PROGRAMMABLE FUSES

R. L. Boggavarapu

INTRODUCTION Fuses and circuit breakers are used as overcurrent protective devices in power utility and industrial systems to isolate faulted sections. The requirements for the fuse are that it should allow for discrimination amongst the various protective devices and also should minimize the let-through I^2t. With the available current vs. time (i vs. t) characteristics, the coordination of fuses and breakers presents problems in some applications, in that the discrimination at either the high-current or low-current region has to be compromised. An i-t characteristic which is more desirable is shown in Figure 1. Use of magnetic structures to control the flow of currents in fuse structures to obtain non-linear characteristics have been proposed earlier [1].

A new concept of "programmable" fuse to represent a fuse package whose i vs. t characteristic could be altered by changing a circuit element external to the fuse package is introduced. The feasibility of this concept is demonstrated both in the laboratory and in experiments using Type K fuselinks. Test results are presented to demonstrate the feasibility. of using magnetic structures both for obtaining non-linear characteristics and for making programmable fuses. Magnetic structures were used in these experiments to provide passive control of current along multiple paths in the fuse structure. There was no active interaction between the magnetic field and the arc.

NON-LINEAR FUSE The principle of this fuse, called Augmented fuse by Aubrey, was described by him in the article referred to earlier [1]. Figure 2 shows schematically the arrangement of the fuse. A toroidal current transformer with a primary winding of N_p turns is connected to its secondary winding of N_s turns. Two fuselinks with their room temperature resistances of R_1 and R_2 are connected to the finish terminals of primary (F_p) and secondary (F_s); the other ends of these fuselinks are connected together to form terminal 2. The fuse package with its terminals (1) and (2) is to be connected in series as an overcurrent protective device. The total current, i_T, entering terminal 1 has to be leaving terminal 2. Transformer action controls the current division among the two fuses until a level of fault current is reached

Dr. R. L. Boggavarapu is with the Research and Development Center,
Westinghouse Electric Corporation,
Pittsburgh, PA 15235 USA

that saturates the magnetic core. Neglecting the magnetizing current, the secondary and primary currents are related by equation (1):

$$i_2 \cong -\frac{N_p}{N_s} i_T \tag{1}$$

The actual direction of current flow in fuselink R_2 is opposite to that shown in Figure 2. The current in fuselink RI is given by equation (2):

$$i_1 = i_T - i_2 \cong (1 + \frac{N_p}{N_s})\ i_T \tag{2}$$

For the transformer having a turns ratio of $(N_p/N_s) = 1$, the currents in the two fuselinks are given by equations (3) and (4):

$$\begin{aligned} i_2 &\cong -\ i_T \\ i_1 &\cong 2\ i_T \end{aligned} \tag{3}$$

These equations indicate that the two currents are out of phase and that the current division is independent of the values of the resistances of the fuselinks.

For a fault current, i_T, much higher than the level at which the core saturates, the current divides according to the inverse ratio of the resistances of the fuses. The currents i_1 and i_2 are in phase and given by equations (5) and (6):

$$i_1 = \frac{R_2}{(R_1 + R_2)}\ i_T \tag{5}$$

$$i_2 = \frac{R_1}{(R_1 + R_2)}\ i_T \tag{6}$$

By proper design of the transformer and choice of cross-sectional areas and resistances for the fuses, a package could be built such that both fuses melt at approximately the same time to isolate the faulted section.

The core size is determined by two factors: the current level at which the "non-linearity" (or change) in fuse characteristic is desired and the total resistance in the secondary loop. The current i_2 in the secondary loop is determined from equation (1). The transformer has to be designed so that a voltage necessary to sustain this current is induced in its secondary winding. Hence this voltage, V_{sec}, is given by equation (7) and the core size is determined by equation (8):

$$V_{sec} = i_2\ (R_1 + R_2) \tag{7}$$

$$V_{sec} = 4.44\ B_m\ A_c\ f\ N_s\ *\ 10^{-8} \tag{8}$$

where B_m is flux density in gauss, A_c is cross-sectional area of the core in sq. cms, f is the frequency and Ns is the number of turns in the secondary.

The operation in a real fuse package is as follows. For a given fault current, the initial resistances of the fuses may not be large enough to cause saturation of the core. As the resistances of the fuses increase due to the heating effect, the core reaches saturation and the current division changes. The waveshapes also change progressively as a function of time. For much higher fault currents, the current waveshapes will be distorted even initially depending on the relative magnitudes of the fault current and the designed current level at which the core saturates. Also, in a real fuse package the initial resistances (R_1 and R_2) of the two fuses need not be the same, and the selection depends on the desired characteristics of the fuse package and the design of the transformer. The determining factor would be to make both the fuses rupture at approximately the same time.

PROGRAMMABLE FUSE In the laboratory investigation of the concept of non-linear fuse using resistors in place of the fuses, it was observed that magnetizing current could cause distortion of the currents in the two paths and also cause errors. The total current i_T is unaffected. Since the r.m.s. values of currents in the two paths represent the effectiveness of melting when fuses are used, ways of reducing these errors were investigated. The principles used in zero-flux transformer [2] for improving the accuracy of current transformer seemed to be applicable here. The circuit shown in Figure 3 is one of the several circuits investigated in the laboratory using resistors. R_1 and R_2 represent the fuses; the winding connections on the transformer marked CTI are essentially the same as before. The variable resistor R_3 is inserted in series in the branch containing fuse FI (R_1). The primary winding of an auxiliary current transformer marked CT2 is connected in series with the primary of the main current transformer (CT1). The secondary winding of CT2 is connected across R_3. By varying the resistance R_3, the current division between fuses R_1 and R_2 and the current level at which the core of CTI reaches saturation could be altered. Thus the i-t characteristics of the fuse package could be altered. The waveshapes and magnitude of the current change with different values of R_3 and for a real system with fuses the i^2t is important in causing melting. In the laboratory experiments a change in r.m.s. current in different paths of about 19% to 39% was achieved by changing R_3 alone without altering R_1 and R_2. A voltage is introduced into the loop formed by R_1 and R_2 and by varying the resistance value of R_3 and changing the polarity of this voltage by changing connections, a large number of fuse characteristics could be achieved. Since these results are obtained with the same fuse elements and with only a change in the value of a circuit element external to the fuse package, this is termed a "Programmable" fuse.

EXPERIMENTS WITH FUSELINKS The results of laboratory experiments on both of the above concepts were very encouraging. Changes in r.m.s. values of current of up to 40% were achieved. The size of the core required was calculated from the nominal resistance of the fuselinks of different voltage and current rating and from the required "transition current". This was found to be not too large and did not vary widely for different fuses. A series of tests using Type K fuselinks were conducted at the A.C. Laboratory of Westinghouse, in East Pittsburgh. The test set-up is shown schematically in Figure 4. A 100 V A.C. supply with variable resistor packs, R_c, is used to obtain a unity power factor circuit. The power factor is not specified in standards for determining the melting characteristics. A brass block is used to mount the two fuselinks, with the buttonheads held in place by two brass nuts. The pigtails hang free in air. The current transformer of the fuse package is mounted on a horizontal board and connections are made through terminal blocks mounted on the same board. Through-type current transformers were used to record the waveforms of the total current, i_T, and the two branch currents, i_1 and i_2. The resistance values of the fuselinks and the information on the cores is given in the appendix.

TEST RESULTS: NON-LINEAR FUSE Test results for one series of tests in which both the primary and secondary of the current transformer have 20 turns and in which 6 amp fuselinks are used in both current paths are reported here. Before conducting these experiments the melting characteristic for this non-linear fuse was "calculated" based on very simple approximations. In a very simplistic approach the current division was assumed to be controlled by the transformer action up to 60 amps and by the resistances alone for currents higher than 60 amps. Based on these assumptions the melting times for the two fuses of four different currents was read from the curves and the maximum melting time is plotted. Oscillographic traces for two real tests are shown in Figures 5 and 6. The currents are distorted due to the magnetizing current component and the phase relationship between i_1 and i_2 is accurately shown. The ratio of current transformer used to indicate total current, i_T, was changed and its polarity is not consistently shown. The peak value of the voltage induced in the search coil on the CT is seen to increase with time. This is attributed to the increase in the resistance of the fuselinks. The time for the total current to go to zero is used to plot the melting characteristic shown in Figure 7. Because of the low voltage of the power supply, the arcing time is assumed negligible. The resulting characteristic in Figure 7 shows a smooth transition from the 6 amp fuse in the low current region to the 12 amp fuse characteristic in the high current region. This measured characteristic agreed very well with the one calculated from the simplistic assumption described earlier. However, the transition was much smoother than was calculated.

TEST RESULTS: PROGRAMMABLE FUSE These tests were conducted with two current transformers. Both transformers have primary and secondary windings of ten turns each. Two 25 amp fuselinks were used. The resistance of the external resistor R_3 should not change due to the momentary large currents. Available current shunts with resistances of 0.5 mΩ and 2.0 mΩ were used and no effort was made to optimize or design for any specific desired characteristics. As before, the melting time characteristics were constructed from the oscillographic traces. The results are shown in Figure 8. The effect of changing the external resistance was clearly evident; this was the only change in the two series of tests.

DISCUSSION The preceding sections described the principles involved in the use of magnetic circuits to obtain non-linear characteristics for fuses, the laboratory work and the tests conducted to determine the melting characteristics of fuselinks. The purpose of this very short program was to explore as many new concepts as possible, rather than to continue with feasibility studies. As such, there was not enough time to investigate completely every phenomenon that was observed. Several series of tests were conducted on the non-linear fuse with different turn ratios of current transformer and with combinations of fuselinks having different rating. At low currents the i-t characteristics of the fuse package should approach those of the lower rated fuse. Sometimes this was not observed. The discrepancy was attributed to the heat loss from the fuselinks to the brass block. In the high current region, beyond the core saturation level, the i-t characteristics of the fuse package should be equivalent to those of a fuse having a rating equal to the sum of the ratings of the two fuses. This has generally been observed. In a few cases the melting characteristic of the fuse package did not follow the slope representing that of the fuselinks and a "speed-up" was observed. The cause of the speed-up and the effect of different magnetic materials and current transformer design and optimization on the characteristics of the fuse packages was not fully investigated.

The errors due to magnetizing current and the distortions introduced in the current waveform due to magnetic nonlinearities could be estimated. The currents i_1 and i_2 for a transformer turn ratio of 1 are given by equations (9) and (10) than equations (3) and (4):

$$|i_2| = i_T - \delta \tag{9}$$

$$i_1 = 2\, i_T - \delta \tag{10}$$

$$\frac{i_1}{|i_2|} = 2 + \frac{\delta}{i_T} \tag{11}$$

The ratio of currents, given by equat:on (11), approaches 2 for large values of currents. The fuse elements could be so chosen that the fuse element carrying the current i_1 will melt first. Other choices could be made depending on the desired characteristics. However, when one of the fuses melts first, the circuit conditions change and the transformer in effect becomes an inductor. The magnitude of the inductance depends on which fuse melts first. If the fuse in branch 2 melts first, the inductance will be due to the primary winding alone. However, if the fuse in branch 1 melts first, the inductance introduced in the circuit would be that due to the primary and secondary turns in series. In the test circuits, this additional inductance could have caused distortions in waveforms. No attempts at making correction due to this factor were made. In real systems the additional impedance may not be large compared to the total system impedance; the design should aim for minimizing such effects.

Several circuits for programmable fuses have been investigated in the laboratory. Only one circuit was used in tests with fuselinks in the available time. Sensitivity aspects could be explored more fully.

The size of the core required is quite small. No attempts at optimization of the core or transformer construction were made. The core loss under steady state conditions is negligible. Depending on the application the fuse can be built with current transformer as an integral part or as a separate component.

CONCLUSION The novel concept of "programmable" fuse, where a change in external element is used to alter the current vs. time characteristic of the fuse package is introduced and investigated. This concept is successfully demonstrated in tests with fuselinks. The use of magnetic structures to control the current flow along multiple paths of fuse package coupled with the use of external circuit elements to alter its characteristics might provide greater flexibility in system design. Solutions based on these principles could be developed for other problems in the application of overcurrent protective devices.

ACKNOWLEDGMENTS The author extends his thanks to Westinghouse Electric Corporation for supporting this work and for permitting publication of the results. He is very grateful to D. D. Blewitt for his help and valuable discussions and to Mrs. I. M. Hesselbart for typing the manuscript.

REFERENCES

(1) D. R. Aubrey, "Coordination of fuses and circuit breakers during lightning storms", IEE Conference on Lightning and the Distribution Systems, Publication No. 108, 1973.
(2) A. Hobson, "The zero-flux current transformer", A.I.E.E. Trans., August 1953, pp. 608-615.

APPENDIX Transformer and fuselink information for the experiments.

A. Non-Linear Fuse

Core: Material: 0.004" thick hypersil
Strip Width: 1.0"
Cross-Sectional Area: 0.438 sq. in.
Number of Turns in Primary and Secondary: 20

Fuselinks: Rating: 6 A each
Resistance: 13.45 mΩ (each)

B. Programmable Fuse

Cores: CT1
Material: 0.012" thick hypersil
Strip Width: 2.0"
Cross-Sectional Area: 1.0 sq. in.
Number of Turns in Primary and Secondary: 10

CT2
Core is same as for non-linear fuse
Number of Turns in Primary and Secondary: 10

Fuselinks: Rating: 25 A each
Resistance: 3.2 mΩ

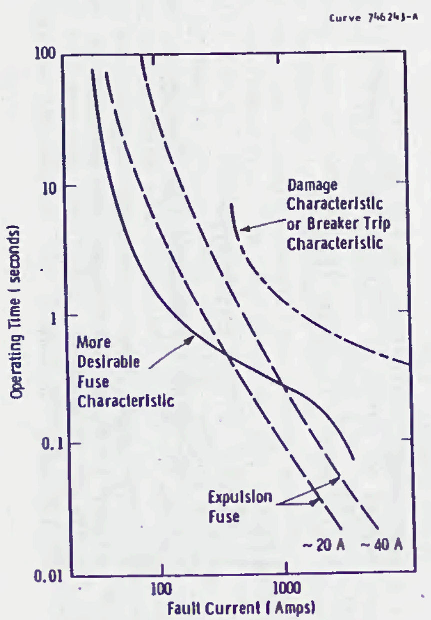

Fig. 1 – General characteristics of fuses and breakers (not to scale)

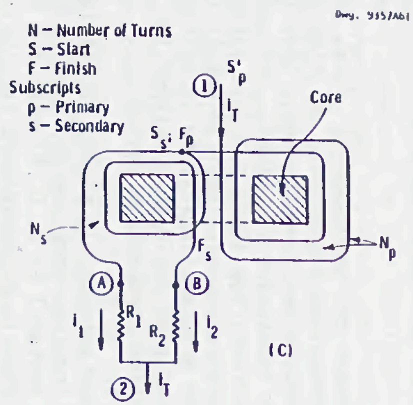

Fig. 2 – Non linear fuse

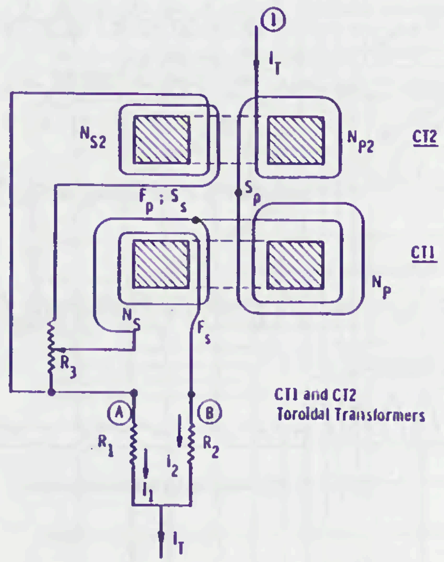

Fig.3 – Schematic of programmable fuse

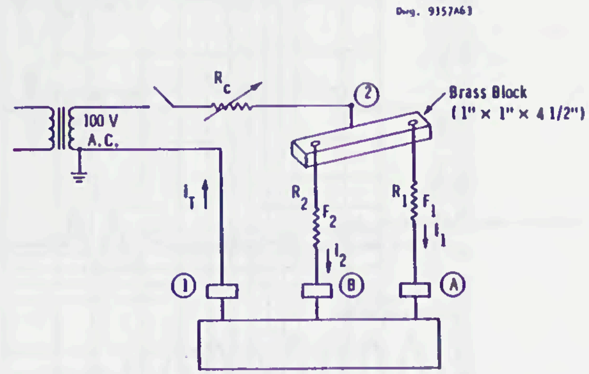

Fig. 4 – Schematic of set up for test on fuselinks

FIGURE 5 TEST RESULTS FOR NON-LINEAR FUSE

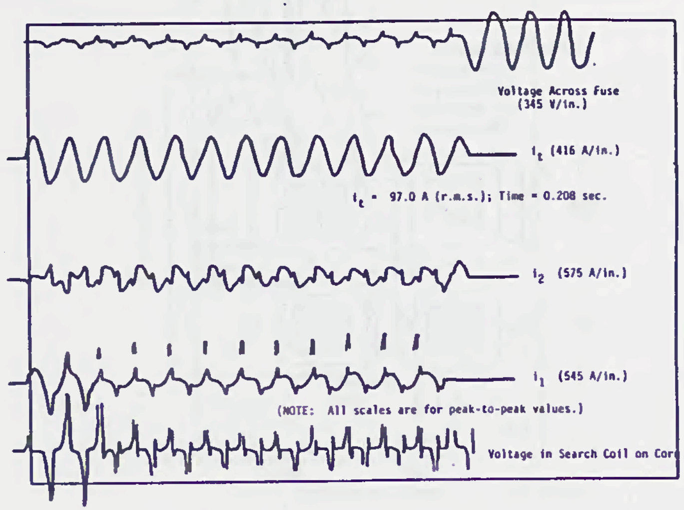

FIGURE 6 TEST RESULTS FOR NON-LINEAR FUSE

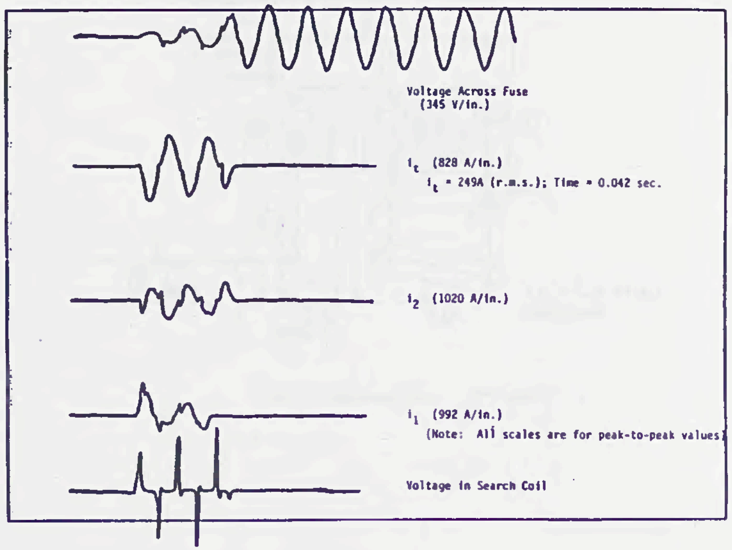

FIGURE 7 MELTING CHARACTERISTIC OF NON-LINEAR FUSE
WITH TWO 6 AMP FUSELINKS

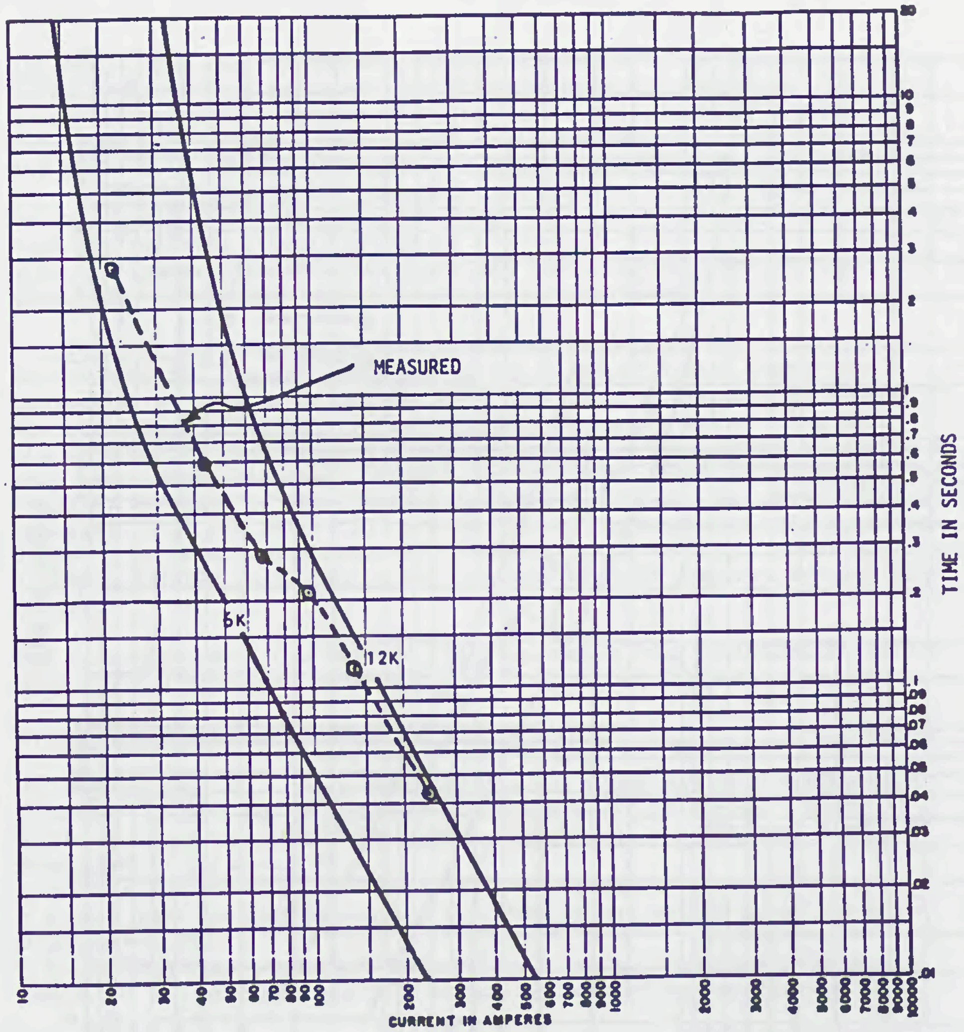

FIGURE 8 MELTING CHARACTERISTICS OF PROGRAMMABLE FUSE WITH TWO 25 AMP FUSES