The effect of repetitive surges on transient overcurrent and overvoltage protective devices

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Significance
Part 7 – Mitigation Techniques

This paper is a condensed version, presented to an international audience, of the IEEE IAS Transactions, "*Matching surge-protective devices to their environment*" which is reproduced in Part 7 of the Anthology under the hyperllink "Matching environment".

THE EFFECT OF REPETITIVE SURGES ON TRANSIENT OVERCURRENT AND OVERVOLTAGE PROTECTIVE DEVICES

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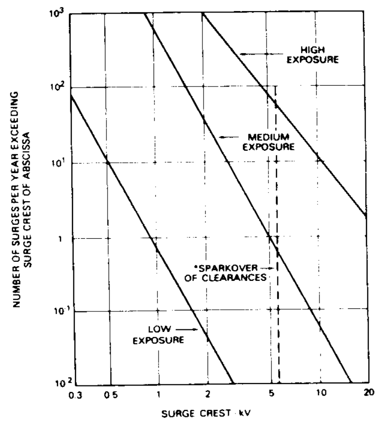
INTRODUCTION

The occurrence of transient overvoltages in low-voltage power circuits has been recognized, and new standards have been published in recent years [1-4] that provide quantitative information on the voltage levels to be expected. Concurrently, the technology of metal oxide varistors has gained wide acceptance in the suppression of these transients [5-7]. These varistors provide an effective method of diverting surges away from sensitive loads by offering a low-impedance path to the flow of current, maintaining a quasi-constant voltage across their terminals. This surge current diverted in the varistor produces within the bulk of the varistor material the deposition of energy, with the long-range effect of a progressive shift in the varistor characteristic. This phenomenon has been well documented [8,9], and the proper application of varistors can deal with the effect without adverse consequences.

Manufacturers of metal oxide varistors publish ratings which include a family of curves, generally described as "Pulse Lifetime," that show the number of surges which a given varistor can absorb before some arbitrary limit of characteristic shift is reached. These curves show numbers of surges of equal amplitudes for a set of waveshapes; the actual occurrence of surges, however, is a full range of values, from the lowest to the highest, and also of different waveshapes.

Attempts to simplify the description of surge occurrences have resulted in the statistical information of IEEE Std 587-1980, where a family of curves has been obtained from actual surge recordings; these curves show the frequency of occurrence of surges as a function of the voltage surge level, for various exposures (Figure 1). Carroll first developed a method [10] whereby the statistical information of IEEE 587 can be combined to predict the effect of the range of surges, as opposed to constant amplitude surges, on the varistor Pulse Lifetime. Korn has shown [11] how a simple set of assumptions and computations based on Figure 1 and Pulse Lifetime curves can provide an estimate of the time required to reach the varistor rated Pulse Lifetime.

This paper provides further guidance in applying this method, including the selection of environmental characteristics in the context of IEEE 587. Since the statistical nature of surges must be recognized, provision must be made for the rare cases where a properly applied varistor might still receive excessive energy, and age or fail prematurely. The common practice in dealing with this eventuality is to add a fuse in series with the varistor in order to eliminate the fault current that might flow in the failed varistor. Thus, the fuse will be subjected to the surges absorbed by the varistor, and should not blow under a single surge, nor should it be affected by the accumulation of surge currents at amplitudes slightly below the melting



*In some locations, sparkover of clearances may limit the overvoltages

Figure 1. Rate of surges occurrence vs. voltage level (from IEEE Std 587-1980)

level. Unfortunately, published time-current characteristics of fuses do not provide information on their performance at the short times and high peak currents involved in the operation of a surge diverter. To fill this void, a series of tests was performed on various types of fuses; the first results are presented in the second part of this paper.

MATCHING THE VARISTOR CAPABILITY TO THE ENVIRONMENT

Two examples of environments will be used to evaluate the effect on typical varistors that might be selected for transient protection. In the first example, the point of application is the service entrance to a building; in the second, we postulate a varistor installed in an appliance located somewhere in the building, with no protection provided at the service entrance. These two examples will illustrate the approach, so that other types of applications can be evaluated in a similar manner.

A table can be developed based on the information of Figure 1 and combined with the Pulse Lifetime data published by the manufacturers, to estimate the time required for a given varistor size to reach its rated life in a given environment. One should recognize that these calculations are based on graphical data which do not allow three-digit accuracy, even if the numbers shown on the table are carried to three digits for the sake of checking the arithmetic. Furthermore, reaching the "rated life" does not mean that the device has reached the end of its service life. The published Pulse Lifetime ratings are based on the arbitrary definition of "rated life" as the point at which the nominal voltage of the varistor has decreased by 10%. This change of voltage is indeed indicative of some physical change in the varistor structure, but it does not affect the ability of the varistor to clamp surges in the high-current region. For properly applied varistors, a change of 20% in the nominal voltage would not be objectionable, so that this "rated life" is a very conservative limit.

The first task of this development is to convert the voltage surge density probability of IEEE 587 (Figure 1) into a histogram of surge occurrences at the different levels of voltage. From Figure 1, selecting a given exposure, one can obtain the level of voltage surges occurring at different frequencies, or the number of occurrences between two voltage levels defining a cell of the histogram.

Referring to Figure 2, the Medium Exposure line of Figure 1 has been redrawn, and voltage cells of approximate equal width (on the logarithmic scale) have been drawn, with the center values as shown in the figure, on the left side : 13000, 10000, 8000, etc. From the Medium Exposure line, the corresponding frequencies of occurrence are read, as shown in the first column of numbers to the right side : 0.03, 0.07, 0.18, etc. These numbers are the number of occurrences *exceeding* the level, so that the number in the the cell itself is the number for the level, *minus* the number for the level to the right. For instance, the number of occurrences in the cell of level 10 000 V is 0.07 - 0.03 = 0.04 occurrences, and so forth for the other cells.

Surge recordings, such as reported in IEEE 587, have shown that switching transients are not likely to exceed 3000 V; therefore, we can attribute all the occurrences above 3000 V to lightning, and assume an 8/20 μs waveform for the resulting current in a varistor connected at the first interface. Conversely, the occurrences below 3000 V can be considered as an undefined combination of switching transients and lightning transients. It seems reasonable and conservative to consider that half of these may be lightning, with the corresponding high energy of the 8/20 μs wave shape, while the other half may be switching surges with the corresponding 0.5 μs - 100 kHz which has negligible energy content, compared with the 8/20 μs. Therefore, the numbers for the cells below 3000 V shown in the last column of Figure 2 are one half of the number of occurrences computed for each cell.

The first example of application will be a 32 mm varistor, rated 250 V, which is assumed to be connected at the entrance of a building, and thus would be subjected to the Category B (IEEE 587) surges. As shown in Figure 3, these surges are defined as 6 kV open-circuit voltage and 3 kA short-circuit current. The ratio of voltage and current can be considered as the source impedance of the surge, 2 Ω in this example.

Referring to Table 1, the first column shows the voltage level of each cell; the number of occurrences for that level, as derived in Figure 2, is shown in the second column. From the varistor V-I characteristic (Figure 4), an expected

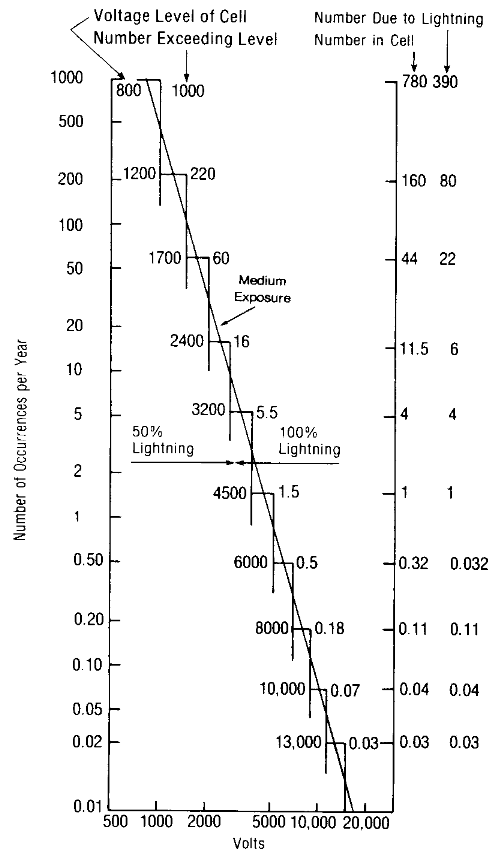


Figure 2. Derivation of the cell histogram

clamping voltage can be derived by iteration for the range of resulting current expected at that voltage level, as shown in the third column. The voltage of the cell, minus the expected clamping voltage, is the driving voltage shown in the fourth column. With the 2 Ω source impedance derived above, this driving voltage, divided by 2, yields the resulting current shown in the fifth column. Turning to the Pulse Lifetime curves of Figure 5, the rated number of pulses for each current level are shown on the sixth column. Finally, the last column shows the percentage of rating consumed for the number of pulses at any level; for instance, at the 3200 V level, with 4 occurrences at a current of 1220 A, hence a rating of 500 pulses, the percentage consumed is 4 : 500 = 0.80%. The sum of the percentages of all levels, then, is the percentage of rating consumed in one year, which yields the number of years required to reach the rated value, as shown at the bottom.

Surge Voltages and Currents Deemed to Represent the Indoor Environment and Recommended for Use in Designing Protective Systems

Location Category	Comparable to IEC No 664 Category	Impulse: Waveform	Impulse: Medium Exposure Amplitude	Type of Specimen or Load Circuit	Energy (joules) Deposited in a Suppressor* with Clamping Voltage of 500V (120 V System)	1000V (240 V System)
A Long branch Circuits and outlets	II	0.5 μs-100 kHz	6 kV	High impedance†	—	—
			200 A	Low impedance‡, §	0.8	1.6
B Major feeders, short branch circuits, and load center	III	1.2 × 50 μs	6 kV	High impedance†	—	—
		8 × 20 μs	3 kA	Low impedance‡	40	80
		0.5 μs-100 kHz	6 kV	High impedance†	—	—
			500 A	Low impedance‡, §	2	4

*Other suppressors having different clamping voltages would receive different energy levels.
†For high-impedance test specimens or load circuits, the voltage shown represents the surge voltage. In making simulation tests, use that value for the open-circuit voltage of the test generator.
‡For low-impedance test specimens or load circuits, the current shown represents the discharge current of the surge (not the short-circuit current of the power system). In making simulation tests, use that current for the short-circuit current of the test generator.
§The maximum amplitude (200 or 500 A) is specified, but the exact waveform will be influenced by the load characteristics.

Figure 3. Voltages and currents in IEEE 587, Categories A and B

Table 1
Time to Reach Rating for a 32 mm, 250 V Varistor in Medium Exposure, Category B Location

Voltage level of cells	Number of 8/20 occurrences	Expected clamping voltage	Available driving voltage	Resulting current at 2 Ω	Rated number of pulses	Percent of rating consumed
13 000	0.03	1 000	12 000	6 000	8	0.37
10 000	0.04	920	9 080	4 540	15	0.26
8 000	0.11	840	7 160	3 580	25	0.44
6 000	0.32	810	5 190	2 595	60	0.53
4 500	1	780	3 720	1 860	200	0.50
3 200	4	760	2 440	1 220	500	0.80
2 400	6	740	1 660	830	1 500	0.40
1 700	22	720	980	490	4 000	0.55
1 200	80	700	500	250	20 000	0.40
800	390	680	120	60	10^6	0.04
				Total Percent of Rating Consumed in One Year		4.29%
				Years Required to Consume 100% of Rating		23

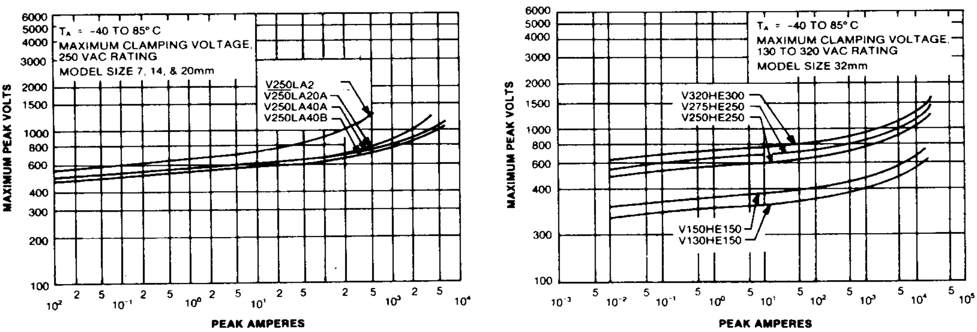
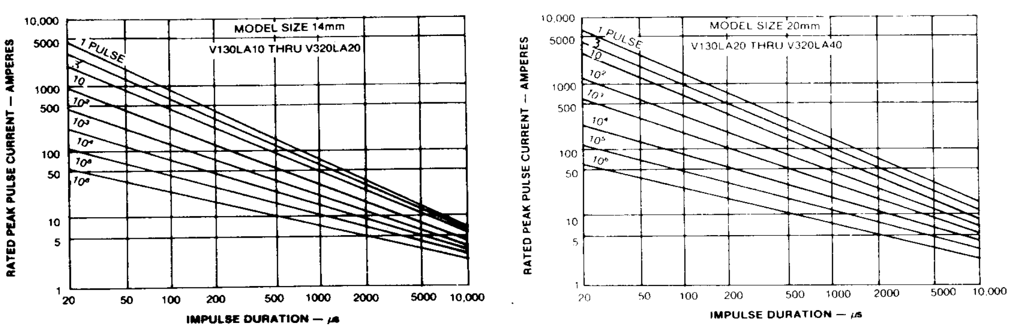
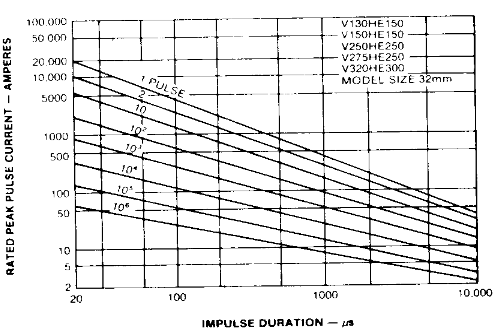


Figure 4. V-I characteristics for 14, 20, and 32 mm varistors rated 250 V RMS





NOTE: End of lifetime is defined as a degradation failure which occurs when the device exhibits a shift in the varistor voltage at one (1) milliampere exceeding ± 10%, ± 1V of the initial value. This type of failure is normally a result of a decreasing V_1 value, but does not prevent the device from continuing to function. However, the varistor will no longer meet the original specifications.

Figure 5. Pulse lifetime ratings for 14, 20, and 32 mm varistors rated 250 V RMS

For the selected example of a 32 mm varistor, rated 250 V and connected in a Category B location at Medium Exposure, it would take 23 years to reach the rated pulse life of the device under the conservative assumptions made in this example. Once again, reaching "rated life" does not mean reaching a device failure level.

Another example of estimation will be useful to illustrate the process and the type of reasonable assumptions that can be made. Consider a varistor installed on an appliance connected at some point distant from the service entrance, still in Category B, Medium Exposure. Table 2 shows the corresponding pairs of numbers of occurrences and levels, from which the same computations can be derived as before. We will add some impedance to the 2 Ω value used in the preceding example, say 2 Ω for an 8/20 μs surge propagating in a few meters of wiring [12]. For this example, we will compare a 20 mm varistor to a 14 mm varistor, both rated 250 V; the same value of expected clamping voltage will be used for both devices (Figure 4), and the resulting surge current will be computed, as shown in the fifth column of Table 2. Referring to the respective Pulse Lifetime rating curves for the 20 and 14 mm devices (Figure 5), we obtain the number of pulses allowed to reach the rating, shown in the next two columns, and compute the yearly consumption for each device at each level. Again, the total is shown, with the resulting number of years required to reach the rating: 20 years for the 14 mm device, and 50 years for the 20 mm device, in the environment of this example.

Thus, we have a method for estimating the effect of the environment, as defined in IEEE 587, on the ability of the varistor to function reliably in that environment. Indeed, the evaluation is only as good as the assumption made on the actual environment, compared to the generalized description given in IEEE 587; nevertheless, it represents a reasonable and reasonably conservative approach to selecting device ratings for reliable operation and make comparisons between different device sizes. Carroll has shown, by computer-aided analysis [14], that the estimation tends to yield increased years as the width of cells is made smaller, reaching an asymptote over one hundred cells. In the examples shown here with fewer cells, aimed at a rapid estimation, the log-log coordinates tend to weigh the results toward a pessimistic estimate when the cell numerical center is taken at the geometric center.

FUSING OPTIONS

It is well recognized that extreme values can be found which will exceed the predictions of limited-base statistics, so that one must always take into consideration the case where excess energy might be deposited in the varistor. Like any other electronic component abused in this manner, it will fail, generally in a short-circuit mode. Depending on the available short-circuit current at this point of the system, the current flowing in the failed varistor can produce melting of soldered connections or shattering of the device. Since these ultimate failure modes are not generally desirable, common practice would be to provide an overcurrent protection in series with the varistor, in order to clear the fault from the circuit.

Two approaches to fusing a varistor can be considered, as shown in Figure 6. In Figure 6a, providing the fuse in series with the load ensures that in case of varistor failure, the power is removed from the load, so that it will not be exposed unprotected from further surges. In Figure 6b, the varistor fuse inserted in shunt with the varistor ensures that the power supply to the load will not be interrupted by a spurious varistor failure, but only at the price of leaving the load unprotected against further surges. As pointed out in industry standards [9], each of these scenarios may be the preferred one to some users, so that the "fail safe" description would be misleading to the opposite view. For instance, an application can dictate that maximum service continuity be ensured, so that Figure 6b would be labeled "fail safe" by those requiring this mode of failure. Other users, anxious to protect their hardware even at the price of losing the function, would label Figure 6a as "fail safe."

For the Figure 6b configuration, the only requirement for the fuse is to ensure fast removal of a failed varistor, and yet not blow under the surges presumed to flow from time to time in the varistor. Hence, the selection of this fuse should reflect the expected surge currents. Unfortunately, data currently made available by fuse manufacturers do not extend the i^2t ratings into the microsecond

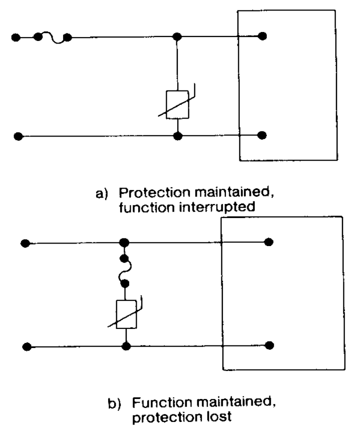


Figure 6. Fusing options for varistors

Table 2
Time to Reach Rating for 20 and 14 mm, 250 V Varistors in Medium Exposure, Category B Location

					14 mm		20 mm	
Voltage of 8/20 occurrences	Number level of cell	Expected clamping voltage	Available driving voltage	Resulting current at 4 Ω	Rated number of pulses	Percent of rating consumed	Rated number of pulses	Percent of rating consumed
8 000	0.18*	800	7 200	1 800	12	1.5	80	0.20
6 000	0.32	760	5 240	1 310	40	0.80	110	0.30
4 500	1	730	3 770	942	100	1	200	0.50
3 200	4	710	2 490	622	600	0.67	1000	0.40
2 400	6	700	1 700	425	1100	0.55	2 000	0.30
1 700	22	690	1 010	252	6 000	0.37	10 000	0.22
1 200	80	680	520	130	50 000	0.16	90 000	0.09
800	390	670	130	32	$2 \cdot 10^6$	0.02	$\geqslant 10^7$	—
		Total Percent of Rating Consumed in One Year				5.07%		2.01%
		Years Required to Consume 100% of Rating				20		50

* Surges above 8000 V are not likely to propagate in low-voltage wiring without causing operation of a protective device, or flashover of a clearance upstream [13], so that the varistor installed downstream in the Category B location will not be subjected to the energy associated with levels above 8000 V.

range, nor do they provide guidance on any necessary derating of the fuse in order to account for the possible effect of repetitive surges at levels slightly below the melting level. The second part of this paper therefore aims at providing some information on this selection process. This information is based on a limited test program conducted on various types of low-voltage fuses that might be considered for fusing a shunt-connected varistor.

It should be noted, of course, that while the operation of the fuse in the series connection (Figure 6b) has generally an obvious effect on the system operation — shutdown — operation of the fuse in the shunt branch is not immediately apparent. Depending upon the application and the economics of the situation, it may be desirable to provide some indication that the varistor is no longer protecting the circuitry.

PERFORMANCE OF FUSES WITH REPETITIVE SURGE CURRENTS

An experimental program was conducted on various fuses in order to determine the minimum ampere rating required for the fuse not to blow under the surge currents that may be diverted by the varistor at its expected point of installation. This minimum limit not only involves a current level for one single surge, but also a current level, presumably lower, for many pulses. This duality is parallel to the situation discussed for the varistors, where the Pulse Life time is a function of three parameters: current peak, current duration, and number of pulses. Unfortunately, fuse manufacturers have not at this time published any information on microsecond-long current pulses, so that users resort to empirical derating factors to anticipate the effect, resembling fatigue, of multiple pulses.

Results of tests made on two types of current-limiting fuses are presented here to illustrate the effects of repetitive surges and to motivate a discussion of the issues and a sharing of information.

The fuses were both rated for 250 V circuit voltage, with an interrupting capacity of 10 kA, representative of what might be used in an application with moderate fault currents. The construction of fuses rated for higher prospective fault currents, such as 100 kA, is different primarily in the current-limiting characteristics; here we are concerned with the element-melting characteristics. A more comprehensive program will have to extend the investigation to the behavior of fuses with high interrupting capacity, as well as circuit voltages up to 600 V. One fuse was the so-called "fast fuse," with a ratio of 13:1 between the melting currents at 1000 and at 0.01 s. The other fuse type, the so-called "time delay," had a ratio of 37:1. Both were rated 3 A; Figure 7a shows an X-ray photograph of the 3 A fast fuse and Figure 7b shows the 3 A time delay fuse.

The current waveform selected for the test was the standard 8/20 μs impulse used for characterizing varistors and other surge protective devices. Figure 8 shows such an impulse, for which the i^2t integral can be computed. For an impulse of 1000 A crest, the i^2t value of an 8/20 μs impulse is 19.5 A^2s.

Fast Fuse Tests

The 3 A fast fuse used in the test has a melting current of 46 A rms at 0.01 s, which corresponds to an i^2t of 21 A^2s. By subjecting each of 10 fuses to a single-shot impulse in the range of 1100 to 1000 A crest, the nominal melting current crest of 1050 A, 8/20 μs, was established. This current impulse has an i^2t content of 21.5 A^2s, which shows a remarkable correspondence to the i^2t at 0.01 s with sine wave current. We will designate this single-impulse melting i^2t as I^2T.

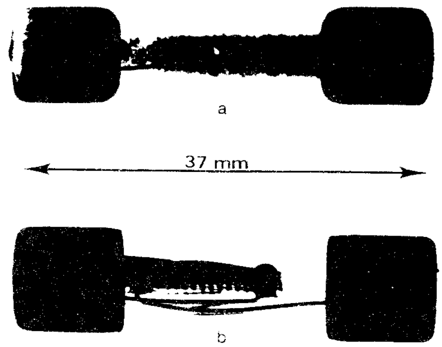


Figure 7. X-ray photographs of fuses

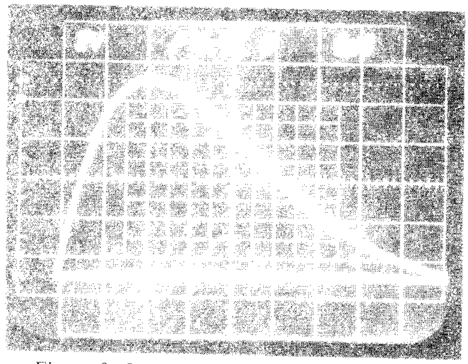


Figure 8. Current impulse 1000 A, 8/20 μs

Repetitive impulses, at a rate sufficiently low to avoid accumulation of heat in the fuse, were applied to several groups of fuses. The first group was subjected to impulses at 90% of the melting current, the second at 60%, and the third at 30%, corresponding respectively to i^2t contents of 81, 36, and 9% of the melting I^2T. In the 81% I^2T group of 10 fuses, all eventually melted as the repetitive impulses were applied. The first went at the third shot, the last at the sixty-third shot. In the 36% I^2T group of 10 fuses, four fuses melted at shot numbers ranging from 5 to 200. No further impulses were applied past 200 shots. Each of the surviving fuses was then subjected to a single impulse of higher value to determine the one-shot melting current in this "aged" condition. That value was found to be 1050 A crest, unchanged from the new condition. The 9% I^2T group, containing 20 fuses, received 800 impulses; none melted. Ten of these were subjected to a single impulse at 1050 A (100% I^2T): 6 out the 10 melted at that current, the four others survived.

From these results, it seems that a reasonably safe i^2t to ensure no melting of the fuse when exposed to repetitive current impulses is in the order of 25% of the single impulse melting I^2T. The value of I^2T to be used for taking the 25% limit can be obtained from the published melting current at 0.01 s. However, even at 10% of the single impulse melting I^2T, a slight aging of the fuse is detectable, leading to a decreased current capacity. At 36% I^2T, some early mortality is observed, but the survivors do not appear to have aged more than the 10% I^2T group.

Time Delay Fuse Tests

As an alternative to substantial derating of a "fast" fuse, the so-called "time delay" offers the possibility of being able to survive larger impulse currents. The larger ratio of 37:1 between 1000 and 0.01 s currents allows maintenance of a comparable overcurrent protecti capability in the medium range, where a varistor failur might require the fuse to melt in relatively short time.

The 3 A fuse tested in this program has a 0.01 s melting current of 130 A rms, or an i^2t of 169 A^2s. By the same bracketing procedure applied to the fast fuse, the I^2T under impulse of this fuse was determined to be 190 A^2t (somewhat higher than the i^2t at 0.01 s), corresponding to a crest current of 3.2 kA at 8/20 μs.

Preparing for repetitive impulses, it was found that at 81% I^2T, the fuses would not survive the second shot; at 64% I^2T, the fuses would melt at the second or third shot. The i^2t had to be lowered to 50% I^2T to allow passing 10 shots. The 36% I^2T group received 100 impulses without having one fuse melt; this is to be compared to 3 fuses out of 10 melted by the twentieth shot in the fast fuse series. These fuses conditioned by the 100 shots were then subjected to one single pulse each to determine the melting level, which was bracketed at 160 A^2s, or a crest of 2.9 kA at 8/20 μs. The third group of fuses in this series was exposed to 800 impulses at 9% I^2T; no melting occurred in 20 samples. Subjecting these successful survivors to one single impulse each bracketed the melting i^2t at 90% of the un-aged I^2T (95% of the current), a small shift downward.

These tests on the "time delay" type fuses also show some degradation or aging in the fuse, but somewhat different from the aging of the fast fuse type. The conclusion will still be that a derating on the order of 25 % of the I^2T (50% of the current) is required to provide reliable continuity of service under repetitive surge conditions.

CONCLUSIONS

1. Varistors can be selected to provide predictable performance under assumed surge conditions by combining the published Pulse Lifetime curves with environment characteristics.
2. Guides on the surge environment in ac power circuits, such as IEEE 587-1980, can be used to generate a reasonable definition of the duty imposed on varistors.
3. Current-limiting fuses that might be used in series with a varistor exhibit aging characteristics when subjected to repeated pulses, as they will in actual application. Pending availability of detailed information from manufacturers, a derating factor needs to be applied to the i^2t ratings computed from the shortest time (0.01 s) of the time-current characteristics.

Readers of this paper and users of fuses in impulse applications are invited to share information with the author in order to generate an improved evaluation of the problem.

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