DEVELOPMENT OF A DC CURRENT LIMITING AND INTERRUPTING SYSTEM FOR MINES

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ABSTRACT

A switching system for high-fault-current 300- and 600-Vdc mine power systems is presented. The system consists of paralleled main and auxiliary contactor circuits with a liquid metal current limiting device (CLD) in series with the auxiliary contactor. Upon detection of a fault, the current is commutated into the CLD circuit. The liquid metal vaporizes, increasing the CLD resistance and considerably decreasing the actual current to be interrupted. This system materially reduces the wear and tear on contactors because of the reduced interrupting requirement. The CLD is pressurized; when the current is interrupted, liquid metal flows back into the bore. Thus, it is self-resetting. Basic design principles, materials used, and test results are presented.

INTRODUCTION

Figure 1 depicts the equivalent circuit of a dc system during switch opening. For the equivalent circuit,

$$V = L\frac{di}{dt} + Ri + V_{arc} \quad (1)$$

Denoting the driving voltage, which causes the current in the circuit to change, a Δe:

$$\Delta e = L\frac{di}{dt} = (V - Ri) - V_{arc} \quad (2)$$

If Δe is negative, i.e., $V_{arc} > (V - Ri)$, the current is driven toward extinction; if Δe is positive, i.e., $V_{arc} < (V - Ri)$, the current will increase until a $\Delta e = 0$ point is reached and arc equilibrium exists. For arc equilibrium, circuit interruption does not occur. These conditions are depicted in figure 2, where the arc characteristic and the load line corresponding to V and R are presented.

The interception of the load line with the abscissa is determined by the value of V/R. Increasing R (decreasing fault current) results in a larger value of Δe and quicker extinction. During arcing, the source is supplying energy which must be absorbed by the contactor. Thus, the quicker the interruption, the less the added energy. The work of interruption approaches the minimum value possible, prolonging the useful life of the interrupter and decreasing fault damage.

One means of increasing Δe is to place a resistor in parallel with the switch. Then

$$i = i_a + i_r \,, \tag{3}$$

where i_a is arc current and i_r is current through the shunt resistor, R_{ac}.

The characteristic of the shunted arc can be incorporated into a graphical diagram solution, as shown in figure 2 by addition of i_a and i_r to obtain total current. This is shown in figure 3.

The lower the value of R_{ac} (the more the skew on the arc characteristic), the higher the value of Δe, and the easier it is to commutate the current into R_{ac}. However, the lower the value of R_{ac}, the greater the value of i_r, the current in the paralleled resistor. It is then necessary to complete the circuit interruption of a series circuit with resistance, $R + R_{ac}$. Higher values of R_{ac} lose the advantages of easy commutation of the current into R_{ac} but make final circuit interruption easier. Fixed value shunting resistance switching entails a compromise or tradeoff of the above factors.

From the above it appears that, to interrupt the dc arc, it is advantageous to have a time-dependent, nonlinear shunt resistor that has low resistance for easy commutation at $t = 0$ and high resistance for easy total interruption. Such a variable resistor was developed under Bureau of Mines-sponsored research by the University of Pittsburgh. It uses a change of state device with small diameter filaments, or bores, filled with a high conductivity liquid metal. This device changes resistance by several orders of magnitude (when subjected to high current densities) by vaporization of the metal in the filaments; it is designated the CLD.

It would be desirable to have the CLD "in line," similar to a conventional fuse application, but heat transfer studies have shown this to be not feasible because of the steady state temperature rise of the device. Thus the system incorporates paralleled contacts with the CLD "off line", as shown in figure 4.

The operation of the system is as follows: M is opened, transferring current into the CLD. The CLD, in the unvaporized state, has a very low resistance. The bore design is selected to cause vaporization of the metal in the vapor chamber in a short time. When the metal vaporizes, the resistance of the CLD changes (increases by an extreme amount, nearly two orders of magnitude). This results in a very sharply decreasing circuit load line, reducing the fault current and permitting A to be opened while carrying a fraction of the previous current.

The liquid metal in the CLD is under 1 atm of pressure, which will force liquid metal back into the bore after the current is interrupted. Thus, the device is self-resetting.

CLD CURRENT-TIME RELATIONSHIPS

Current limiting action in the bores results from vaporization of the metallic current carrying filament(s) of the CLD vapor chamber. Prior to commutation of the fault current into the CLD, taken as time zero, steady state thermal equilibrium exists in the filament. Time, t, to vaporize the liquid metal is determined by equating the energy input from the joule loss within the filament due to current and filament resistance to the energy necessary to elevate filament temperature to the boiling point of the material. Heat conducted through the electrical insulating material (the vapor chamber containing the bores) is neglected, since the time frame involved is in the millisecond range.

The incremental energy-unit time required to reach vaporization temperature, assuming constant average physical properties, is approximated by

$$\gamma v c \frac{d\theta}{dt} = \gamma \pi r^2 l c \frac{d\theta}{dt} \qquad (4)$$

and the Joule heat liberated by current flow through parallel filaments is

$$\left(\frac{i(t)}{q}\right)^2 R = \left(\frac{i(t)}{q}\right)^2 \frac{\rho l}{\pi r^2} \text{ watts,} \qquad (5)$$

- v — volume of the metal in the bore, cm^3,
- t — time, secs,
- θ — temperature, °C,
- c — specific heat, g-cal/g-°C,
- γ — density of the metal in the bore, g/cm^3,
- r — bore radius, cm,
- i(t) — total current flow into the device, amps,
- q — number of parallel bores in the device,
- R — resistance of each bore, ohms,
- l — length of each bore, cm,
- and ρ — resistivity of metal in the bore, ohm-cm.

From the energy balance, equating equations (4) and (5),

$$\int_0^t i(t)^2 dt = \frac{\pi^2 q^2 r^4}{0.239} \frac{\gamma c}{\rho} \Delta\theta = K q^2 r^4 . \qquad (6)$$

Mercury and NaK (78%K, 22%Na) were evaluated for use in the CLD. Values of K, calculated for 1 atmosphere gage of pressure and for a temperature rise from 50°C ambient metal temperature to the vaporization temperature, follow:

For Hg $K = 43.65 \times 10^6$,
For NaK $K = 66.1 \times 10^6$.

A model of the steady state cylindrical arc for liquid metals was developed, and the relationship between the voltage gradient (volts/cm) across the arc, the bore radius, and the average conductivity of the arc was obtained. The data present average conductivity, σ, of the arc as a function of the product of voltage gradient, E, and bore radius, r. A curve depicting the $E \cdot r$ vs σ relationship for Hg and NaK at 1 atm gage pressure is presented in figure 5. This curve is a locus of arc temperature. As the arc persists, temperature rises, and the operating point, based on length, voltage, and radius, moves from low temperature (the left hand side) to a stable arc point and temperature on the right hand side of the parabolic curve, based on the value of $E \cdot r$. A stable arc dictates a value of $E \cdot r$ greater than 2.0. However, values of $E \cdot r$ greater than 12 result in conductivity that is not sufficiently current limiting to be practical. Thus, a CLD design parameter should be such that $2 < E \cdot r < 12$.

The $E \cdot r$ value, on the right hand portion of the curve, gives the average conductivity of the vaporized arc, to be used for calculating current to be interrupted after the CLD changes state, or "operates."

When the current limiting action begins, the interior of the bore is subjected to an arc across the vaporized metal in the bore. The arc power per unit of bore wall area is indicative of the energy being absorbed, and the ultimate life of the bore wall is determined by the intensity the energy absorption. The more intense the power per unit area, the greater the rate of erosion and bore enlargement.

The power per unit wall area is

$$\frac{P}{A} = \frac{E^2 r \sigma}{2} \ \frac{\text{watts}}{\text{cm}^2} . \quad (7)$$

The power per unit wall area is controlled by the selection of l and r and should be a minimum consistent with the other system requirements.

MECHANICAL DESIGN CONSIDERATIONS

The CLD basically consists of two pressurized liquid metal reservoirs insulated from each other except via one or more relatively small diameter bores filled with liquid metal. The materials used must be compatible with the liquid metal chosen. The CLD design described in this paper (figure 6) used Hg as the liquid metal. The "vapor chamber" through which the bore(s) were drilled was constructed of Corning Macor,[1] a machinable glass ceramic. This material has low porosity, high dielectric strength, and high thermal conductivity, and withstands the extreme thermal shock situations where the Hg goes from room temperature to arc temperature in milliseconds.

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[1]Use of manufacturer and trade names is for identification only and does not imply endorsement by the Bureau of Mines.

The Macor is sealed inside a Delrin insulating housing. Delrin, an acetal homopolymer, has excellent mechanical, electrical, and thermal properties. It is threaded at each end to screw into retainers of 316 stainless steel. These retainers are capped by silicone rubber diaphragms, which pressurize the mercury to 1 atm gage pressure and provide for the expansion of the mercury when the CLD operates, i.e., the mercury in the bore vaporizes.

After assembly, the unit is filled and pressurized by pulling a vacuum in the diaphragm housing caps while the Hg is loaded through filler holes. After the holes are plugged, the retainer caps are opened to the atmosphere and the Hg is then under a pressure of 1 atm.

PRESSURE-VOLUME RELATIONSHIPS

It is necessary for the diaphragm to expand to accommodate the volume of vaporized mercury after the CLD operates.

The mercury is pressurized to only 1 atm gage in the cold or unvaporized state. Pressure increases after vaporization when the mercury volume increases, stretching the diaphragm, which in turn increases the pressure of the mercury.

Based on the length and radius of the bores, the volume and mass of the Hg to be vaporized can be calculated. The vapor pressure and the density of saturated Hg vapor vary with temperature. For given temperatures, the relationship between pressure and density can be determined and the data plotted as shown in figure 7, which is for a CLD with a single 0.113-cm-radius, 6-cm-length bore.

If the diaphragm is treated as a thin circular flat plate, uniformly loaded at p atm and with edges fixed, maximum stress is at the center and is given by

$$\text{stress} = 3876\ p(m+1)\left(\frac{r}{t}\right)^2\ \text{Kg/m}^2\ , \qquad (8)$$

where r = radius of diaphragm,
t = thickness,
and m = Poisson's ratio.

The tensile strength of the rubber diaphragm used was 7.734×10^5 Kg/m^2. For a given ratio of r/t, dividing equation (8) into the maximum tensile strength of the rubber yields the maximum pressure permissible, p, in atmospheres. The next step is to determine if the volume of vaporized mercury is less than the volume expansion provided for by the diaphragms. Using the pressure obtained above, the vapor volume is determined from figure 7 (plotted for a specific bore design).

The material specifications for the diaphragm material indicate a permissible linear elongation of 550%, or 5.5 per unit. The unstretched area of the diaphragm is then calculated. The maximum surface area, S, of the hemisphere segment formed by pressure is found by multiplying the unstretched area by 5.5. The relationship between surface area, S, the height of the segment, h, and the radius of the base, r, is

$$S = \pi(h^2 + r^2). \tag{9}$$

Solving for h and substituting in the equation for the volume of a hemispherical segment

$$V = \frac{1}{6} \pi h(3r^2 + h^2) \tag{10}$$

yields one half of the total volume available to accommodate the vaporized mercury (two diaphragms). The total volume available must be greater than the volume determined from figure 7. The design variables, for a specific diaphragm material, are the radius and thickness of the diaphragm.

STEADY STATE TEMPERATURE RISE

In the switching configuration, figure 4, it can be noted that there will be a steady state, continuous current flowing in the CLD. The magnitude is determined by the relative resistance of the main and auxiliary contactor paths. Addition of external resistance in series with the CLD will hold the current magnitude to a level that will yield an acceptable steady state (preswitching) temperature rise. The Delrin housing has a maximum continuous service temperature of 84°C. A heat transfer analysis was conducted on the CLD designed for the test program and it was determined that a steady state current of 80 A was permissible.

EXAMPLE DESIGNS

The system configuration of figure 4 yields the current-time relationships shown in figure 8 while switching and interruption are taking place. Electrical designs for three typical systems, shown in Table 1, were made. Table 2 presents the design parameters. Figure 9 shows the time to fault current reduction as a function of the available fault current, and figure 10 shows the calculated reduction in current interrupted with the CLD, for a unit designed for System 1.

TABLE 1. - System characteristics

System No.	Nominal voltage, V	Trip setting, A	Maximum fault current, A
1.........	300	1,000	10,000
2.........	300	4,000	30,000
3.........	600	2,500	14,000

System 2 presents a problem because the heavy fault current level requires more bores than practical in one housing. Consequently, it appears that the most practical solution is to use three paralleled units, each with five bores. The result seems quite satisfactory in that only 47 V of arc voltage is required for commutation of the fault current, and the current to be interrupted is reduced from 30,000 A down to 5,754 A. This reduction should materially decrease wear and tear on the contactor.

The design for the 600-V system (No. 3) does have a rather high arc voltage, but in view of the current level, it should commutate satisfactorily.

VOLTAGE SURGE PROTECTION AND CONTROL

When the CLD changes state, its resistance changes by approximately two orders of magnitude in a millisecond time frame. It induces a relatively high voltage to maintain constant flux linkages in the circuit inductance unless surge protection is provided.

The surge voltage control package used consisted of placing metallic oxide varistors (MOV) in parallel with each phase of the transformer secondary winding and a dry-type electrolytic capacitor across the dc terminals of the rectifier output.

The capacitors are sized by equating the energy stored in the transformer leakage reactance to the energy that can be absorbed in charged capacitors by elevating their voltage. Values of C required for limiting the surge overvoltage for 500-and 1,000-kva size rectifiers, with leakage reactance of 0.08 per unit, are presented in figure 11.

TEST RESULTS

Six different prototype configurations were tested; only the Macor vapor chamber unit demonstrated a satisfactory service life. The units were designed for the 300 V, 300 kW surface rectifier power supply at the Pittsburgh Research Center, Bureau of Mines, Bruceton, PA.

A GE IC3801 AY 125 G4 contactor and a Siemans-Allis Type 700 contactor were connected as shown in figure 12. The Siemans-Allis contactor is closed to impose a system fault through the closed GE contactor. Note that the GE contactor was modified in that the CLD and any desired auxiliary circuitry resistance were connected in series with the arcing contact of the contactor. Thus, no separate auxiliary contactor, per se, was utilized.

Since the purpose of the tests was to determine the ability of the CLD to withstand the trauma of the fault limiting operation, tests were conducted as rapidly as possible. Time between successive tests averaged between 5 and 10 minutes during the working days and the condition of the CLD was monitored after each test by Kelvin Bridge resistance measurements.

TABLE 2. - Typical CLD designs

Bore data			Temperature rise		Vaporization		Arc power	Arc volts
Radius cm	Length cm	# in parallel	Hg °C	Interface °C	t_4-t_3 msec	Current A	P_{arc}/area of wall W/cm^2	V
System 1, 300 V, I_{trip} = 1,000 A, $I_{fault\ max}$ = 10,000 A								
0.159	6	4	15	12	3.33	2,676	45,712	19
.179	6.3	4	15	12	6	3,240	50,696	16
.198	6	3	13	10	5	3,566	74,250	16
System 2, 300 V, I_{trip} = 4,000 A, $I_{fault\ max}$ = 30,000 A (Use 3 of the following units in parallel)								
0.139	4	5	25	15	3.6	5,797	125,000	47
System 3, 600 V, I_{trip} = 2,500 A, $I_{fault\ max}$ = 14,000 A								
0.179	12	4	25	35	2.92	3,912	59,293	69

The CLD successfully withstood 141 operations (estimated 6 months service in a mine) before failing. It failed in the electrically open mode; the failure was not traumatic. The unit can be monitored for failure with a relatively simple control circuit and an audio alarm, or a contactor-circuit breaker lock-out.

A typical test waveform is shown in figure 13.

CONCLUSION

Through an evolutionary materials research and design configuration process, a CLD configuration that is easily and inexpensively fabricated has been developed and tested for life expectancy in excess of 140 operations, equivalent to 6 months or more of typical mine system duty. The CLD is included in a switching system. Such incorporation will reduce the fault current-time relationship and the magnitude of the current that must be interrupted, for a given fault situation. Thus economy and safety are enhanced.

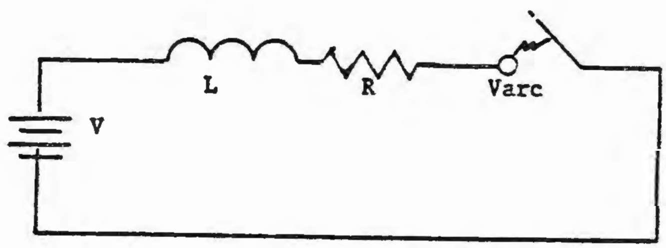

FIGURE 1. - Equivalent circuit of DC system

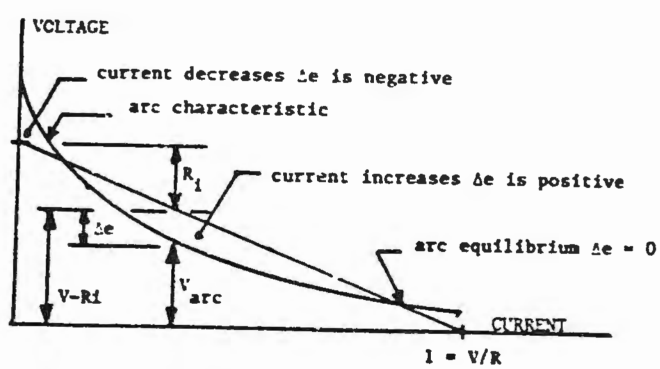

FIGURE 2. - Arc and load line voltage of the circuit

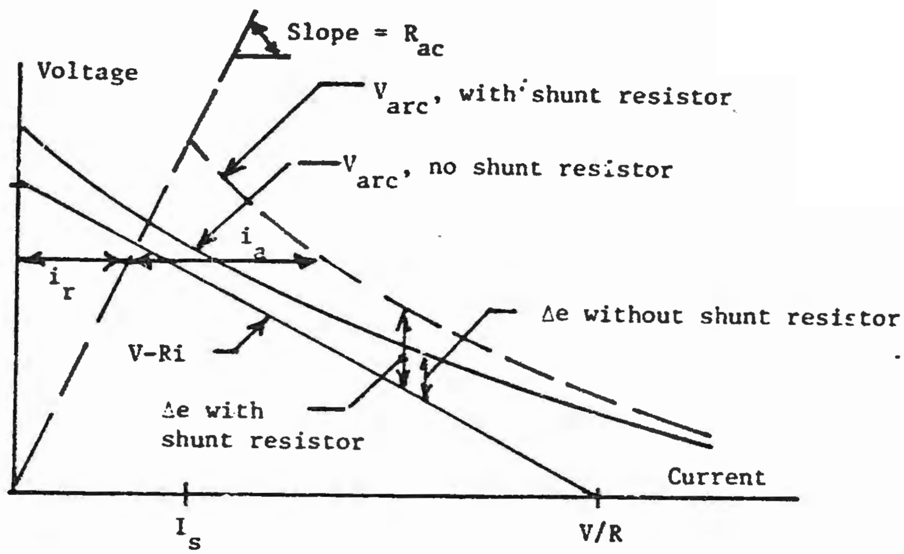

FIGURE 3. - Effect of paralleled resistor on dc switching

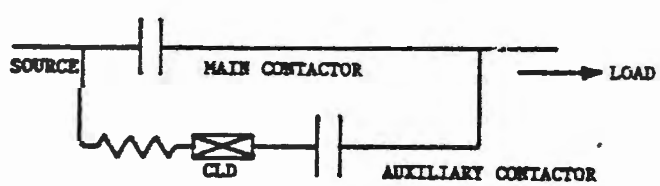

FIGURE 4. - Switching system configuration

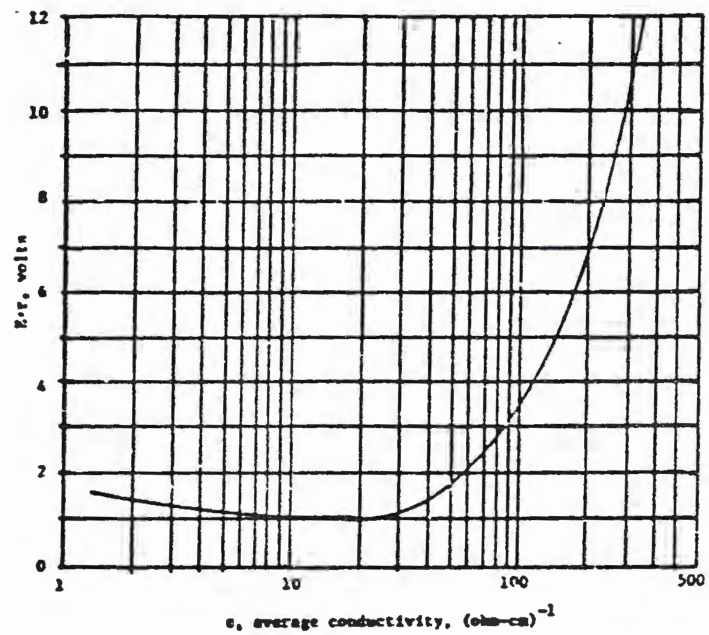

FIGURE 5. - E·r vs average conductivity

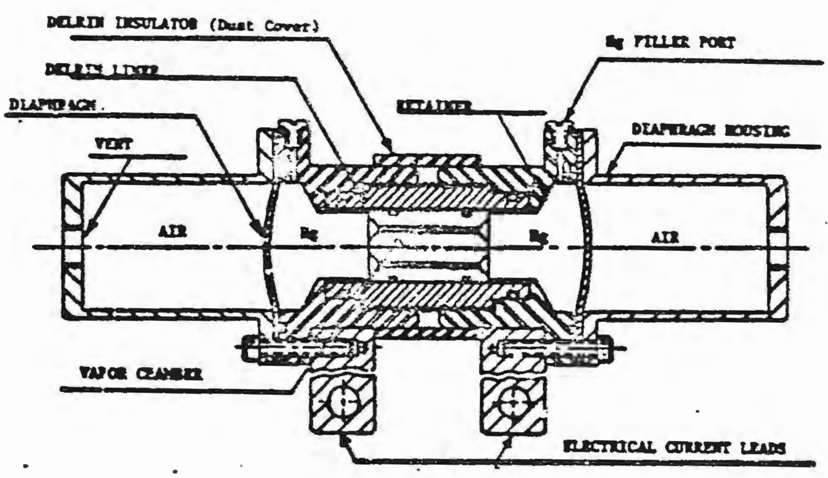

FIGURE 6. - Final CLD design

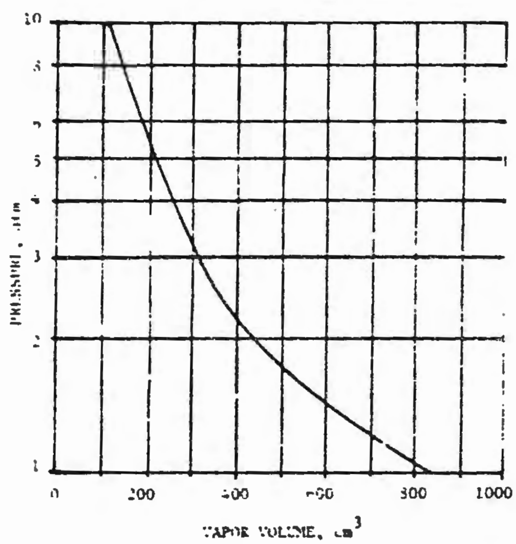

FIGURE 7. - Pressure-volume relationship

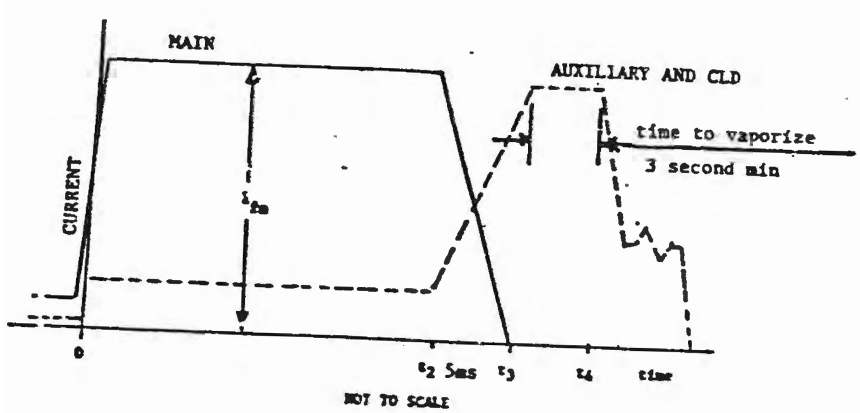

FIGURE 8. - Current-time relationship

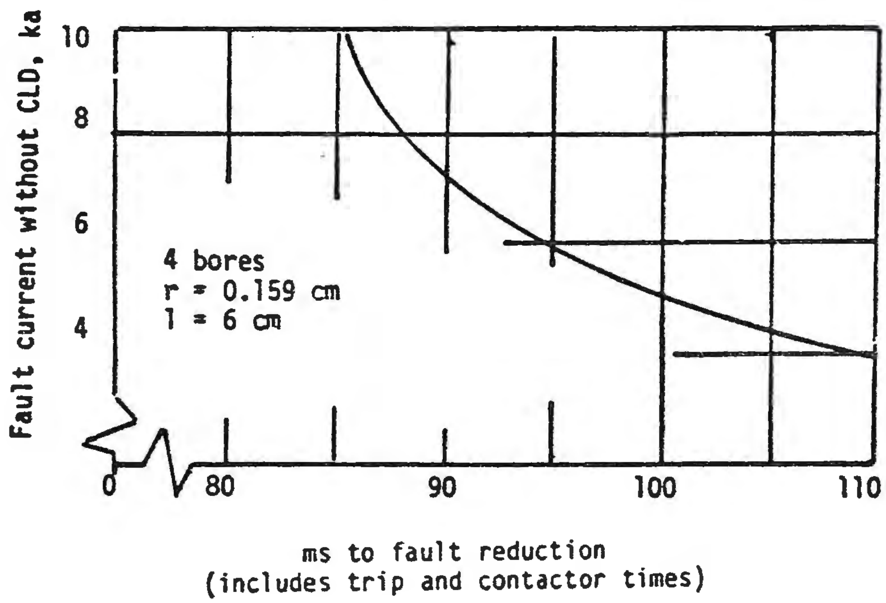

FIGURE 9. - I_{fault} vs time to vaporize

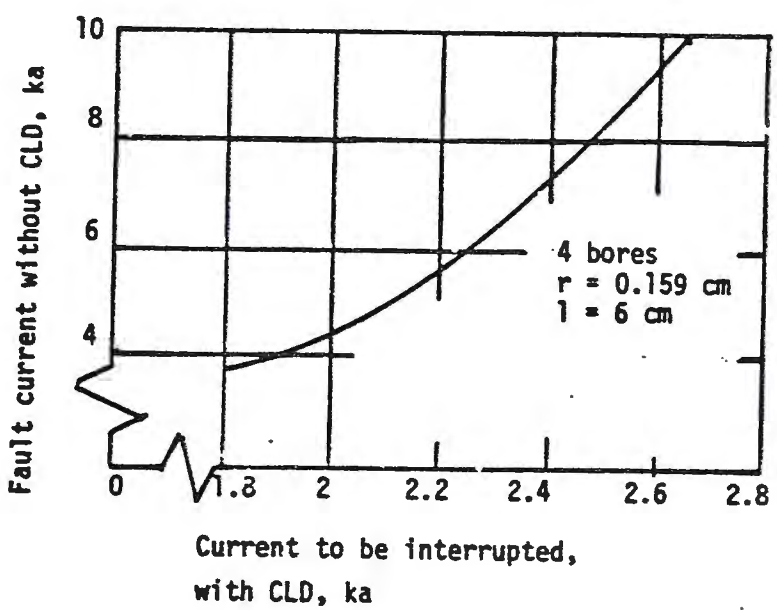

FIGURE 10. - Reduction in fault current with CLD

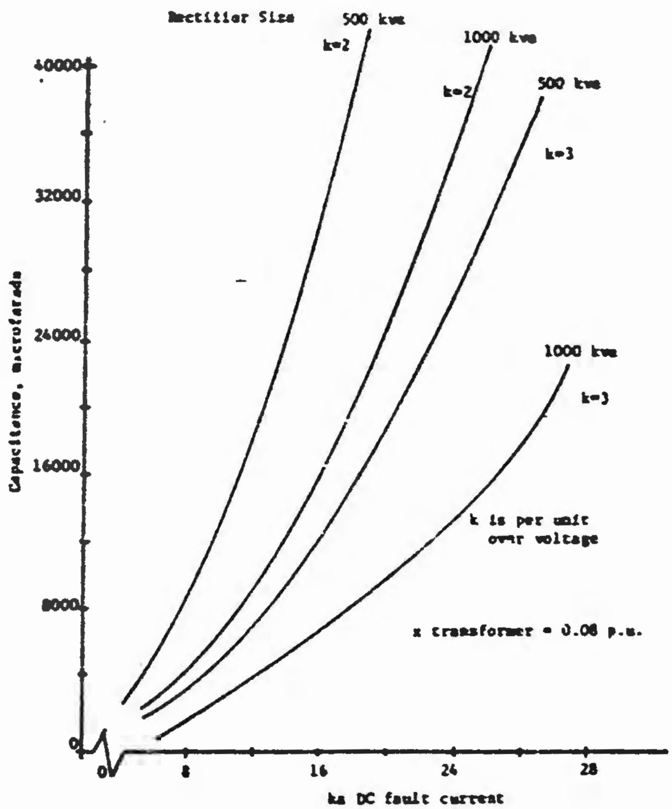

FIGURE 11. - Calculated capacitance values

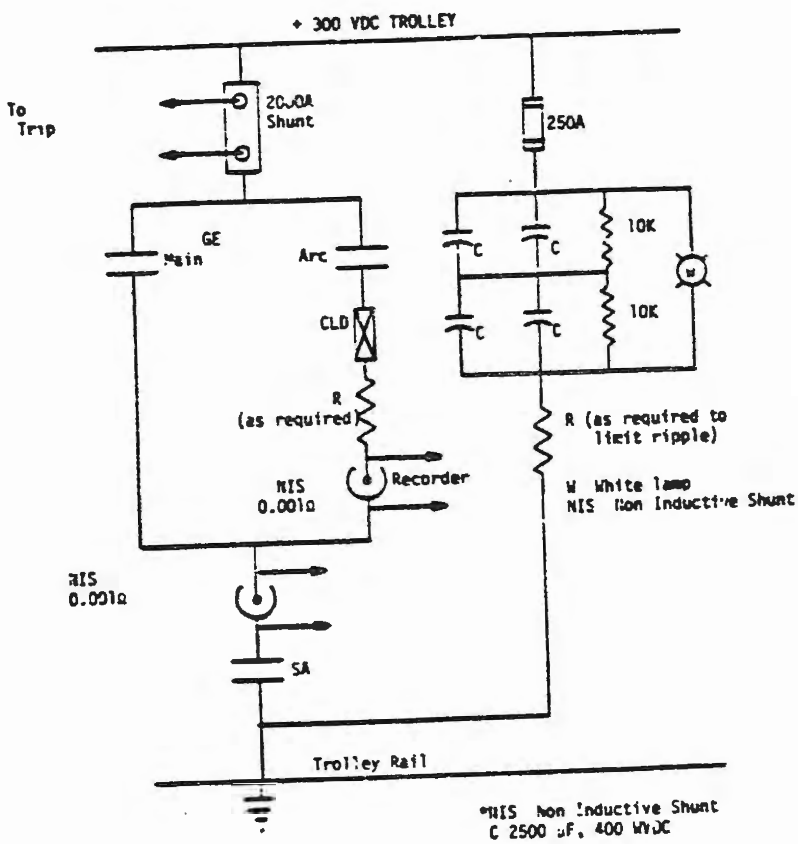

FIGURE 12. - Test power circuit

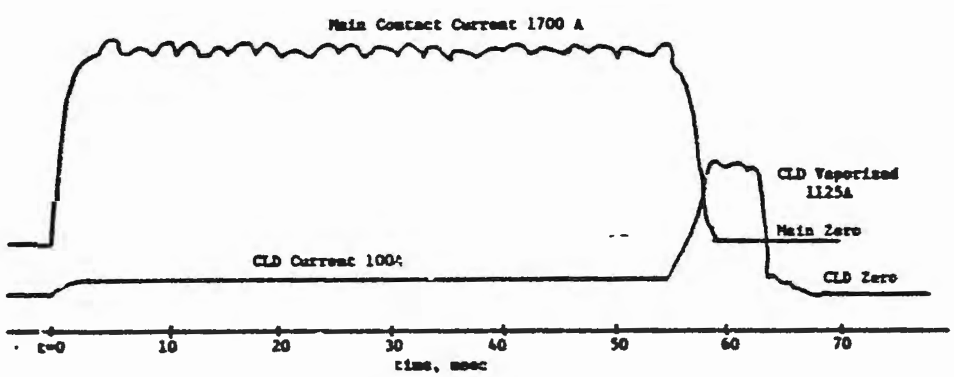

FIGURE 13. - Typical test waveform

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