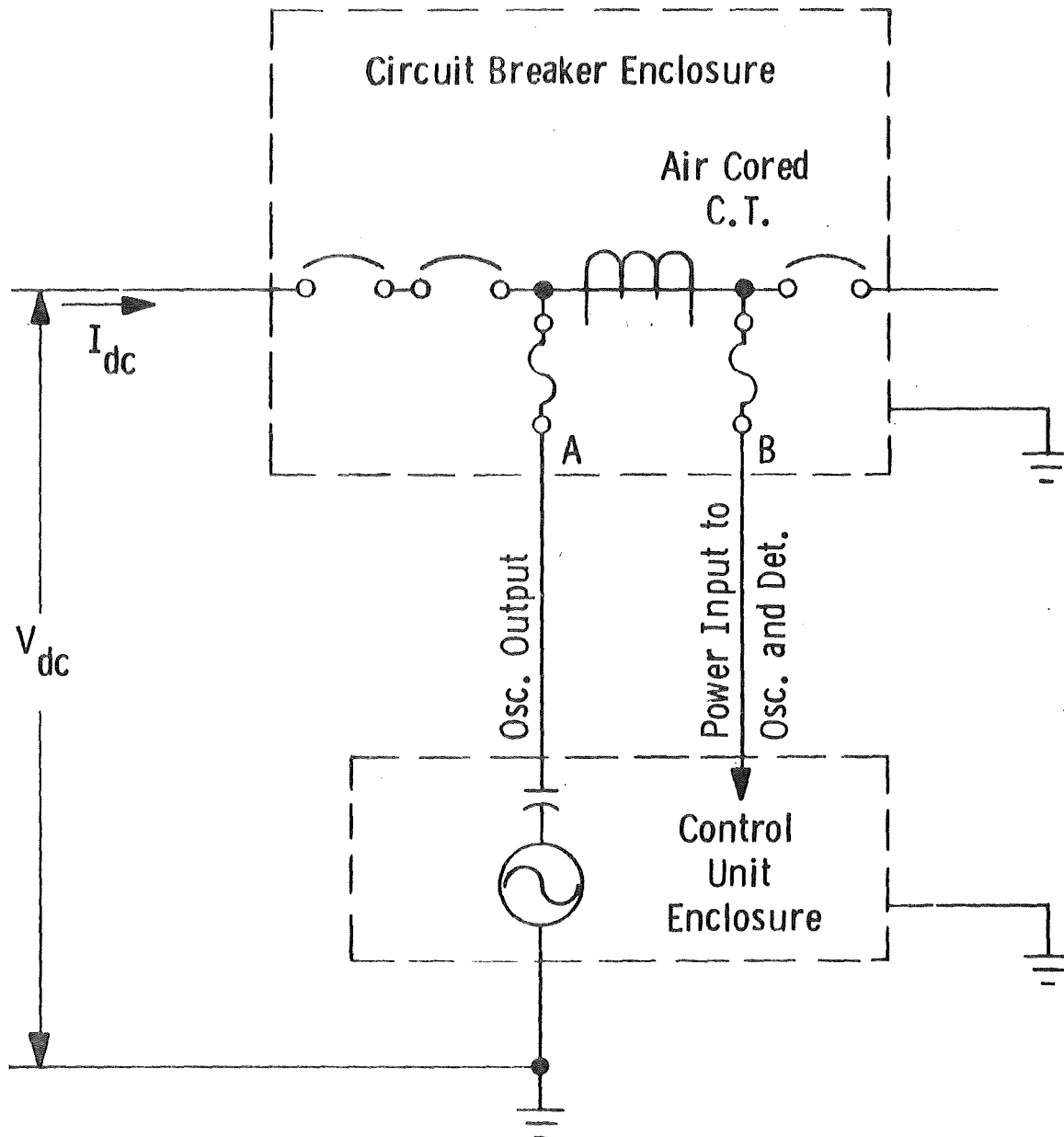


Fig. 6.2-1 — Test arrangement for determining power consumption and thermal characteristics of control unit

Table 6.2-2. Temperature rise above ambient
for critical components of control unit

	Supply Voltage Volts dc	
	<u>600</u>	<u>700</u>
ZD7 temperature rise	59.5°C	83°C
ZD1 temperature rise	59.5°C	81°C
Enclosure air temperature rise	19°C	24.5°C

To determine the sensitivity of the circuit breaker to illegitimate loads the test arrangement was modified to that shown in Figure 6.2-2.

In this test arrangement the illegitimate load does not directly load the 600 volt supply, which can therefore be of reduced power rating. The 3 kHz oscillator and detector are however able to function correctly and this simplified testing procedure gives satisfactory results.

Because the control unit which detects illegitimate load exhibits a substantial time delay (see Section 4.7) before operating the main circuit breaker shunt trip a test point marked "T" on the detector board is used to determine the precise instant of trip. This test point responds instantly when the illegitimate load exceeds the threshold detected value.

Tests were carried out with the supply voltage varying from 400 to 700 volts dc and with illegitimate loads being applied at points simulating the most sensitive (2500 ft of mine cable) and the least sensitive (6400 ft of mine cable). The results are shown in Table 6.2-3.

SECTION 7. REFERENCES

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- Reference 3. "Solid Short-Circuit of DC Motors and
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APPENDIX 1. TO DETERMINE THE EFFECT OF BREAKER
TRIP SETTING AND BREAKER UNLATCHING TIME ON THE
CIRCUIT BREAKER ENERGY DISSIPATION

Consider a dc circuit breaker being closed into a fault of resistance R and inductance L . The system voltage is V and the system time constant is $T = L/R$. A plot of current through the breaker and voltage across the breaker vs time is shown in Figure 1.1-1.

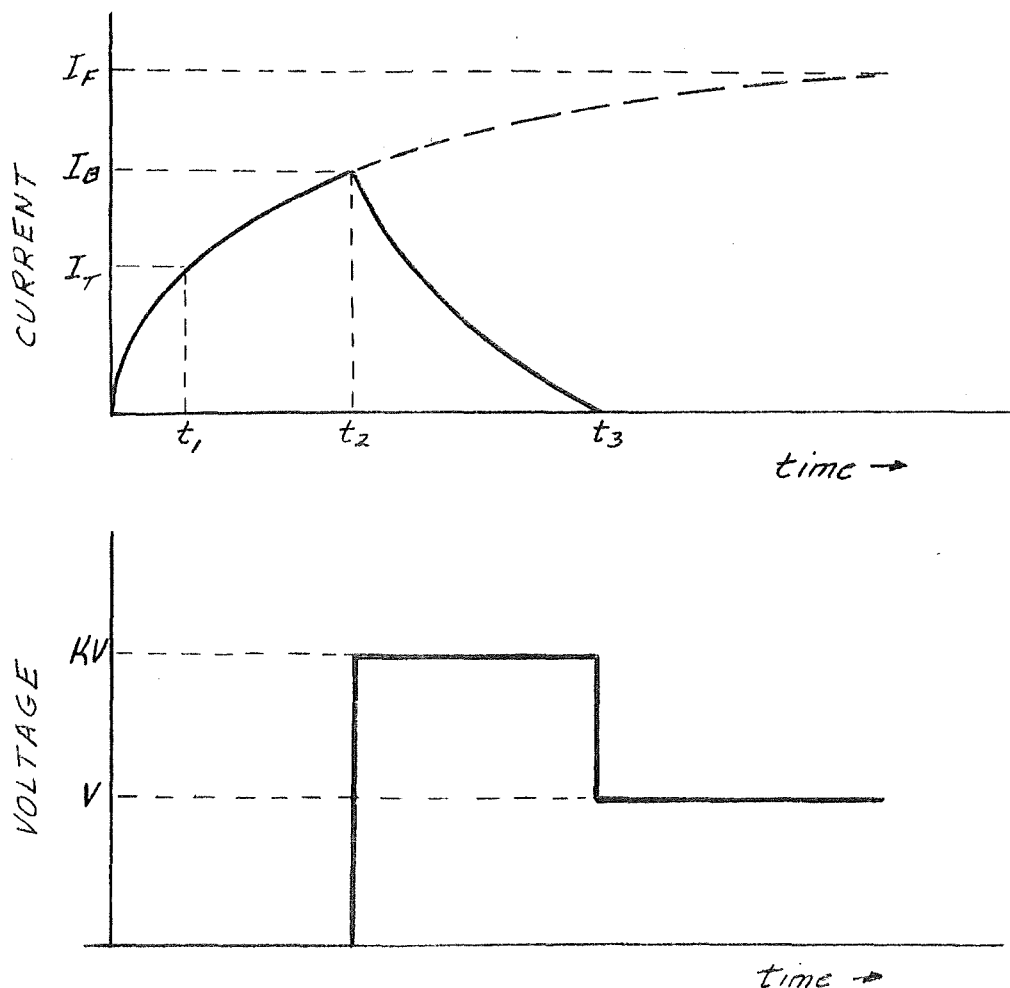


Fig. 1.1-1. Idealized waveforms for circuit breaker interrupting dc current

When the breaker is closed into the fault, the current increases according to $i = \frac{V}{R} (1 - e^{-t/T}) = I_F (1 - e^{-t/T})$. I_F is the prospective current, that is the steady state value the current would reach provided the breaker never opened. At time t_1 , the current reaches the trip current setting of the breaker, I_T . At this point operation of the breaker trip mechanism commences. All breakers have a finite operating or unlatch time caused by unavoidable delays in the trip mechanism linkages. This delay is shown as the interval t_1 to t_2 on Figure 1.1-1. During this time the main contacts remain closed even though the breaker mechanism is in the process of operating.

At time t_2 the breaker contacts part. At this time the breaker current has reached a value I_B and it is assumed that an arc voltage K times the source voltage, V , appears across the breaker contacts. The arc voltage is shown as an idealized constant value in Figure 1.1-1 rising instantaneously. In practice there is some small delay while the arc voltage rises to this value. Also the arc voltage fluctuates with time. However, the assumptions are reasonable practically and, for, analysis an equivalent steady value kV is chosen as the average value of these fluctuations.

During the time interval t_2 to t_3 the breaker current is driven to zero by the arc voltage and energy is dissipated in the arc. The total amount of energy dissipated is equal to the time integral of the product of instantaneous breaker current and arc voltage. It is obvious that the lower the current I_B at which the contacts open the smaller will be the arc energy. There are two ways in which I_B can be lowered. One is to reduce the trip setting (I_T) of the breaker so that the breaker can sense the fault sooner. The other is to reduce the breaker unlatching time so that a smaller increase in current occurs during unlatching. Since both of these factors are crucial to the amount of arc energy dissipated in the breaker, it is of interest to analyze mathematically how they affect the arc energy. The arc energy J_{arc} is given by:

$$J_{arc} = kV \int_0^{(t_3 - t_2)} i(t)dt \quad (1)$$

taking time zero at the start of arcing. Time $t_3 - t_2$ is given by:

$$t_3 - t_2 = t_A = T \log_e \left[1 + \frac{I_B R}{V(K-1)} \right] \quad (2)$$

and during this interval $i(t)$ is given by:

$$i(t) = I_B e^{-\frac{t_A}{T}} - I_F (K-1) \left[1 - e^{-\frac{t_A}{T}} \right] \quad (3)$$

The solution of equation (1) is

$$J_{arc} = V I_B K T \left[1 - \frac{V}{I_B R} (K-1) \log_e \left(1 + \frac{I_B R}{V(K-1)} \right) \right] \quad (4)$$

It is the value of I_B that is affected by the breaker trip setting I_T and the breaker unlatch time. The value of I_B is generally unknown but can be calculated using the value of I_T and the breaker unlatch time as follows:

The time t_1 to reach the trip setting is given by:

$$t_1 = T \log_e \left(\frac{1}{1 - \frac{I_T}{I_F}} \right) \quad (5)$$

The breaker unlatch time is $t_u = t_2 - t_1$. The time from initiation of the fault until the breaker unlatches is:

$$t_1 + t_u = T \log_e \left(\frac{1}{1 - \frac{I_B}{I_F}} \right) \quad (6)$$

The unlatch time is found by combining (5) and (6) to give:

$$t_u = T \log_e \left(\frac{1 - I_T/I_F}{1 - I_B/I_F} \right) \quad (7)$$

or

$$I_B = I_F \left[1 - \left(1 - \frac{I_T}{I_F} \right) e^{-\frac{t_u}{T}} \right] \quad (8)$$

By combining equations (8) and (4) the arc energy can be calculated in terms of the trip setting and unlatch time for any system condition. Values of arc energy calculated by this method for some typical conditions are given in Section 3.2.

APPENDIX 2 - TO DETERMINE THE EFFECT OF CABLE AND LOAD IMPEDANCE ON CIRCUIT BREAKER ENERGY DISSIPATION

The circuit for analysis is shown below in Figure A2-1 in which the generator or dc supply characteristics have an inductance L_s henrys and resistance R_s ohms. The load (e.g. cable) has parameters L_c and R_c . The dc source voltage has a value of V volts and a short circuit is applied after the load.

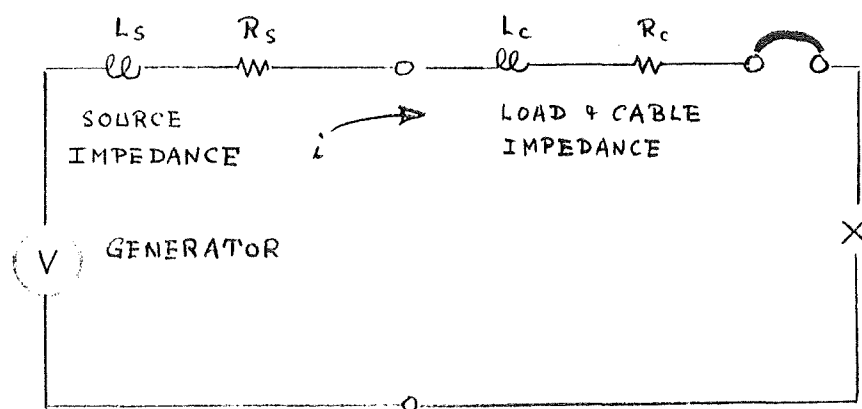


Fig. A2-1. Circuit for Analysis
of Fault Parameters

Assume the circuit breaker has to interrupt when the current i has reached the steady state value as given by $i_F = \frac{V}{R_s + R_c}$. Then if the circuit breaker idealized arc voltage has a value of K times the source voltage V the waveforms of current with respect to time are shown in Figure A2-2.

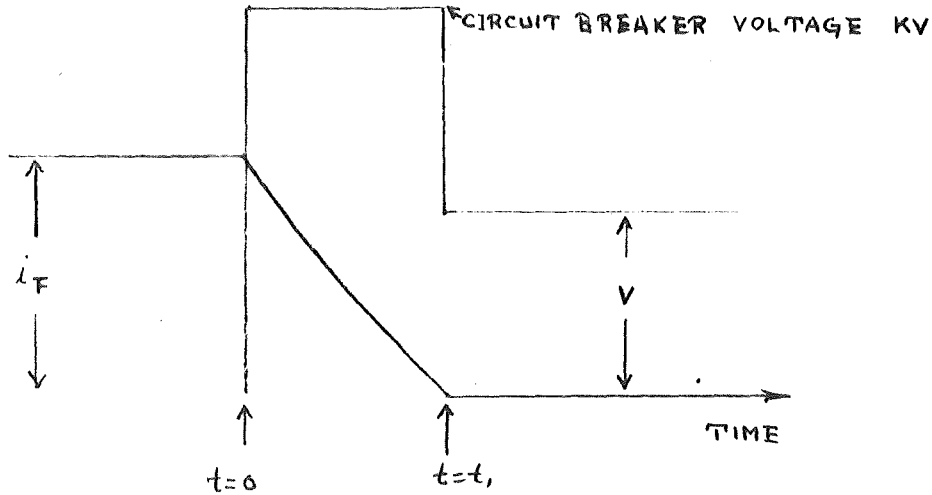


Fig. A2-2. Illustrating Simplified Voltage and Current Waveforms During Current Interruption

Referring to the figure, the solution for current is

$$i(t) = I_F [K e^{-t/T} - (K - 1)] \text{---(A2,1)}$$

$$\text{where } T = \left(\frac{L_S + L_C}{R_S + R_C} \right)$$

The energy dissipated in the circuit breaker arc is given by

$$J_{\text{arc}} = \int_0^{t_1} kV i(t) dt \text{ joules---(A2,2)}$$

where t_1 is the time to reach current zero given by

$$t_1 = T \log_e \left(\frac{K}{K-1} \right) \quad (\text{A2,3})$$

Assuming a typical practical value for the arc voltage of twice the generator voltage, i.e. $K = 2$, the current falls to zero in time of $0.6937 T$.

To find under what conditions the cable impedance will make the task of circuit interruption more arduous, i.e. more dissipative the energy in the arc is calculated as follows:

$$J_{\text{arc}} = kV \int_0^{t_1} i(t) dt \quad (\text{A2,4})$$

which yields on solution

$$J_{\text{arc}} = V i_F KT [1 - (K - 1) \log_e \frac{K}{K-1}] \quad (\text{A2,5})$$

Thus, it is noted that for a given value of arc voltage, i.e. K , the energy in the arc is simply a function of $i_F T$. Thus, by analyzing the function $i_F T$ we can determine the effects of cable inductance and resistance.

$$\text{Thus, } J_{\text{arc}} \propto i_F T \propto \frac{1}{(R_s + R_c)} \frac{(L_s + L_c)}{R_s + R_c} \propto Li_F^2 \quad (\text{A2,6})$$

It is seen that the energy dissipated in the arc is related to the total energy stored in the system, namely $\frac{1}{2} Li_F^2$ and the greater is this energy the more arduous, i.e. more dissipative, will be the circuit breaker operating conditions.

There are two mechanisms by which energy is applied to the arc when the circuit is interrupted. Firstly, energy stored in the circuit inductance must be dissipated in the arc and any series circuit resistance, also it is noted that energy is taken from the source while the current decays to zero. The latter term will vary depending on the amplitude of arc voltage, e.g. the higher the arc voltage the more rapidly will the current be forced to zero and the less will be the extra energy drawn from the supply. Since the total energy to be dissipated varies with Li_F^2 we can, by determining the conditions for this to be maximum, find the most arduous load conditions for the circuit breaker.

Without the cable of impedance, $L_c + R_c$, the maximum stored energy caused by a bolted fault at the generator terminals is

$\frac{1}{2} L_s \left(\frac{V}{R_s} \right)^2$ thus, we can observe the effects of the cable by comparing

$$\frac{\text{Energy Stored With Load}}{\text{Energy Stored Without Load}} = \frac{0.5 (L_c + L_s) (V/(R_c + R_s))^2}{0.5 (L_s) (V/R_s)^2} = \text{say } F_J \text{ -- (A2,7)}$$

$$\text{Thus } F_J = (1 + L_c/L_s) \cdot \frac{1}{(1 + R_c/R_s)^2} \text{ -- -- (A2,8)}$$

$$\text{defining } \frac{\text{Load Time Constant}}{\text{Source Time Constant}} = n = \frac{L_c R_s}{R_c L_s} \text{ (A2,9)}$$

$$\text{we obtain } \frac{L_c}{L_s} = n \frac{R_c}{R_s} \text{ (A2,10)}$$

and substituting A2,10 in A2,8 we get

$$F_J = (1 + n R_c/R_s) / (1 + R_c/R_s)^2. \text{ (A2,11)}$$

Differentiating F_J with respect to R_c/R_s and equating to zero, it is found that F_J has a maximum value when

$$\frac{R_c}{R_s} = \frac{(n - 2)}{n} \text{ (A2,12)}$$

$$\text{substituting we find } F_{\max} = \frac{n^2}{4} \frac{1}{(n - 1)} \text{ providing } n > 2 \text{ (A2,13)}$$

The foregoing analysis shows that if the factor n is greater than 2 the duty of the circuit breaker will be more arduous when a certain length of cable is included in the fault circuit than if the short circuit is applied directly at the substation terminals, in other words the worst case condition for the circuit breaker is not necessarily associated with the greatest fault current.

In the mine systems the cable time constants are 17.4 ms and 25 ms for the 600 volt and 300 volt systems whereas the 500 kW generator time constants are 18 ms and 80 ms, respectively. Thus for generator power sources n is less than 2 and maximum demand is made of the circuit breaker for faults at the generator terminals.

The time constants for 1000 kW rectifier sources are substantially less, namely 3.64 ms and 3.62 ms for 600 volt and 300 volt rectifier units respectively. This leads to a worst case for the circuit breaker when faults are applied along the cable at 460 feet for 600 volt systems and 220 ft for 300 volt systems.

Although this worst case analysis does not include breaker speed as a variable affecting the worst case impedance the results are considered practically representative of actual mine operating conditions and a table of worst case fault levels which may be used for tests of candidate circuit breakers are given in Table A2-1.

Combined Source and Cable Parameters

<u>Power Source</u>		<u>Prospective Fault Amperes</u>	<u>Inductance mH</u>	<u>System Time Constant ms</u>	<u>kJ Energy Stored at 18 ms</u>
1000 kW Rect	600 Volt	22,400	0.54	20	47.2
500 kW Gen	600 Volt	12,500	0.86	18	27
1000 kW Rect	300 Volt	40,000	0.092	12.3	43.6
500 kW Gen	300 Volt	25,000	0.96	80	12.2

Table A2-1. Worst Case Bolted Fault Conditions
for Mine DC Electrical Systems

In the above table the total kilojoules stored in the system are given at a time of 18 ms after the fault is applied, because this is typically the value at which candidate circuit breakers have operated. Thus this energy is the maximum stored energy that practical circuit breakers may be called upon to interrupt.

APPENDIX 3 - CIRCUIT BREAKER EQUIVALENT ARC VOLTAGE

It is observed from oscillograph traces showing the actual arc voltage across the circuit breaker that significant perturbations of arc voltage occur during circuit interruption. The frequency of the perturbation varies widely but is typically of the order of 400 Hz. Amplitude variations of arc voltage are significant, for example, on a single pole the arc voltage may vary from 540 to 250 volts with an average value of about 400 volts. When poles are connected in series a more consistent overall arc voltage is obtained and in deciding on the capability of candidate circuit breakers to perform satisfactorily it is convenient to accommodate the transient fluctuations by defining an equivalent steady arc voltage which has the same average effect. Taking the equivalent a stage further it has been convenient to define a per unit arc voltage which is the ratio of total circuit breaker arc voltage to the system supply voltage. The per unit arc voltage is calculated from the test system parameters in the following way.

Figure A3-1 indicates the test circuit in which the circuit breaker allows the current to build up to a value i_B before the circuit

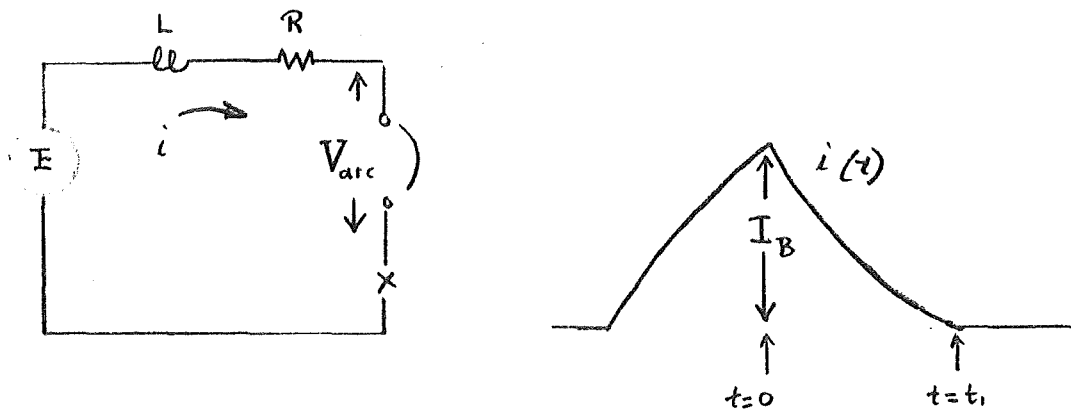


Fig. A3-1

breaker arc voltage V_{arc} causes the current to be reduced to zero. Assuming that V_{arc} has a steady value then solving for current we get

$$i = \left(\frac{E - V_{arc}}{R} \right) (1 - e^{-t/T}) + I_B e^{-t/T} \quad (A3-1)$$

where T is the circuit time constant L/R and t is the elapsed time starting from $t = 0$ at $i = I_B$. Let the time to reach current zero be t_1 then

$$\frac{V_{arc}}{E} = 1 + \frac{I_B}{I_F} \frac{e^{-t_1/T}}{(1 - e^{-t_1/T})} \quad (A3-2)$$

where I_F is the final current E/R and $\frac{V_{arc}}{E}$ is the per unit arc voltage.

From measured test data for t_1 the per unit arc voltage can be derived from Equation A3-2.

It is of interest to determine what ratio of per unit arc voltage would be considered a good design value. Although the matter is subjective it is known from tests and application of the molded case circuit breakers that very satisfactory performance results if the current can be reduced to zero is about 16 milliseconds or less, since in this short time there is little chance of the arc voltage collapsing.

Rearranging A3-2, we get

$$t_1 = 16 \times 10^{-3} = \frac{L I_F}{E} \log \left[1 + \frac{I_B}{I_F} \frac{1}{(V_{arc}/E - 1)} \right] \quad (A3-3)$$

now the factor LI_F/E is a system parameter which from Section 2.5 is determined as typically

$$LI_F/E \approx 0.036 \text{ for 300 volt systems}$$

and $LI_F/E \approx 0.0176$ for 600 volt systems.

The ratio of I_B/I_F is variable depending on circuit breaker response and system time, however, for molded case breakers and loads similar to the mine dc system a typical value for I_B/I_F is about 0.5. Substituting these factors into Equation A3-3, gives desirable per unit arc voltages of 1.89 for a 300 volt dc system and 1.34 for a 600 volt dc system. Higher per unit arc voltages would of course be even more satisfactory.

APPENDIX 4 - SELF-INDUCTANCE OF IRON RAILS

In a circular wire, maximum flux density occurs at the periphery of the wire and assuming a relative permeability of 2000 for the iron the current at which magnetic saturation of the rail occurs is estimated as follows. Based on a resistivity for the steel rail of 138 ohms-circular mils per foot, the equivalent circular conductor representing the two steel rails has a cross section of 21,900 kcmil and a diameter of 4.68 inches. To determine saturation effects both rails must be considered each carrying a current of $I/2$. The effective diameter of each rail is 3.32 inches and the field strength at the periphery of the rail is given by $\frac{I}{2}/(\pi \times 3.32 \times 2.54)$, namely $I/53$ ampere turns/cm. Assuming a permeability of 2000 and a saturation flux of 13,000 gauss, the equivalent rail section will start to saturate when the current exceeds about $\frac{13,000 \times 53}{2000}$, i.e. 344 amps.

It is recognized that some fairly drastic simplifications have been made in the above calculations, however, in the mine system since the fault currents expected are typically at least five times greater than the value at which the rail saturates, it is concluded that the loop inductance of the mine wiring will be the main factor determining the energy stored in the system during faults and therefore the controlling factor effecting circuit breaker performance. Also since the rail is at ground potential if currents flow through the parallel path of the earth then although the rail may not saturate the parallel resistance will swamp the effects of the rail self inductance. Typically the resistance of the earth paths are given as $0.054 \Omega/1000 \text{ ft}$. It is noted that if a high resistance rail-to-ground connection occurs and low values of dc current are flowing, the rail inductance could be a significant factor effecting ac currents if carrier type systems are used for discrimination of ground faults. As an approximation of the

rail self-inductance consider the rails as two circular conductors of diameter 3.32 inches and permeability 2000. Neglecting the mutual coupling of the rails which would reduce the inductance only a small amount, the low frequency self-inductance of the two parallel rails is estimated from

$$^*L_o = \frac{0.00508 \ell}{2} (2.303 \log_{10} \frac{4\ell}{d} - 1 + \frac{\mu}{4}) \text{ microhenry}$$

where ℓ is the length and d the diameter in inches.

Thus $L_{\text{rails}} = 15.6 \text{ mH/1000 ft.}$

* Radio Engineers Handbook - Terman

APPENDIX 5. WORST CASE CURRENT AND INDUCTANCE PARAMETERS FOR MULTIPLE PARALLEL SYSTEM

In a practical mine system there may be a number of substations operating in parallel and in the event of a fault each can contribute current to the fault. In setting up test conditions for the circuit breakers it is necessary to specify current and inductance values representative of mine operations. To determine what is the worst case (i.e. greatest stored energy) associated with a given prospective current I , then it is necessary to compare the energy associated with a single generator, namely $\frac{1}{2} L I^2$ with that contributed by a number of substations, for example, $\frac{1}{2} L_1 i_1^2 + \frac{1}{2} L_2 i_2^2 + \dots + \frac{1}{2} L_n i_n^2$ where $i_1 + i_2 + \dots + i_n = I$

For a single generator

$$E_n = \frac{1}{2} (L_s + L_c) I_F^2$$

since the cable time constant is fixed

$$L_c/R_c = K_c \text{ and } I_F = \frac{V}{R_c + R_s} = \frac{V}{\frac{L_c}{K_c} + R_s}$$

then

$$L_c = (V/I - R_s) K_c$$

$$\text{Stored Energy} = \frac{1}{2} L_s I_F^2 + \frac{1}{2} \left[\frac{V}{I_F} - R_s \right] K_c I_F^2$$

$$\text{Stored Energy} = \frac{1}{2} R_s \left(\frac{L_s}{R_s} - \frac{L_c}{R_c} \right) I_F^2 + \frac{1}{2} V I_F K_c \quad (1)$$

Referring to Figure 2.6-1 if

$$I_F = (i_1 + i_2 + \dots + i_n)$$

the term $\frac{1}{2} V I_F K_C$ is unaltered, however, the first term of Equation (1) becomes

$$\frac{1}{2} R_S \left(\frac{L_S}{R_S} - \frac{L_C}{R_C} \right) (i_1^2 + i_2^2 + \dots i_n^2)$$

since $i_1^2 + i_2^2 + \dots i_n^2 = (i_1 + i_2 + \dots i_n)^2 -$

$$f(i_1 i_2 \dots i_n) = I_F^2 - f(i_1 i_2 \dots i_n)$$

then $(i_1^2 + i_2^2 + \dots i_n^2) < I_F^2$

Providing L_S/R_S is greater than L_C/R_C which is true for most rotating power sources then it is concluded that maximum energy is stored with a given current if that current is supplied from a single generator substation.

APPENDIX 6 - SPECIFICATIONS FOR TRANSFORMERS AND
CHOKES REQUIRED FOR DISCRIMINATING CIRCUIT BREAKER

TRANSFORMER SPECIFICATION DCB-CT1

Date Submitted MARCH 73

AIR CORED CURRENT

Date Wanted _____

TRANSFORMER for

Date Delivered _____

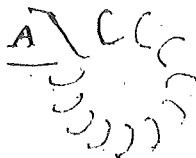
3 kHz DETECTOR

DRAW DIAGRAM BELOW

Quantity Wanted 1

Tuned with 0.1 μ F approx
before potting

With 300mA through
a single turn primary output
of winding A in 5.1 k Ω is
0.283 volts at 3kHz



$$L \approx 26 \text{ mH}$$

$$r = 32 \Omega$$

Winding	A	B	C	D	E	F	G	H	I	J
Turns	3000									
Wire Size PDS	25									
Single-Bifilar-Other										
Foil Shield Between										
Winding Insulation Glass Tape	5mil									
Layer Insulation										
Lead Wire	Flex	26 gauge								
Lead Length	24"									
Lead Insulation	PVC									
Lead Marking Start	Red									
Finish	Black									
HiPot Volts Before Pot										
After Pot										
Vacuum Impregnate	Yes/No	W2100	Varnish	Other						
Dip Coat										
CORE	Type of Band	Type of Stand	Vert.	Wound By	Banded By	HiPot By	Continuity			
			Hor.				Polarity By			
	Type	Single	Stacked	Other	Hrs	Hrs	Hrs	Hrs	Total Hrs	

Special Instructions if any (use reverse side or separate sheet if needed)

COIL TO BE WOUND ON MICARTA TOROID 1" HIGH 5" OD, 3" ID

DIP COAT WITH W 2100 AFTER ASSEMBLY

Please fill in all pertinent information. Blank spaces are considered not wanted.

Location _____ Phone Ext. _____

Charge Number 9G20-MIBRK-01

Originator D. A PAICE

TRANSFORMER SPECIFICATION DCB-CT2

3 kHz Interstage Current Transformer
for Discriminating Circuit Breaker.

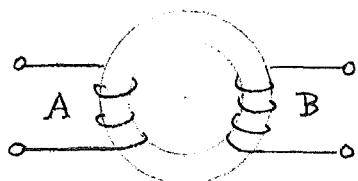
DRAW DIAGRAM BELOW

Date Submitted APRIL-73

Date Wanted _____

Date Delivered _____

Quantity Wanted 1



With 7 volts at 3 kHz
applied to wdg A, magnetising
current must be not greater
than 0.7 mA

Winding	A	B	C	D	E	F	G	H	I	J
Turns	300	1500								
Wire Size PDS	34	38								
Single-Bifilar-Other										
Foil Shield Between										
Winding Insulation Glass Tape	5mil	5mil								
Layer Insulation	NONE	NONE								
Lead Wire	7/34 Flexible									
Lead Length	4"	4"								
Lead Insulation	Pvc	Pvc								
Lead Marking Start	Red	Green								
Finish	Black	Blue								
HiPot Volts	Before Pot	After Pot								
Vacuum Impregnate	yes	no	W2100	varnish	Other					
Dip Coat			W2100							
TOROID CORE	Type of Band	Type of Stand	Vert. Hor.	Wound By	Banded By	HiPot By	Continuity Polarity By			
	Type	Single	Stacked	Other	Hrs	Hrs	Hrs	Hrs	Total Hrs	
	5233P1									

Special Instructions if any (use reverse side or separate sheet if needed) _____

DO NOT VACUUM IMPREGNATE

Please fill in all pertinent information. Blank spaces are considered not wanted.

Location _____ Phone Ext. 7601

Charge Number 9620-MIBRK-01

Originator D. A PAICE

TRANSFORMER SPECIFICATION DCB CT3

CURRENT TRANSFORMER

FOR POWER TRANSISTOR DRIVE

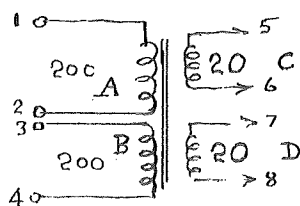
Date Submitted MAY 1973

Date Wanted _____

Date Delivered _____

Quantity Wanted 1

DRAW DIAGRAM BELOW



Primary $r = 10 \Omega$ per coil
Secondary $r = . \Omega$ per coil

Winding	A	B	C	D	E	F	G	H	I	J
Turns	200	200	20	20						
Wire Size PDS	35 G		31 G							
Single-Bifilar-Other	BIFILAR		BIFILAR							
Foil Shield Between	NO									
Winding Insulation	5 mil tape									
Layer Insulation	NONE									
Lead Wire			DIRECT							
Lead Length	3"		3'							
Lead Insulation	PVC Sleeve									
Lead Marking	Start	Finish	1	2	3	4	5	6	7	8
HiPot Volts	Before Pot	After Pot	yes/no		varnish		Order		Airgap	
Vacuum Impregnate									Size	
Dip Coat									Mtl.	
									per leg	
FERRITE CORE	Type of Band	Type of Stand	Vert.	Wound By	Banded By	HiPot By	Continuity			
	Type	Single	Stacked	Hor.				Polarity By		
	D 42616			Other	Hrs	Hrs	Hrs	Hrs	Total Hrs	

Special Instructions if any (use reverse side or separate sheet if needed)

Please fill in all pertinent information. Blank spaces are considered not wanted.

Location _____ Phone Ext. _____

Charge Number 9-G 20-MIBRK-01

Originator D A PAICE

TRANSFORMER SPECIFICATION DCB-L1

3 kHz FILTER INDUCTORS

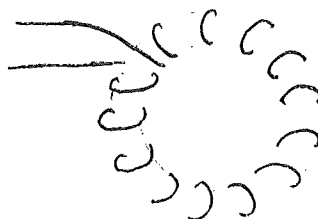
Date Submitted MAY 1973

Date Wanted _____

Date Delivered _____

Quantity Wanted 2

DRAW DIAGRAM BELOW



$L = 0.85 \text{ mH}$

$r = 0.15 \text{ in}$

Winding	A	B	C	D	E	F	G	H	I	J
Turns	100									
Wire Size PDS	20									
Single-Bifilar-Other										
Foil Shield Between										
Winding Insulation	6 mil Tape									
Layer Insulation										
Lead Wire	Direct									
Lead Length	8"									
Lead Insulation	PVC									
Lead Marking	Start	Finish								
HiPot Volts	Before Pot	After Pot								
Vacuum Impregnate	Yes/No	W2100 Varnish	Other							
Dip Coat	✓	✓								

MOLYBDENUM PERMALLOY CORE	Type of Band	Type of Stand		Vert.	Wound By	Banded By	HiPot By	Continuity	
				Hor.				Polarity	By
	Type	Single	Stacked	Other	Hrs	Hrs	Hrs	Hrs	Total Hrs
	W099075-4								

Special Instructions if any (use reverse side or separate sheet if needed)

LEAVE A HOLE AT LEAST 1/8" DIAMETER IN CENTER OF COIL

Please fill in all pertinent information. Blank spaces are considered not wanted.

Location _____ Phone Ext. _____

Charge Number 9 G 20-MIBRK-01

Originator D. A. PAICE

TRANSFORMER SPECIFICATION DCB VT 1

OUTPUT TRANSFORMER
FOR POWER OSCILLATOR

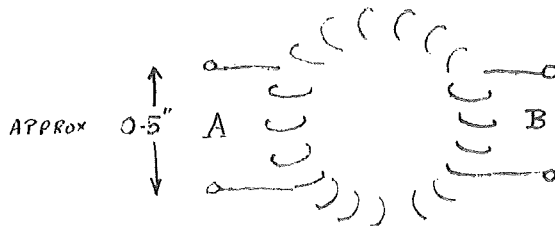
DRAW DIAGRAM BELOW

Date Submitted JUNE 1973

Date Wanted _____

Date Delivered _____

Quantity Wanted 1



Primary (A) $r = 1.5 \Omega$

Secondary (B) $r = 0.43 \Omega$

$L_p = 200 \text{ mH}$

Leakage inductance
referred to secondary = $150 \mu\text{H}$

Winding	A	B	C	D	E	F	G	H	I	J
Turns	400	160								
Wire Size PDS	23	20								
Single-Bifilar-Other										
Foil Shield Between										
Winding Insulation	6 mil	$\frac{1}{2}$ lapped	glass tape - two layers							
Layer Insulation	NONE									
Lead Wire	DIRECT									
Lead Length	12"	12"								
Lead Insulation	PVC	TEFLON								
Lead Marking	Start	Finish								
2000 Volts HiPot	Before Pot	After Pot								
Vacuum Impregnate	yes/no/w2100 varnish Other								Airgap	
Dip Coat	X	X							Size Mtl. per leg	
FERROX CUBT	Type of Band	Type of Stand	Vert.	Wound By	Banded By	HiPot By	Continuity			
CORE	Type	Single	Hor.				Polarity By			
	400/T 750/3C5	Stacked	Other	Hrs	Hrs	Hrs	Hrs	Total Hrs		

Special Instructions if any (use reverse side or separate sheet if needed)

HALF LAP CORE WITH 1 MIL MYLAR TAPE - DIP COAT FIRST COIL WITH W2100 BEFORE WINDING SECOND COIL. DIP COAT ASSEMBLY WITH W2100. DO NOT LET WDG B OVERLAP LEAD OUTS FOR WDG A

Please fill in all pertinent information. Blank spaces are considered not wanted.

Location _____ Phone Ext. _____

Charge Number 9 G 20 - MIBRK - 01

Originator D. A. PAICE

TRANSFORMER SPECIFICATION DCB - 12

Date Submitted JUNE 1973

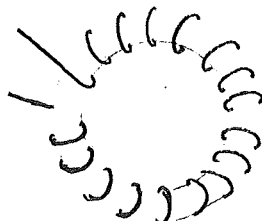
OUTPUT SUPPRESSION CHOKE

Date Wanted _____

Date Delivered _____

DRAW DIAGRAM BELOW

Quantity Wanted 1



$$L = 300 \mu H$$

$$r = 0.09 \Omega$$

Winding Turns	A	B	C	D	E	F	G	H	I	J
Wire Size PDS _____	20									
Single-Bifilar-Other										
Foil Shield Between										
Winding Insulation	6 mil	glass	tape	$\frac{1}{2}$ lap	two	layers				
Layer Insulation										
Lead Wire	Direct									
Lead Length	8"									
Lead Insulation	PVC									
Lead Marking	Start	Finish								
HiPot Volts	Before Pot	After Pot								
Vacuum Impregnate	Yes	No	W2100	varnish	Other					
Dip Coat	☒	☒								

MOLYBDEN PERMALLOY CORE	Type of Band	Type of Stand		Vert. Hor.	Wound By	Banded By	HiPot By	Continuity Polarity By	
	Type W 099075-4	Single	Stacked	Other	Hrs	Hrs	Hrs	Hrs	Total Hrs

Special Instructions if any (use reverse side or separate sheet if needed)

LEAVE A HOLE AT LEAST $\frac{1}{8}$ " DIAMETER IN CENTER
OF COIL

Please fill in all pertinent information. Blank spaces are considered not wanted.

Location _____ Phone Ext. _____

Charge Number 9620-MIBRK-01

Originator D. A. PAICE

APPENDIX 7. DESCRIPTION OF DISCB LOGIC CIRCUITRY OPERATION

Five possible operating conditions can exist for the discriminating circuit breaker and the control unit (schematic diagram given in Figure 4.5-1) with its associated logic. The operation of the logic under these conditions is described below:

1. Normal operation. The breaker is closed but no illegitimate load exists.
 - a. Relays CR1, CR2, and CR3 are dropped out.
 - b. Capacitors C6 and C7 are charged to 48 volts and transistor Q5 is off.
 - c. Because no ground fault exists, transistor Q3 is off.
 - d. Because CR1 is dropped out, trip indicator light IL2 is off.
2. Operation when an illegitimate load occurs after the power is on.
 - a. Initially the system is in condition 1.
 - b. An illegitimate load occurs. After a delay, the detector circuitry turns on transistor Q3 and picks up relay CR1.
 - c. Relay CR1 turns on trip indicator light IL2 and also seals itself in through the path-resistor R24, a normally open contact of CR1, a normally closed contact of CR3, the base emitter of transistor Q5, and diode D13.

- d. The current into the base of Q5 turns it fully on. Capacitors C6 and C7 are now rapidly discharged through the breaker shunt trip coil causing the breaker to trip.
- e. When the breaker trips, the power supply for the control circuitry may or may not be removed depending on the particular power system arrangement. If the control power is removed both indicator lights will be off. Reclosing the breaker in this case puts the system into condition 5 described below. If on the other hand the control power is not removed when the breaker trips, relay CR1 will stay sealed in and indicating lights IL1 and IL2 will remain on. The opening of the breaker will however remove the illegitimate load and the detector will cause transistor Q3 to turn off.
- f. If control power remains on with the breaker tripped, pushing the test and reset button SW-1 will pick up relay CR2 instantaneously and approximately 100 milliseconds later pick up relay CR3. The seal-in path for relay CR1 is now through a normally open contact of CR2. Releasing SW-1 drops out CR2 instantly and after a 100 millisecond delay CR3. This momentarily opens the seal-in path for CR1 causing it to drop out. When CR1 drops out, IL2 turns off and Q5 turns off. The breaker can now be reset without tripping via the shunt

trip (assuming the illegitimate load has been removed). If the breaker handle is pushed to the reset position before SW-1 is depressed, the breaker will trip within 5 seconds because of the periodic pulses described in Section 4.5 being delivered to the shunt trip coil.

3. Instantaneous breaker overload trip. The breaker trips due to a high current through its series trip. The discriminating control unit does not affect this operation.
4. Test condition.
 - a. Initially the system is in condition 1.
 - b. The test and reset button SW-1 is then depressed and held down.
 - c. Relay CR2 picks up instantly. One contact of CR2 changes the detector reference, and another contact increases the sensitivity of the control. As described in Section 4.5 the small dc current drawn by the control unit is now "seen" as an illegitimate load.
 - d. Approximately 100 milliseconds after CR2 picks up relay CR3 picks up. This shorts the base of transistor Q5 and opens its base current supply. Now Q5 cannot turn on and the breaker shunt trip cannot operate.
 - e. About one second after CR2 and CR3 picks up, the simulated illegitimate load causes transistor Q3 to turn on and pick up CR1. Relay CR1 now turns on the trip indicator light IL2 and seals in through the

normally open contact of CR2. The illumination of IL2 indicates the detector circuit operates properly.

- f. If SW-1 is released before (e) above occurs, the system goes back to condition 1. If SW-1 is released after (e) above occurs, CR2 drops out and Q3 turns off instantaneously. Relay CR1 then drops out and IL2 turns off.
- g. Approximately 100 milliseconds after CR2 drops out CR3 drops out. This re-establishes a current path to the base of Q5 again which enables the operation of the shunt trip if it is necessary. The system is now back in condition 1 and ready to detect the presence of illegitimate loads.
- h. Note the breaker cannot trip due to an illegitimate load during the short time SW-1 is depressed.

- 5. Power is applied to the system when an illegitimate load already exists.

When control power comes on, circuitry is provided to hold transistor Q5 off until capacitors C6 and C7 have charged to a minimum of 38 volts (a value large enough to ensure operation of the shunt trip). Once the capacitors have charged Q5 is permitted to turn on condition described above exists. The result is a delay of about 5 seconds between energizing of the system and the breaker tripping.

APPENDIX 8. ACTIVE IMPEDANCE MULTIPLIER
FOR MINE GROUND FAULT DETECTOR SYSTEM

Westinghouse Electric Corporation

INVENTION DISCLOSURE (Signature Sheet)

DISCLOSURE NO.

CASE NO.

PATENT NO.

RES
73-106

IMPORTANT:

When complete, sign and date and have witnesses read, sign, and date this sheet and all description sheets. Attach all original sketches or descriptions signed, dated and witnessed or identify the permanent location thereof. Complete and attach transmittal sheet. Do not alter after signed and witnessed.

February 1 19 73

DATE WHEN WRITTEN OR TYPED ON THESE SHEETS

LOCATION AND DATE OF EARLIER DESCRIPTION

DISCLOSURE TITLE:

ACTIVE IMPEDANCE MULTIPLIER FOR MINE GROUND FAULT DETECTOR SYSTEM

LIST RECORDS OF FIRST CONCEPTION AND DEVELOPMENT OF INVENTION SUCH AS FIGURING BOOK NUMBER AND PAGE, NOTEBOOKS, ETC.				LOCATION AND DATE OF RECORD
(W) Figuring Book 205412, pp 96,97				R&D - 1/26/73
"	"	"	p 98	R&D - 1/29/73
"	"	"	p 99	R&D - 1/30/73
"	"	"	p 100	R&D - 1/31/73

INVENTOR(S) PRINT OR TYPE NAME(S)	INVENTOR(S) SIGNATURE(S)	DATE OF SIGNATURE	DATE OF CONCEPTION	LOCATION/DEPT.
A. B. Shimp	<i>A. B. Shimp</i>	2-9-73	1-26-73	R&D - SSE
D. A. Paice	<i>D. A. Paice</i>	2-9-73	1-26-73	R&D - SSE

TWO WITNESSES PRINT OR TYPE NAMES	WITNESSES' SIGNATURES	DATE OF SIGNATURE	DATE EXPLAINED TO AND UNDERSTOOD BY ME	LOCATION/DEPT.
D. S. Kimmel	<i>D. S. Kimmel</i>	2/9/73	1/30/73	R&D - SSE
F. J. Prines	<i>F. J. Prines</i>	2-9-73	2-9-73	R&D - SSE

IF EXPLAINED TO WITNESSES OR OTHERS EARLIER, IDENTIFY DOCUMENTS OR OTHER CIRCUMSTANCES INVOLVED AND RESPECTIVE DATES

A8-2

DISCLOSURE TITLE:

ACTIVE IMPEDANCE MULTIPLIER FOR MINE GROUND FAULT DETECTOR SYSTEM

DESCRIPTION OF THE INVENTION (Typewritten, if possible)

SUMMARY OF THE PROBLEM

Electric trains which are used in mines usually operate from 300 to 600 volt dc, one side of which returns to the source through grounded rails. Accidental grounds can occur in these systems which although drawing much less current than the operating current of a train can cause severe damage and start mine fires. Simple overcurrent sensing will not detect these ground faults. What is needed is a protection scheme which discriminates between legitimate train loads and illegitimate ground faults.

Superimposing an ac voltage on the dc line can be used to provide a discriminator system. In such a system the legitimate loads are made to present a high impedance to ac at the frequency used. Any ac current that flows is then a measure of the illegitimate load impedance. Such a system has been successfully used in France.

A problem arises in applying this type of discriminator to dc systems which have very large legitimate train loads, such as are common in the U.S.A. The legitimate load impedance increases with the ac frequency (experimentally it has been found to increase about as $(f)^{0.67}$). The line impedance, which is practically all inductive, increases directly with frequency and the length of line. Therefore, there is a conflicting requirement on the frequency because it is desirable to make the legitimate load impedance high and to protect long lengths of cable. It has been found that tuning the legitimate loads to the frequency of the ac signal increases their impedance but only by a factor of about 2. The use of filters in series with each legitimate load is possible but since each filter must carry several thousand amps dc continuously, these filters are comparatively large, and costly. For example, a parallel LC filter tuned to produce 100 Ω at 10 kHz and suitable for a 300 volt, 3600 amp legitimate load would weigh about 1000 lbs.

SOLUTION

A circuit which effectively multiplies the impedance of the legitimate loads is shown in Figure 1. The current source which is fed by the detector is arranged to produce an output current k times the current in the detector and in phase with it. The ac current, I, that flows from the source is thus

$$I = \frac{V}{Z_{\text{source}} + (1 + K) Z_L}$$

Use additional description sheets (Form 17778K Sheet 3), if necessary

NOTE: All sheets should be signed and witnessed.

INVENTOR(S) SIGNATURE(S)	DATE OF SIGNATURE	WITNESSES' SIGNATURES	DATE OF SIGNATURE	DATE EXPLAINED TO AND UNDERSTOOD BY ME
A. B. Shandy	2-9-73	A. S. Bammel	2/9/73	1/30/73
K. A. Vane	2-9-73	[Signature]	2-9-73	2-9-73

DISCLOSURE TITLE:

ACTIVE IMPEDANCE MULTIPLIER FOR MINE GROUND FAULT DETECTOR SYSTEM

DESCRIPTION OF THE INVENTION (Typewritten, if possible)

or in other words the load impedance is multiplied by $(1 + K)$.

In a practical system the detector can be an air core transformer tuned to the frequency used so that the magnitude of dc load current will not affect the detector output. The current source can be an amplifier of typically 25 to 50 watts output. A value of 9 or 10 for K, which is easily obtained, provides sufficient multiplication for a practical system. If desired, the legitimate load can be tuned with capacitors to provide a still higher impedance. Alternatively a phase shift can be introduced in the amplifier to achieve the same result. The previous assumption of zero phase shift in the detector and amplifier is not a necessary requirement for the impedance multiplication system to operate satisfactorily. In the appendix it is shown that the multiplication factor varies from $(1 + K)$ with zero phase shift to $\sqrt{1 + K^2}$ as the phase angle varies from 0 to 90°. For even modest values of K the multiplication is nearly the same in either case. By using a suitable lagging phase shift in the detector plus amplifier a lagging power factor load can be tuned to look more resistive at the operating frequency.

To verify the predictions, a breadboard system was built in which the amplifier plus detector had a value for K of 12 at 10 kHz, the tuned frequency of the detector. The load used was a 4 HP, 36 volt dc, series motor. On Figure 2 is plotted the impedance of the motor both with and without the active impedance multiplier connected for various frequencies. The results verify the principle quite closely. In a practical system the exact value of impedance multiplication is not critical anyway.

ADVANTAGES

1. The legitimate load impedances can be increased significantly with the use of relatively small inexpensive components.
2. The impedance of the legitimate load is removed as a determining factor in the choice of frequency for the discriminator system. This permits the system to be optimized for sensitivity and length of line protected.
3. The impedance multiplying circuitry can also be used to tune the legitimate load if desired.

Use additional description sheets (Form 17778K Sheet 3), if necessary

NOTE: All sheets should be signed and witnessed.

INVENTOR(S) SIGNATURE(S)	DATE OF SIGNATURE	WITNESSES' SIGNATURES	DATE OF SIGNATURE	DATE EXPLAINED TO AND UNDERSTOOD BY ME
<i>A. B. Schenck</i>	2-9-73	<i>A. S. Zimmer</i>	2/9/73	1/30/73
<i>L. A. Dancer</i>	2-9-73	<i>[Signature]</i>	2-9-73	2-9-13

DISCLOSURE TITLE:

ACTIVE IMPEDANCE MULTIPLIER FOR MINE GROUND FAULT DETECTOR SYSTEM

DESCRIPTION OF THE INVENTION (Typewritten, if possible)

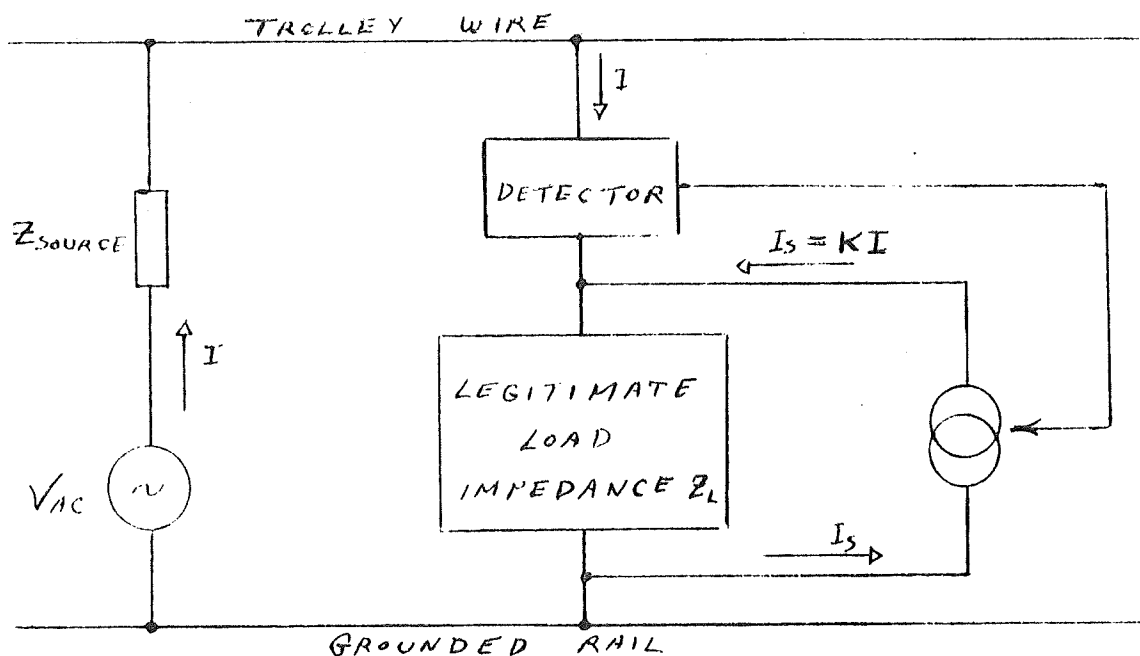


FIGURE 1

Use additional description sheets (Form 17778K Sheet 3), if necessary

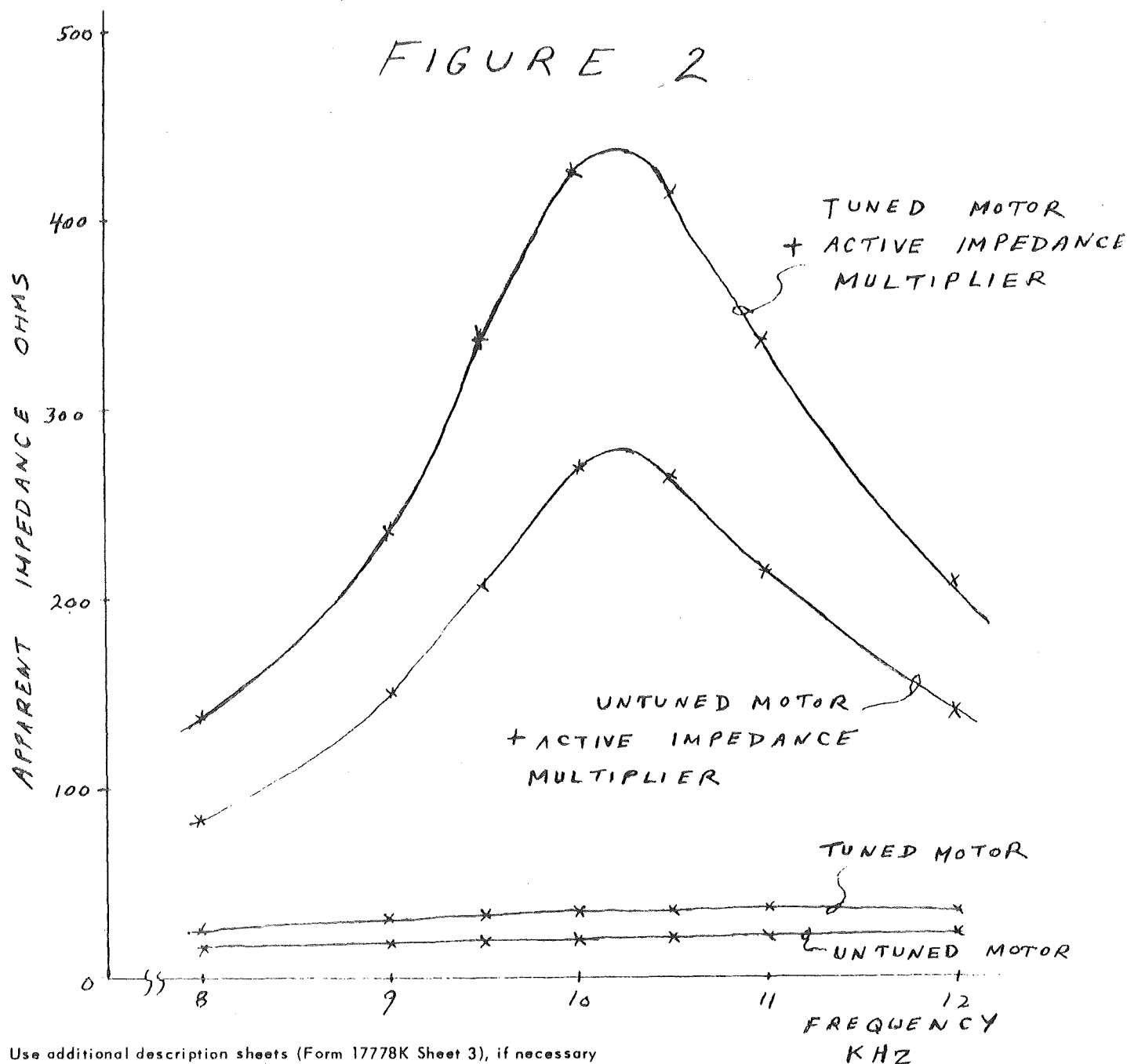
NOTE: All sheets should be signed and witnessed.

INVENTOR(S) SIGNATURE(S)	DATE OF SIGNATURE	WITNESSES' SIGNATURES	DATE OF SIGNATURE	DATE EXAMINED TO AND UNDERSTOOD BY ME
<i>H. B. Shugart</i>	2-9-73	<i>A. S. Kimmel</i>	2/9/73	1/30/73
<i>A. A. Vance</i>	2-9-73	<i>[Signature]</i>	2-9-73	2-7-73

DISCLOSURE TITLE:

ACTIVE IMPEDANCE MULTIPLIER FOR MINE GROUND FAULT DETECTOR SYSTEM

DESCRIPTION OF THE INVENTION (Typewritten, if possible)



Use additional description sheets (Form 17778K Sheet 3), if necessary

NOTE: All sheets should be signed and witnessed.

INVENTOR(S) SIGNATURE(S)	DATE OF SIGNATURE	WITNESSES' SIGNATURES	DATE OF SIGNATURE	DATE EXPLAINED TO AND UNDERSTOOD BY ME
<i>H. P. Sherry</i>	2-9-73	<i>D. S. Bimmel</i>	2/9/73	1/30/73
<i>A. J. Davis</i>	2-9-73	<i>[Signature]</i>	2-7-73	2-7-73
		A8-6		

DISCLOSURE TITLE:

ACTIVE IMPEDANCE MULTIPLIER FOR MINE GROUND FAULT DETECTOR SYSTEM

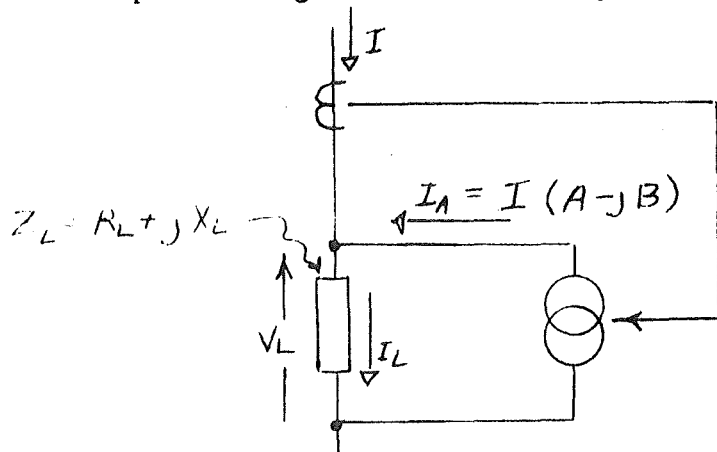
DESCRIPTION OF THE INVENTION (Typewritten, if possible)

NOVELTY

The use of an active impedance multiplier on mine ground fault discriminator systems is believed novel.

APPENDIX

Assume the detector and amplifier has a gain of $A - jB$ that is the output current from the amplifier lags the detector input current I . $[K = A^2 + B^2$ is assumed.]



Now the apparent load impedance Z is:

$$Z = \frac{V_L}{I} = \frac{I [1 + A - jB] [R_L + jX_L]}{I}$$

$$Z = (1 + A) R_L + BX_L + j [(1 + A) X_L - BR_L]$$

The magnitude of Z is:

$$|Z| = \sqrt{[(1 + A)R_L + BX_L]^2 + [(1 + A)X_L - BR_L]^2}$$

Use additional description sheets (Form 17778K Sheet 3), if necessary

NOTE: All sheets should be signed and witnessed.

INVENTOR(S) SIGNATURE(S)	DATE OF SIGNATURE	WITNESSES' SIGNATURES	DATE OF SIGNATURE	DATE EXPLAINED TO AND UNDERSTOOD BY ME
<i>H. B. Skilling</i>	2-9-73	<i>D. S. Kimmel</i>	2/9/73	1/30/73
<i>H. A. Lurie</i>	2-9-73	<i>[Signature]</i>	2-9-73	2-9-73
		A8-7		

APPENDIX 9. CIRCUIT BREAKER MODIFICATIONS

In all of the circuit breakers determined to be adequate it is necessary that the insulation of the microswitch assembly associated with the shunt trip coil be improved. To achieve this improvement it is recommended that the microswitch be deleted.

Breaker type NB requires additional pole insulation for 600 volt operation and drawing 1257C59 indicates the details.

jm
7/9/73

