SELF-REHEALING PERFORMANCE OF THE P.P.F. FOR A CONTROL CENTER

* Y. Wada, S. Hamano, T. Mori and T. Miyamoto
** T. Inoue, I. Ishii and T. Shirasawa

Mitsubishi Electric Corporation

INTRODUCTION Permanent Power Fuse, which is called by the abbreviated name PPF is an entirely new reusable fuse utilizing metallic sodium as a current limiting material. It is developed by Mitsubishi Electric Corp. of Japan. Since 1969, various PPF used devices have been applied to the actual field. Self-rehealing property of the PPF, which is not possessed by a conventional current limiting fuse suggests us the applicability of the PPF in place of a current limiting reactor in a control center. In this application, the PPF employed in a main circuit which feeds 20 to 30 branch circuits provides both selective and cascade fault protection to all of those branches by utilizing a breaker with short time delayed trapping in the main circuit.

When we use the PPF in the application, the PPF has to have the following properties.

(1) Current limiting performance for high prospective short circuit current is better than that of a current limiting reactor.

(2) The fuse has to maintain its current limiting function for about 3 cycles, which is requested for the time delayed back up in the main circuit. The PPF also should have reasonable life of fault protection during its life in actual fields up to 30 years.

(3) The fuse has to have a quick rehealing characteristics so as to recover the load current of the sound branches immediately after the disconnection of the short circuited branch.

(1) & (2) have already been treated in our previous papers.(1)(2)(3) The purpose of this paper is to make clear the definition of rehealing functions revealing their processes in the PPF experimentally and to give brief discussions on the mechanism of the rehealing. Our study which has given a design basis of the PPF shows that cooling of a sodium element by heat conduction to a heat sink of BeO ceramics is a predominant power of rehealing.

THE OUTLINE OF THE PPF USED CONTROL CENTER Fig-1 is a skeleton circuit of a control center utilizing the PPF in the main circuit. A cascade connection of a moulded case main circuit breaker NF and the PPF provides the current limitation to every fault in each feeder circuit so as to elevate rupturing capacity of all the feeder breakers up to 200 kA. at 460 V. NF1 to NF_n are branch breakers and MS1 to MS_n are magnetic contactors of the branch. After a fault A at one of the branch circuits is removed by a feeder breaker NF1, the PPF continuously feed the normal load current to other sound branches recovering immediately its current carrying functions.

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* Messrs. Y. Wada, S. Hamano, T. Mori and T. Miyamoto are with Arcs and Plasma Research. Central Research Laboratory, Mitsubishi Electric Corporation.

** Messrs. T. Inoue, I. Ishii and T. Shirasawa are with Ceramics molding Research, Manufacturing Development Laboratory, Mitsubishi Electric Corporation, Hyogo, JAPAN.

Besides those requirements (1) to (3) given above, the continuous current carrying capacity of the PPF must be designed to be higher than the sum of the all branch breakers, while the peak let-through current should be lower than the allowable let-through current of the smallest branch breakers. Fig-2 is an example of the PPF used control center with fin-cooled PPFs rated 800 A. which feeds 30 branches.

PRINCIPLE OF OPERATION OF THE PPF Fig-3 is a cross sectional drawing of the PPF modified for the experiments of rehealing characteristics. In Fig-3, TI and TII represent terminals. The continuous current flows from the terminal TI to TII through the sodium element inside of the ceramic tube (made of beryllium oxcide) which is reinforced with an outer metallic cylinder through another special ceramics. The sodium element which shows low resistance for a continuous current evaporates immediately on the flowing of a fault current establishing a high temperature and pressure plasma with high resistivity. With abrupt change of the resistance of the sodium element, the fault current is effectively limited. The piston in Fig-3 controls the expansion of the sodium reducing the pressure rise and also it provides the self-rehealing force to the expanded sodium by the high pressure gas behind the piston. The sodium element is constricted at one end (of the terminal-I-side) so as to effectively reduce the peak let-through current and to fix the start point of the evaporation at the constricted portion. The current constriction with diameter of d_1 and length of ℓ_1 is connected in tandem with the rest of the element with diameter of d_2 and length of ℓ_2. The structure and dimensions of the PPF in Fig-3 are quite the same as those applied in actual fields in control centers, except a probe electrode and a lead extended out of the PPF. Experimental model PPFs were specially prepared by inserting the probe at the boundary between the current constriction and the rest of the element. The probe electrode is intended to catch variations of floating potential at the probe.

Difference of the specific and local properties of plasma between the constricted section and the rest of the element was suggested in our previous paper (3). Since this difference is expected to affect the rehealing properties in the PPFs, the probing at the boundary is essentially necessary to understand the rehealing process, provided that the probe picks up the potential at the boundary exactly.

The probe electrode is disc shaped with inner diameter of 8 m/m and 5 m/m thick. Sodium element of the model PPF tested has dimensions of $d_1 = 3.5$, $\ell_1 = 7$, $d_2 = 6$ and $\ell_2 = 30$ m/m.

As shown in Fig-1, a resistor R_p is connected in parallel with the PPF for the lowering of voltage surges which appear due to the abrupt change of the resistance of the PPF at the evaporation of the sodium. As the PPF is essentially not a switching element but a non-linear resistor, the addition of R_p does not lower the current limiting function of the PPF provided that R_p does not seriously affect the current limiting performance. The R_p is also useful to reduce the mechanical stresses impressed on the PPF during the operation by dissipating the electrical energy stored in the inductance of the circuit. The last but not least, another important function of R_p is to feed necessary power to the feeder branches within its heat capacity whenever the power supplying is effective to attain the maximum service continuity against the branch feeders. Especially, when resistance of the PPF is higher than R_p, R_p shares the function of the power supply. It is needless to say that R_p does not have continuous current carrying function since the resistance of the PPF is always extremely lower than R_p for the continuous current.

THE SELF-REHEALING FUNCTION In the PPF used control center, the maximum service continuity should be provided to sound branches after the removal of a short circuited branch. Continuity of the supply of load current must be sustained to the sound branches without break. The parallel connection of the sodium element and R_p should provide the load current. To supply the load current under low ohmic drop across the sodium element shunted by R_p, resistance of the sodium element should become low enough as soon as possible after the current limiting operation. The load current means both the rated continuous current and over load current.

Generally, the over load current flows through the main circuit transiently when various types of perturbations occur on the bus line (V_B in Fig-1) voltage. Among these perturbations, instantaneous break due to high speed reclosing on h.v. primary line, and drop of line voltage caused by the fault at one of branches are included. The latter perturbation is caused by the fault at one of branches. In clearing the fault, the sodium element should evaporate and limit the fault current. In this case, over current always flows through the hot sodium element just after its current limiting operation.

Since the magnitude of the over current becomes considerable value when many motors are driven in feeder branches, it has been quantitatively estimated by means of a digital simulation program SCAP-M developed by Mitsubishi Electric Corp. assuming various types of perturbations with various durations. The calculated results shows that the maximum over current is about 1800 A. peak for a motor of 460 V. 90 kW. and it decays within 200 ms. finally to a rated continuous load current of 160 A. Such a transient rush over load current integrated over every motor in sound branches should be fed through the hot sodium element. The sodium element should recover its initial resistance for the continuous supply of the rated total load current.

It is thus requested for the element in the PPF for a control center to recover its initial resistance supplying the over load current through the element of itself during it is still hot.

Hereafter, the rehealing characteristics of the sodium element from high temperature current limiting plasma to transcritical liquid of sodium are investigated experimentally chosing the magnitude of the over load current as a parameter.

TEST CIRCUIT Fig-4 is the test circuit. In Fig-4, NFB which simulates the short circuited branch breaker and the resistor RL which simulates the over load current of other sound branches are connected in parallel each other.

At first, S and NFB are closed. The closing switch S initiates the fault through the PPF and NFB. The prospective short circuit current was adjusted to 60 kA asym. peak for all test cases.

After the arcing time of one half cycle, NFB removes the fault disconnecting the circuit of itself. Immediately after that, the current is continuously transferred to the resistor RL. Each of I_N, I_{NFB} and I_R is current through the sodium element, NFB and the resistor respectively. I_{NFB} limited by the PPF was 30 kA. crest. I_R from 140 A to 6000 A rms was tested. Variations of the potential of the probe electrode were measured with V_1 and V_2 by grounding one end of the sodium element at E.

EXPERIMENTAL RESULTS AND DISCUSSION Fig-5 and 6 are typical oscillograms which contain transients of V_T, V_2, I_R, I_N, I_T, I_{NFB} from the beginning of the fault untill the sodium element finally recovers current carrying capability of I_R after the clearing of the fault. I_R in Fig-5 and 6 is 140 A. and 3520 A. respectively. In these figures, v_T and v_2 are magnified signals of V_T and V_2.

Typical current wave forms are schematically shown in Fig-7. Fig-7 corresponds to the oscillogram of Fig-6 at I_R = 3520 A. In Fig-7, I_{NF} is limited effectively untill I_{NF} is interrupted finally at point X. I_N does not instantly recover I_R at X but at point Y. While, I_T in Fig-7 demonstrates that the over load current I_R starts to flow continuously at Z just after the finish of current limitation for the first major loop of the fault current. I_R is supplied through R_p as is illustrated clearly by the wave form of I_{Rp}. The continuity of the supplying of the over load current beyond X until Y is attained through R_p. Beyond the point Y, I_N fully recovers I_R and I_{Rp} disappears. In other wors, I_N is quite the same with I_R beyond the point Y. The resistivity of the sodium element is considered to be low enough to let-through I_R at the point Y. It should be noted that I_N recovers I_R instantly at the point X when I_R is smaller than 1200 A.r.m.s.

Fig-8 and 9 represent variations of the resistivity of the sodium element against time. X and Y correspond to each notation in Fig-7. The resistivity is expressed by a ratio P/P_o, where P_o means a resistivity of the solid sodium at 0 °C. (4.5 μΩ•cm). Point A in Figures of 8 and 9 corresponds to the point of the abrupt decrease of I_N just after the peak let-through current. Point B corresponds to the first current zero of I_N for Fig-8 and to the second current zero of I_N for Fig-9. $P\ell_1$ and $P\ell_2$ represents the variation of P/P_o at the current constriction and at the rest of the element respectively.

From Figures 8 and 9, the followings are deduced.

(1) Self-rehealing of the sodium element is performed in 2 steps with double time constant. The first and fast time constant is observed at point B untill the sodium reheals to transcritical liquid through a phase transition. This first time constant is the order within 1 ms. The second time constant of the order of 50 ms. is observed beyond the point B, where the element reheals under liquid phase.

(2) In the first step rehealing, the resistivity changes widely from high temperature plasma with P/P_o of the order of 10^3 to the transcritical liquid with that of 35.

(3) When I_R is small, sodium element reheals to transcritical liquid at t = X. When I_R is larger than 1200 A. the element reheals to the same state at t = Y. Since I_R is supplied continuously through R_p during X < t < Y, service continuity is satisfactorily sustained still in this case.

(4) Beyond the point B, after the sodium element recovers to transcritical liquid state, both $P\ell_1$ and $P\ell_2$ decrease steady even when I_R flow through the element and $P\ell_1$ is slightly higher than $P\ell_2$.

The self-rehealing capability of the sodium element were revealed to be satisfactory within the range of I_R tested.

Fig-10 represents variations of $P\ell_1/P_o$ with I_R, setting point B in Figures of 8 and 9 at t = 0. For all cases, the fast decrease of $P\ell_1/P_o$ at t = 0 laps in a line. The first time constant is within 1 ms. for all cases even when I_R up to 6000 A.r.m.s. flows through the sodium element.

A characteristic of P/P_o vs. temperature is attached to Fig-10. Continuous increase of P/P_o is expected up to the temperature of a transcritical point of the sodium(4)(5) pressurized with the high pressure gas behind the piston. The value of the gas pressure is denoted on the curve at each corresponding transcritical temperature. Beyond the transcritical temperature, definition of phase, gas or liquid, becomes to be impossible. Since sodium in the PPF is pressurized at 100 atm. by the high pressure gas behind the piston, the transcritical conditions are T_C = 1700 °C and P/P_O = 35.

Digital simulation was made on the process of the decrease of P/P_O below P/P_O = 35 in a liquid phase. Radial heat conduction from the sodium element coaxially confined in a BeO ceramic tube to the wall of the ceramics was treated on a digital computer simplifying the problem by utilizing cylindrical symmetry of the PPF. The initial conditions for the sodium element were chosen at P/P_O = 35 and transcritical temperature T_C = 1700 °C with enthalpy at T_C.

The calculated results are given in Fig-10 by C_1 and C_2. Each of C_1 and C_2 corresponds to experimentally obtained curve of 1 and 2 respectively. The calculations were made for the initial decrease of the resistivity just after the transcritical point. Considerable fast decrease of $P\ell_1/P_o$ in a liquid phase is explained from the calculation. These agreements suggest that cooling of the sodium element by heat conduction to a heat sink of BeO is a predominant power of rehealing.

According to a survey on the number of branches of motor circuit, capacity of motors in the branch circuits of actual control centers in the fields and to the results of the analysis made by the digital simulation method on the magnitude of the over current, it has been concluded that the PPF is satisfactorily applicable to the main circuit of a control center rated 800 A.r.m.s., if the PPF has a capability of rehealing, supplying a over current of 400 A.r.m.s. for a duration of 30 ms.

Steady rehealing capability of the PPF is demonstrated in Fig-10 up to 5340 A. r.m.s. Although data are not shown in Fig-10, successful rehealing were confirmed under I_R up to 6000 A. and its duration of 200 ms.

Magnitudes of I_R tested are plotted with their durations on the cold start over current vs. time characteristic of the PPF as shown in Fig-11. It should be noted that the cold start over current vs. time characteristic is very close to the plots, especially to I_R of 6000 A.r.m.s. for a duration of 200 ms.

The current limiting operation enabled by the super critical plasma of the sodium does not have an influence on the over current carrying capability of the sodium element.

In other words, the over current carrying capability of the PPF is given always by its over current vs. time characteristic for a cold start even immediately after a current limiting operation.

The self-rehealing properties of the PPF thus revealed in this paper have given a coordination design basis of the PPF for control centers which provide both selective and cascade fault protection up to 200 kA keeping the maximum service continuity against sound branches.

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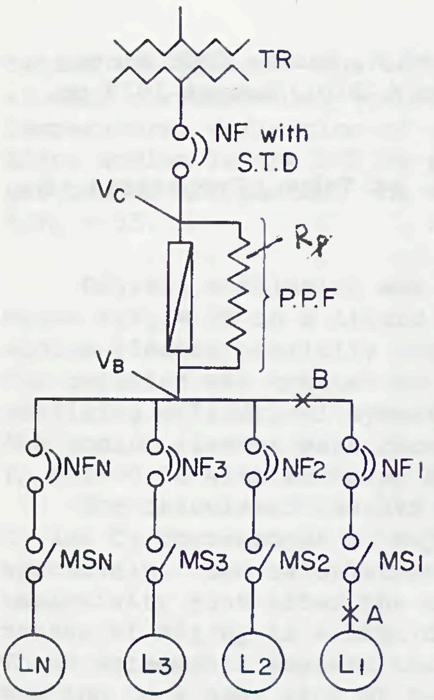

Fig-2. Outside view of the PPFused control center

Fig-1. Skeleton circuit diagram of a control center utilizing the P.P.F

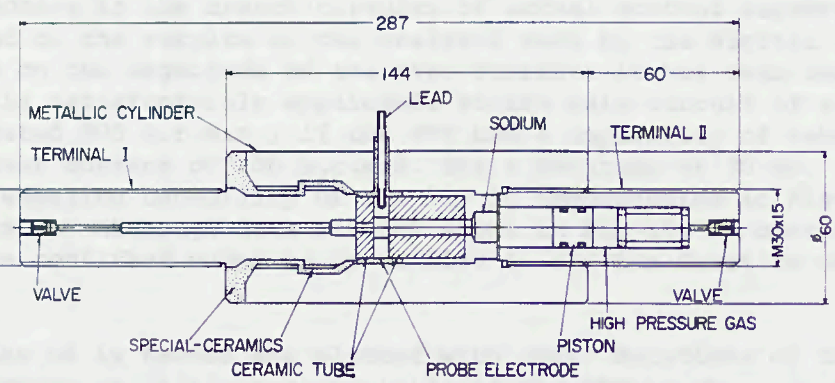

Fig-3. Cross sectional drawing of the P.P.F with a probe electrode

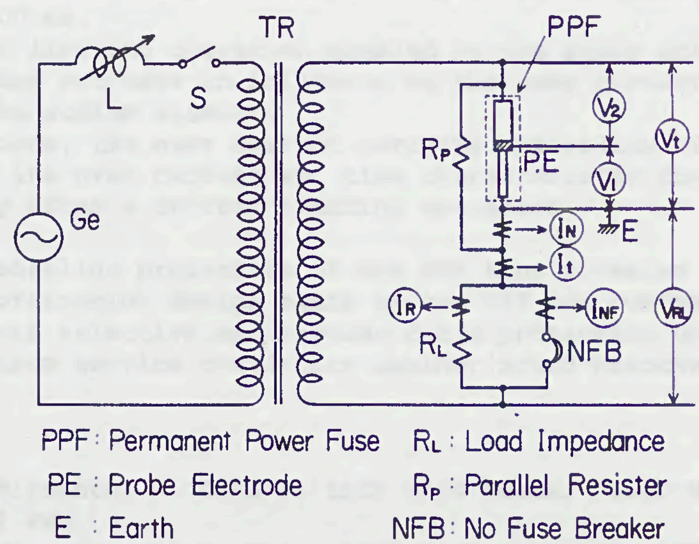

Fig-4. Equivalent test circuit for the rehealing characteristic of the P.P.F

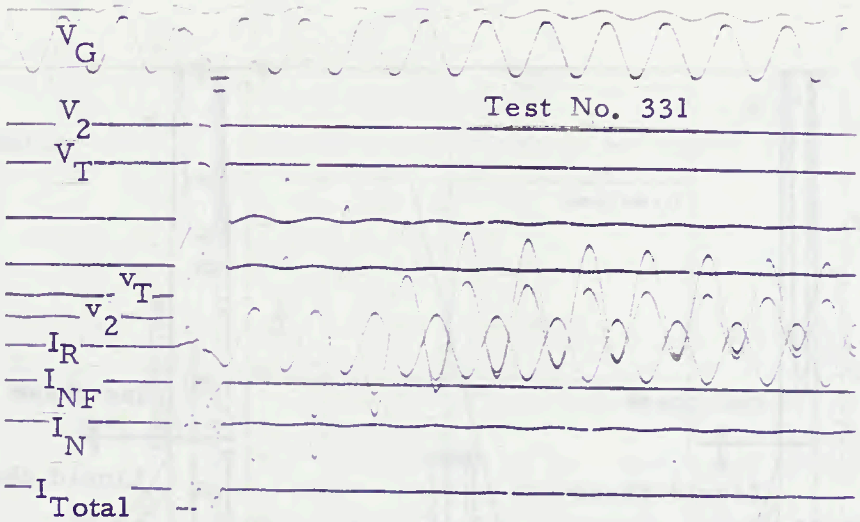

Fig-5. Typical oscillogram of a equivalent test at I_R =]40A_{rms}

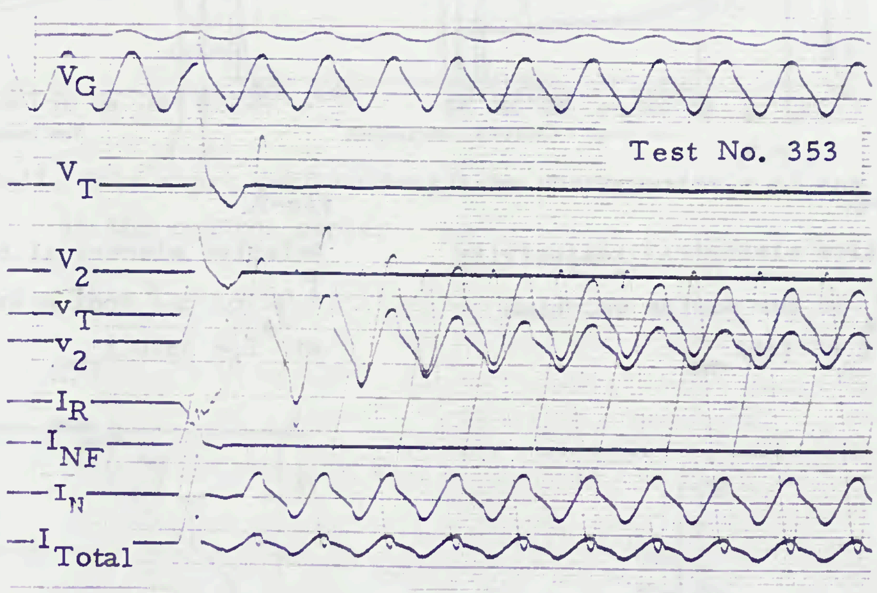

Fig-6. Typical oscillogram of a equivalent test at I_R= 3520A_{rms}

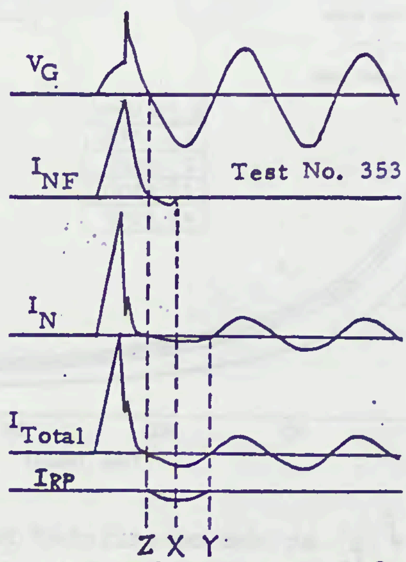

Fig-7. Voltage and current waveforms during the first few cycles (correspond to Fig-6.)

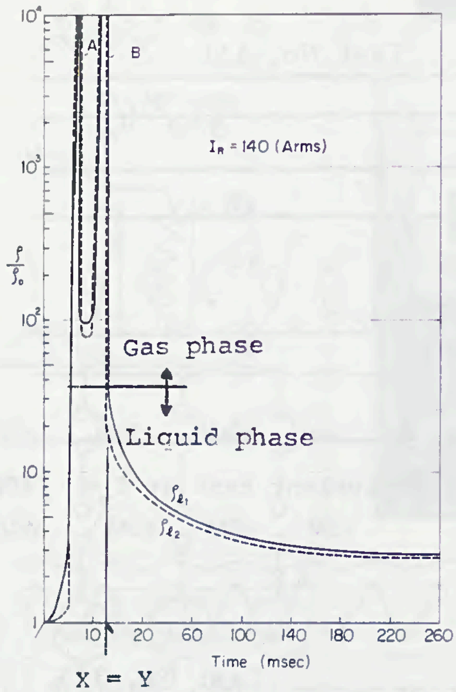

Fig-8.

Relative electrical resistivity ρ/ρ_0 of the Sodium vs. time at $I_R = 140A_{rms}$.

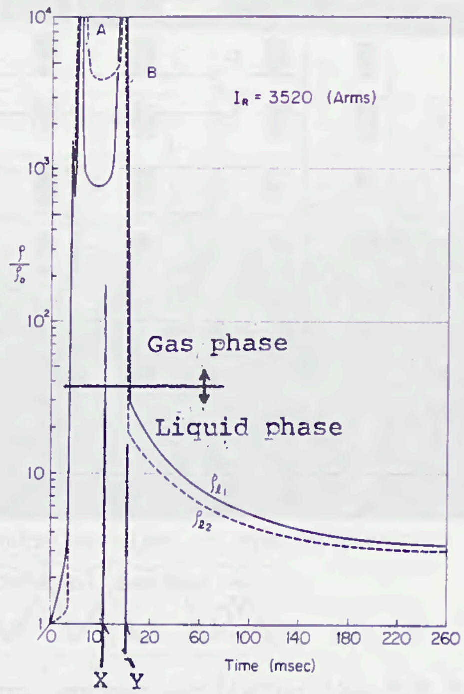

Fig-9.

Relative electrical resistivity ρ/ρ_0 of the Sodium vs. time at $I_R = 3520\ A_{rms}$

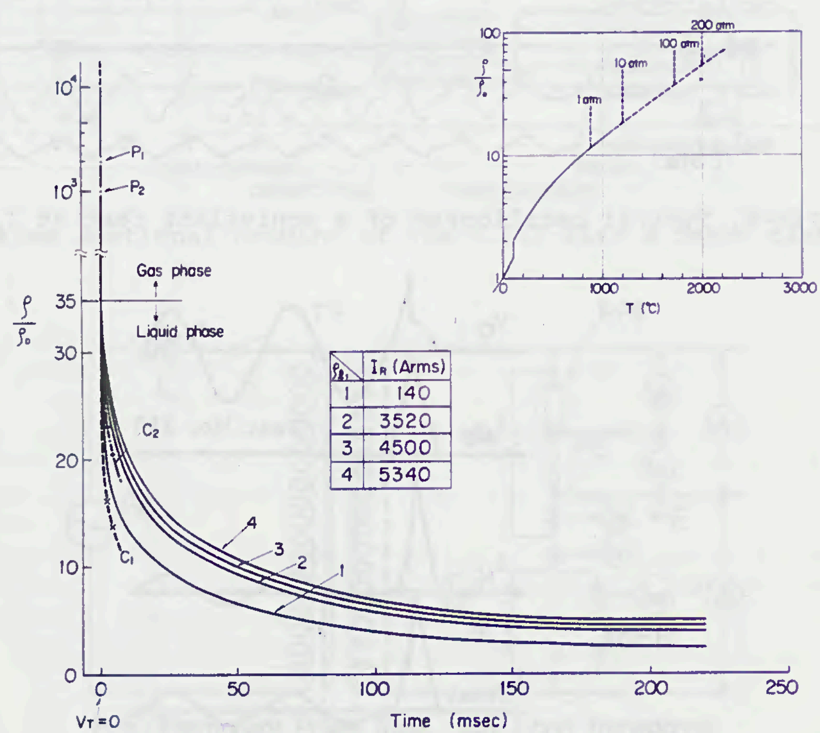

Fig-10. ρ/ρ_0 at the constricted portion vs. time and characteristic of ρ/ρ vs. temperature (4) (5)

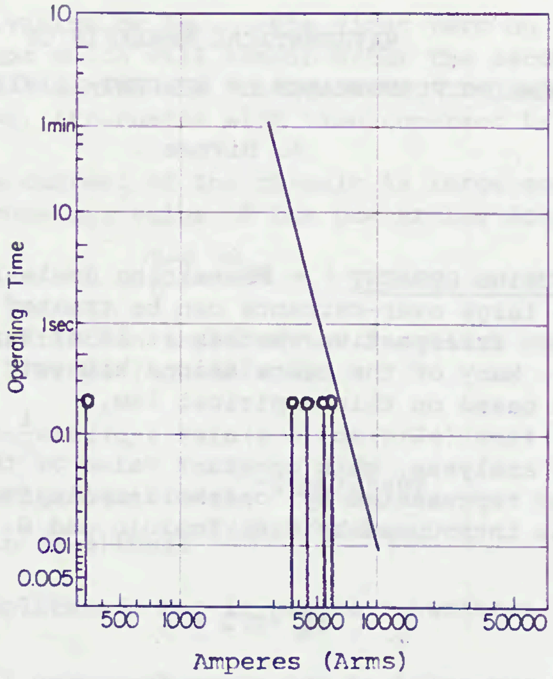

Fig-11. Cold start over current/time characteristic of the P.P.F in the control center