Matching surge-protective devices to their environment

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Significance
Part 7 – Mitigation Techniques

Fuses connected in series with SPDs (those are now called "disconnector" but, although suggested in SPD application information but not mandated by then-applicable SPD standards) will be subjected to the same surge currents that the SPD is expected to carry as its function of surge diverter. In the eighties, as the work covered by this paper was conducted, fuse manufacturers did not provide data on the effect of repetitive surges of microsecond duration and thousands of peak amperes.

In a first part, the paper shows how the frequency of occurrence of surge voltages in a low-voltage installation, as described in IEEE Std C62.41-1980, can be used to generate a histogram of the surge currents that might be expected during the life of an SPD and its series-connected fuse. Using the pulse life rating published by varistor manufacturers, a varistor size might then be selected to provide an acceptable lifetime for repetitive surges of magnitude less than the maximum single-shot rating often emphasized in application and marketing information.

In a second part, the paper describes experiments conducted on commercial fuses to subject them to repetitive current surges as defined in the first part. Empirical information is then suggested on how the rating of a fuse should be modified to account for the effect of repetitive surges.

At the time of publication, the paper was recognized by an IEEE award. Twenty years later, as the importance of the role of SPD disconnectors and their proper design is gaining momentum, the concerns expressed in this paper still appear timely.

Matching Surge Protective Devices to Their Environment

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Abstract—**A method is described for the rational selection of metal oxide varistors as surge protective devices in low-voltage applications, combining data on the surge environment and device characteristics. Fuses that may be connected in series with the varistors will be exposed to current surges resulting from the varistor operation. Experimental results on the effect of repetitive current surges on such fuses are described, and some guidance is provided on the necessary derating of fuses for series applications with varistors.**

INTRODUCTION

SURGE CURRENTS diverted from sensitive loads into a protective low-voltage varistor will deposit energy into the varistor material, resulting in a long-term shift in the standby characteristics of the varistor. This behavior has been well documented [1], [2]. The proper application of varistors, nevertheless, prevents any adverse consequences of this behavior.

Pulse lifetime curves published by manufacturers to describe this behavior show families of repetitive pulses at equal amplitude; however, the real world involves a full range of amplitudes, as described in [3]. Analytical and numerical methods have been suggested [4]—[6] to combine the statistical information on surges of [3] with pulse lifetime curves in order to estimate the time required for a given varistor in a given environment to reach its rated life. In this manner, a rational selection can be made by matching the capability of the protective varistor to the known or postulated characteristics of the surge environment. The first part of this paper describes the numerical method, with examples for 120/240-V circuits.

Both the statistical distribution of surges in the environment and the legitimate economic wish not to overprotect call for an awareness that a varistor might fail when subjected to a surge with an energy content greater than the rating of the device. The usual practice is to connect a fuse in series with the varistor in order to clear the shorted varistor from the circuit. The fuse, then, is subjected to a current surge each time the varistor diverts a surge. Data published by fuse manufacturers do not provide guidance on the selection of fuses for applications where surges of microseconds' duration are encountered. To fill this void, a set of tests was performed on various types of fuses. The second part of this paper presents the results of these tests, with suggestions on the necessary derating for the fuses.

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MATCHING THE VARISTOR CAPABILITY TO THE SURGE ENVIRONMENT

Two examples of surge environments will be used to evaluate the effect of repetitive surges on typical varistors. In the first, the varistor is installed at the service entrance to a building; in the second, the varistor is installed somewhere in the building, with no protection provided at the service entrance. Other types of applications can be evaluated in a similar manner.

The procedure for evaluating the effect of repetitive surges involves developing a table for computing the effects at the various levels of surges, such as those shown in Fig. 1, on the basis of the pulse lifetime data published by the manufacturers of varistors. In this manner, an estimate can be made of the time required for a given varistor to reach its rated life in a given surge environment. These calculations are based on graphical data which do not allow three-digit accuracy, even though the numbers shown on the table are carried to three digits for the sake of checking the arithmetic. Futhermore, reaching the "rated life" does not mean that the device has reached the end of its service life. Pulse lifetime ratings are based on the arbitrary definition of rated life as the point at which the nominal voltage of the varistor [1] has decreased by ten percent. This decrease indicates some physical change in the varistor structure but does not affect the ability of the varistor to clamp surges. For properly applied varistors, a change of 20 percent in the nominal voltage would not be objectionable. Thus the rated life of a varistor is a very conservative designation.

The first task in this evaluation is to convert the voltage surge density probability of [3] (Fig. 1) into a histogram of surge occurrences. From Fig. 1, selecting a given exposure, we read the number of occurrences between two voltage levels, defining a cell of the histogram.

In Fig. 2, the medium exposure line of Fig. 1 has been redrawn. Voltage cells of approximately equal width (on the logarithmic scale) have been drawn. The center values of the cells are shown to the left of Fig. 2: 13 000, 10 000, 8000, etc. From the medium exposure line, the corresponding number of occurrences can be read on the vertical scale. These numbers are shown to the right of each cell: 0.03, 0.07, 0.18, etc. These numbers represent the number of occurrences exceeding the voltage level, so that the number in 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 10 000-V level cell is 0.07 − 0.03 = 0.04 occurrences, and so forth for the other cells.

Surge recordings, such as those reported in [3], show that switching transients are not likely to exceed 3000 V. We can

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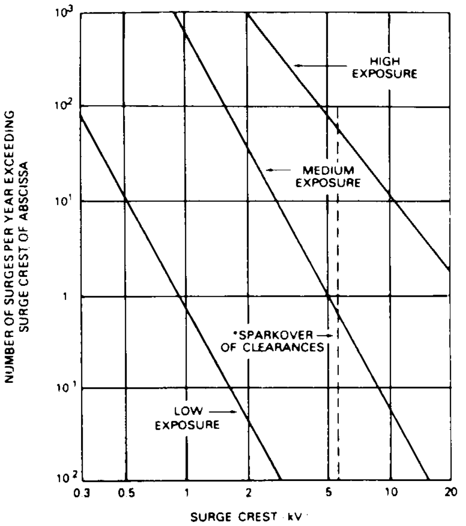


*In some locations, sparkover of clearances may limit the overvoltages

Fig. 1. Rate of surge occurrence versus voltage level [3].

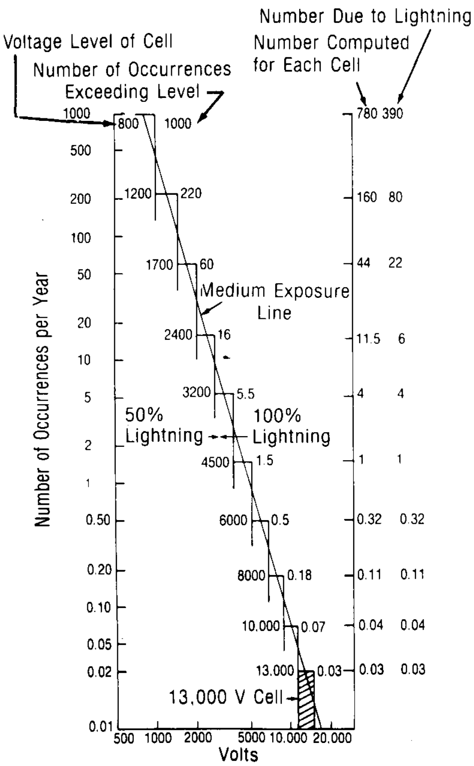


Fig. 2. Derivation of cell histogram.

then attribute all occurrences above 3000 V to lightning; hence we can assign an 8/20-μs waveform to the resulting current flowing in a varistor connected at the service entrance, or at a point where no protective device has been installed upstream, which could divert part of the surge. Conversely, 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 occurrences computed for each cell. Furthermore, continuing the histogram beyond the limits of Fig. 1 by extrapolating the lines above 10^3 occurrences per year would imply more than 1000 lightning discharges per year at one location. Because this situation is unlikely, the histogram is truncated at that level.

The first application example is a 32-mm varistor, rated 150 V, which is assumed to be connected at the entrance of a building and thus would be subjected to the Category B [3] surges. As shown in Fig. 3, these surges are defined as having 6-kV open-circuit voltage and 3-kA short-circuit current. The ratio of voltage to current can be considered as the source impedance of the surge, which is 2 Ω in this example. Another definition of the source impedance is implied in a requirement of the Federal Communications Commission [7] applicable to the ac input of devices interfacing with the telephone plant. In that requirement, a 1000-A short-circuit current is specified for the test generator having an open-circuit voltage of 2500 V, hence a source impedance of 2.5 Ω. Thus the selection of 2 Ω in this example is based on accepted industry standards.

In Table I, the first column shows the voltage level of each cell; the number of occurrences for that level, as derived from Fig. 2, is shown in the second column. From the varistor *V-I* characteristics (Fig. 4), an expected clamping voltage can be determined by iteration, for the current corresponding to 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 from Fig. 3, this driving voltage, divided by two, yields the resulting current shown in the fifth column. From the pulse lifetime curves of Fig. 5, the rated number of pulses for each current level is entered in the sixth column. Finally, the last column shows the percentage of rating consumed for the number of pulses at that level; for instance, at the 3200-V level, with four occurrences at a current of 1360 A, hence a rating of 500 pulses, the percentage consumed is 4:500 = 0.80 percent. The sum of the percentages of all levels is the percentage of rating consumed in one year. The number of years required to reach the rated value, shown at the bottom of the table, is the inverse of the yearly percentage.

For the selected example of a 32-mm varistor, rated 150 V and connected in a Category B location at medium exposure, 16 years would be needed 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 estimation example will be useful to illustrate the process and the types of reasonable assumptions that can be made. Consider a varistor installed in an appliance connected at some distance from the service entrance, still in Category B, medium exposure. Table II shows the corresponding pairs of occurrence numbers and levels, from which computations similar to those of Table II can be derived. We add some impedance to the 2-Ω value used in the preceding example, say

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)	Energy (joules) Deposited in a Suppressor* with Clamping Voltage of 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.

Fig. 3. Voltages and currents shown in ANSI/IEEE Std. C62.41-1980 (formerly IEEE 587) [3] as representative for Locations Categories A and B.

TABLE I
TIME TO REACH RATING FOR A 32-mm 150-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	620	12 380	6 190	6	0.5
10 000	0.04	580	9 420	4 710	15	0.27
8 000	0.11	550	7 450	3 725	25	0.44
6 000	0.32	520	5 480	2 740	60	0.53
4 500	1	560	4 000	2 000	150	0.67
3 200	4	480	2 720	1 360	500	0.80
2 400	6	460	1 940	970	1 000	0.60
1 700	22	440	1 260	630	3 000	0.73
1 200	80	430	770	385	9 000	0.89
800	390	420	380	190	60 000	0.65

Total Percent of Rating Consumed in One Year 6.08%
Years Required to Consume 100% of Rating 16

2 Ω for an 8/20-μs surge propagating in a few meters of wiring [8]. In this example, we compare a 20-mm varistor to a 14-mm varistor, both rated 150 V; the same value of expected clamping voltage is used for both devices (Fig. 4), and the resulting surge currents are computed, as shown in the fifth column of Table II. Referring to the respective pulse lifetime rating curves for the 20- and 14-mm devices (Fig. 5), we obtain the number of surges needed to reach the rating, shown in the next two columns, and compute the yearly consumption for each device at each level. Again, the totals are shown, with the resulting number of years required to reach the ratings: 20 years for the 14-mm device and 33 years for the 20-mm device, in the medium exposure environment.

Thus we have a method for estimating the ability of a varistor to function reliably in a particular surge environment. Clearly, the estimate is only as good as the assumption made about the actual environment: for instance, an assumption based on the generalized description given in [3]. Nevertheless, this method of estimating represents a reasonable and conservative approach to selecting device ratings for reliable operation, and to comparing between different device sizes.

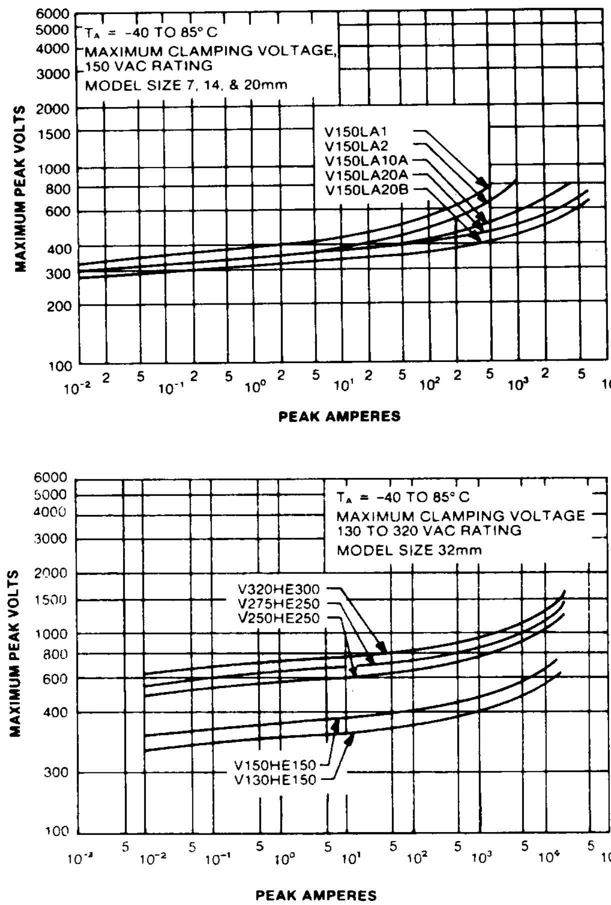
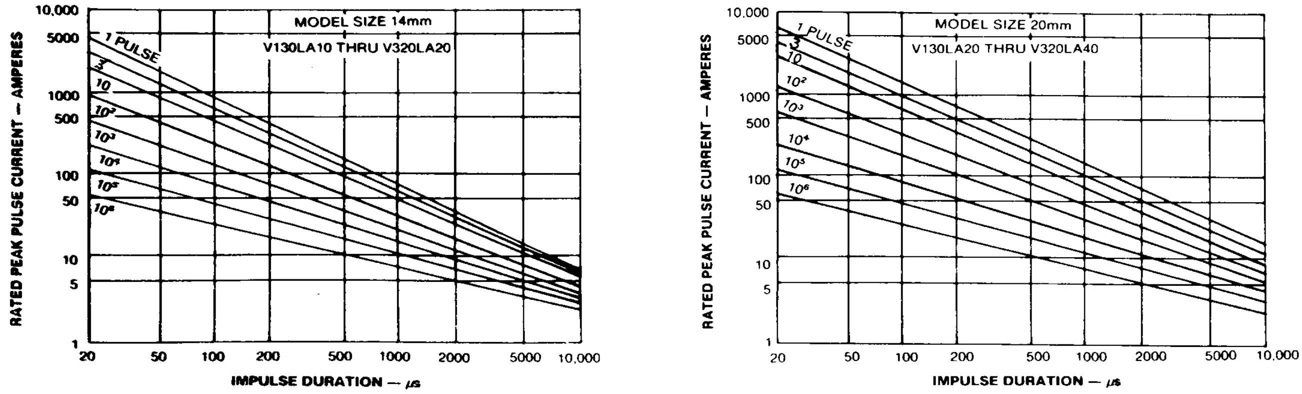
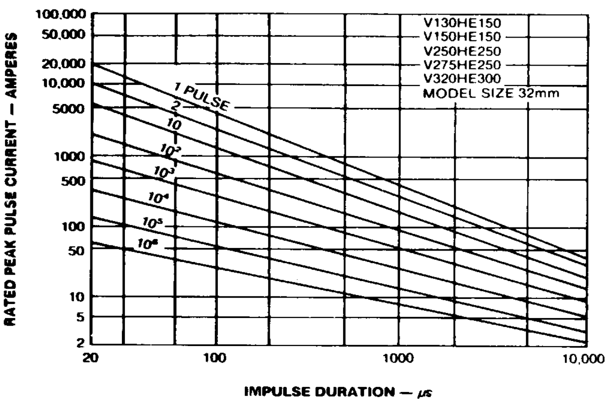


Fig. 4. *V-I* characteristics for 14-, 20-, and 32-mm varistors rated 150-V rms.

FUSE CONNECTION OPTIONS

Extreme surge values can occur which will exceed the predictions of limited-base statistics, so that one must take into consideration the case in which excess energy might be deposited in the varistor. Like any other electronic component abused in this manner, a varistor will fail, generally in a short-circuit mode. Depending on the available short-circuit current from the power system, the current flowing in the failed varistor can melt soldered connections or shatter the device.





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, value, but does not prevent the device from continuing to function. However, the varistor will no longer meet the original specifications.

Fig. 5. Pulse lifetime ratings for 14-, 20-, and 32-mm varistors rated 150-V rms.

TABLE II
TIME TO REACH RATING FOR 20- AND 14-mm 150-V VARISTORS IN MEDIUM EXPOSURE, CATEGORY B LOCATION

					14 mm		20 mm	
Voltage level of cells	Number of 8/20 occurrences	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
6 000	0.5*	550	5 450	1 360	40	1.3	80	0.6
4 500	1	500	4 000	1 000	80	1.3	200	0.5
3 200	4	460	2 740	685	300	1.3	800	0.5
2 400	6	430	1 870	465	1 000	0.6	1 500	0.4
1 700	22	400	1 300	325	10 000	0.2	10 000	0.4
1 200	80	380	820	205	60 000	0.1	20 000	0.4
800	390	370	430	107	150 000	0.3	200 000	0.2
Total Percent of Rating Consumed in One Year						5.1%		3.0%
Years Required to Consume 100% of Rating						20		33

*Surges above 6000 V are not likely to propagate in low-voltage wiring without causing operation of a protective device, or flashover of a clearance upstream [9], so that the varistor installed downstream in the Category B location will not be subjected to the energy associated with levels above 6000 V.

Since these ultimate failure modes are not generally desirable, the common practice is to provide a fuse in series with the varistor, in order to clear the fault from the circuit.

Two approaches can be considered for disconnecting a failed varistor by melting a fuse. In Fig. 6(a) the fuse in series with the load ensures that power is removed from the load in case of varistor failure. The load, then, will not be exposed, unprotected, to further surges. In Fig. 6(b) the varistor fuse in shunt ensures that the power supply to the load will not be interrupted by a spurious varistor failure. Thus the load is left undisturbed but unprotected from further surges. As pointed out in industry standards [1], one or the other of these scenarios may be preferred by users, so that defining a particular one as fail safe would appear misleading to those taking the opposite view. For instance, an application can dictate that maximum service continuity be ensured; Fig. 6(b) would then be labeled fail safe by those requiring this mode of failure. Other users, eager to protect their hardware even at the price of losing the function, would label Fig. 6(a) fail safe.

For the Fig. 6(b) configuration, the only requirement for the

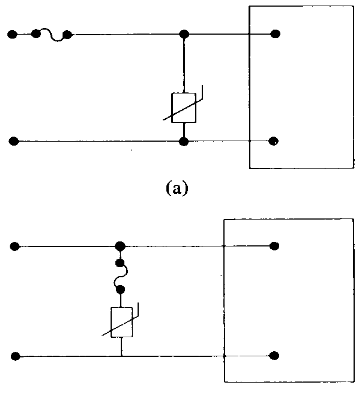


Fig. 6. Options for varistor fuse connection. (a) Protection maintained, function interrupted. (b) Function maintained, protection lost.

fuse is to ensure fast removal of a failed varistor, without blowing under the surges expected to flow from time to time in the varistor. The selection of this fuse, therefore, should reflect the expected surge currents. Unfortunately, data presently available from fuse manufacturers do not extend the i^2t ratings into the microsecond 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 a shunt-connected varistor with a fuse in series with the varistor.

It should be noted, of course, that while the operation of the fuse in the series connection (Fig. 6(a)) generally has 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 to determine the minimum ampere rating required to prevent the fuse from being blown by the surge currents diverted by the varistor at its expected point of installation. This minimum limit involves a current level for one surge and another level, presumably lower, for repetitive surges. Fuse sensitivity to the number of surges is parallel to the situation discussed for varistors, where the pulse lifetime is also a function of the number of surges.

Results of tests made on three types of commercial current-limiting fuses and one circuit board fuse wire are presented here to illustrate the effects of repetitive surges and to motivate a discussion of the issues and the sharing of information. The fuses were all rated 250 V, 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, differs primarily in the current-limiting characteristics. Here, we are concerned only with the element-melting characteristics. One fuse was a "fast fuse," rated 3 A, with a ratio of 13:1 for the melting currents at 1000 and at 0.01 s. The second fuse was a "time delay fuse," also rated 3 A but with a ratio of 37:1. The third, rated 10 A, has a ratio of 13:1. Fig. 7(a) shows an X-ray photograph of the 3-A fast fuse, Fig. 7(b) shows the 3-A time-delay fuse, and Fig. 7(c) shows the 10-A fuse.

As an alternative to the steep melting time-current characteristic (Fig. 8) of a fast fuse, the 'time-delay' fuse offers the possibility of surviving larger impulse currents. The larger ratio between 1000 and 0.01-s currents of the time-delay fuse maintains a comparable overcurrent protective capability at current values between the minimum melting current and the high currents associated with a short circuit, where the fuse may be required to melt in a relatively short time.

The test current waveform was the standard 8/20-μs impulse used for characterizing varistors and other surge protective devices. Fig. 9 shows such an impulse, for which the i^2t integral can be computed. For a 1000-A crest, the i^2t value of the 8/20-μs impulse is 19.5 A^2s.

Test Results on 3-A Fuses

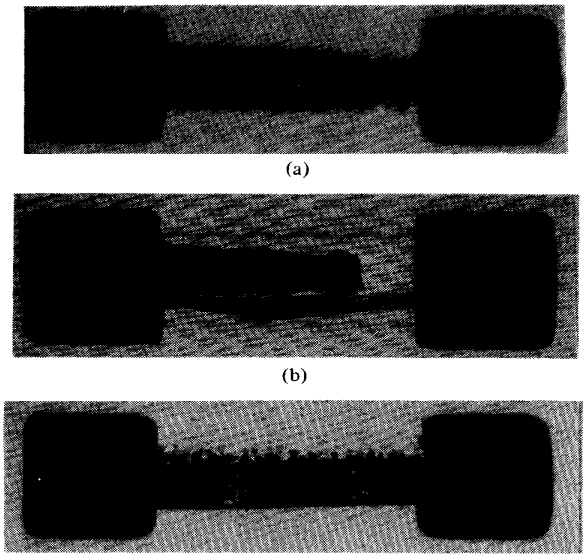
Melting curves for the 3-A fuse show a melting current of 46 A rms at 0.01 s, which corresponds to an i^2t of 21 A^2s. By subjecting each of ten fuses to a single-shot impulse in the range of 1000–1100 A crest, a one-shot melting current crest of 1050 A was established. This current impulse has an i^2t content of 21.5 A^2s, compared to 21 A^2s at 0.01 s with sine wave current. We will designate this observed single-impulse melting i^2t as I^2T. Likewise, the 3-A time delay fuse with a published 170 A^2s at 0.01 s was found to have an I^2T of 190 A^2s.

Repetitive impulses, at a rate sufficiently low to avoid accumulation of heat in the fuse, were applied to several groups of fuses. The impulses ranged from 90 to 30 percent of the melting current, corresponding, respectively, to i^2t contents of 81 to 9 percent of the observed I^2T. Table III shows the results for these two fuses.

Test Results on 10-A Fuse

The I^2T of this fuse, as defined earlier, was found to be 180 A^2s, somewhat less than the value expected from the published melting current at 0.01 s which would have been 220 A^2s. The purpose of the test at that point of the experiment was to find the amount of derating from the 8/20-μs I^2T needed to account for repetitive pulses, not to compare i^2t values at 8/20 μs to i^2t values at 0.01s. That would be an interesting further investigation.

Table IV summarizes the results of repetitive tests performed on three groups of ten each of these 10-A fuses. By comparison with the results on the 3-A fuses, the aging process is less noticeable: no effect is detectable at 36 percent I^2T and only a slight effect at 50 percent I^2T. One each of the fuses aged at 50 and 36 percent of I^2T was submitted to X-ray photograph; no visible sign was found of an alteration in the ribbon structure.



(a)

(b)

(c)

Fig. 7. X-ray photographs of test fuses.

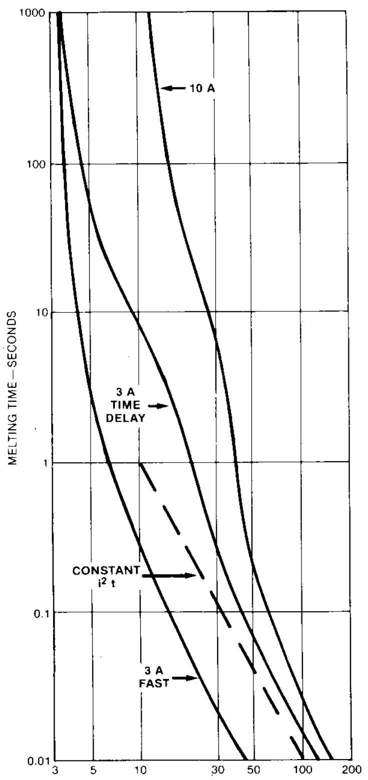


Fig. 8. Time-current characteristic of fast fuse and of time-delay fuse.

Test Results on Circuit Board Fuses

In some electronic printed circuit boards, a bare wire is sometimes used to provide a fusible link (with low interrupting capacity) in the circuitry. The same concerns on the effect of repetitive current surges that led to tests on commercial fuses also apply to these fuses. Some of the parameters influencing the behavior of such bare wire fuses were also investigated.

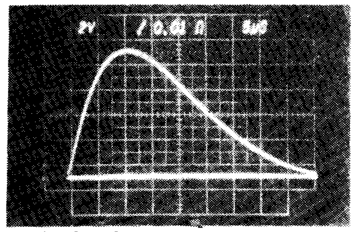


Fig. 9. Curent impulse of 8/20 μs.

Two silver wire sizes were selected as representative of what might be used: 0.005- and 0.010-in diameter. The I^2T of these wire was first determined with an 8/20-μs current pulse. For the 0.005-in wire, the I^2T is 16 A^2s, for the 0.010-in wire, it is 240 A^2s. This is consistent with the fact that the I^2T of a wire is proportional to the square of its cross section, but with a slightly lower value than expected for the 0.010-in wire. Since there was a suspicion that electromagnetic forces associated with higher surge currents might contribute to an earlier breaking of the wire than with lower surge currents, an experiment was conducted to vary this electromagnetic force.

In one test configuration, the fuse wire was spanning the space between two pads of the printed circuit, with the return path of the current flowing in an adjacent run only 5 mm away from the fuse wire. In the other configuration, the fuse wire was part of a straight line conductor with the return path 20 cm away. In this manner, two conditions could be evaluated, an unusually high and a negligible electromagnetic force effect.

For the close configuration at 95 percent I^2T, a visible stretching of the wire occurred after each successive shot. The wire broke at its middle point during the fifth to the seventh shot during several tests. Just prior to the last shot, the 20-mm long wire had been bowed away from the straight line with a maximum permanent deflection of about 5 mm.

For the remote return configuration, at the same 95 percent I^2T, no visible stretching of the wire occurred, and the wire withstood 14–25 shots before melting. Melting occurred at a point apparently randomly located along the wire length, probably due to a local wire defect which concentrated the heating process. At 90-percent I^2T, the wire withstood 200 shots before melting at a random point along the length.

These results indicate that indeed there is some contribution from electromagnetic forces at the high surge currents of interest associated with surge suppression. Therefore, mechanical fatigue of the fuse element can be expected after a high number of repetitive surges.

Discussion of Test Results

The results of these tests indicate that in order to avoid premature blowing of a fuse, the i^2t of the fuse should be selected such that the expected surge current will not exceed 25 percent of the observed I^2T required to produce one-shot melting of the fuse. Previous experience in semiconductor fuse applications [10] for semiconductor protection and cyclic duties, where the duration of the surges ranges from a fraction

TABLE III
EXPERIMENTAL RESULTS FOR 3-A FUSES

Fuse Type	% of I^2T	Number of Fuses in Group	Number of Shots On Each Fuse Before Melting	Effect Observed On Survivors
FAST	81	10	Minimum: 3 Maximum: 63	No survivors
	36	10	Minimum: 5 Maximum: 4 6 survived 200 shots	Nominal I^2T unchanged
	9	20	All survived 200 shots	Nominal I^2T unchanged
TIME DELAY	81	5	All at 2	
	64	5	All at 2 or 4	
	50	5	All survived 10 shots	
	36	10	All survived 100 shots	Average observed i^2t of aged fuse is 85% of nominal I^2T
	9	10	All survived 800 shots	Average observed i^2t of aged fuse is 90% of nominal I^2T

TABLE IV
EXPERIMENTAL RESULTS FOR10-A FUSES

% of I^2T	Number of Shots on Each Fuse Before Melting	Effect Observed on Survivors
81	Minimum 2 Maximum 12	No survivors
50	1 at 45 1 at 650 8 survived 800 shots	3 fuses out of 8 melt at 95% I^2T
36	All 10 survived 800 shots	Observed i^2t is unchanged from I^2T

of a second to a few seconds, had indicated that the i^2t of the fuse for these applications should be selected such that the expected surge i^2t would be less than 25 percent of the observed I^2T of the fuse. We find good agreement between this established empirical rule and the new observations in the microsecond range.

There are good reasons for this agreement. What we have called "observed I^2T" for a fuse is actually the sum of three parts of the heat deposition in the fuse:

1) heat necessary to bring the solid wire to melting temperature (this heat is about 70 percent of the total I^2T for typical metals used in fuse manufacturing at short melting times),
2) latent heat required to change the wire to the liquid state,
3) vaporization heat to cause rupture of the wire.

Clearly, a fuse wire that has been brought to its melting temperature will have experienced some change in its physical condition. Furthermore, the last restriction in the cross section, such as nicks or pinches, will accelerate this process of changed condition.

Another effect, one likely to become more significant with repetitive pulses, is that of alloying the fuse wire at its soldered connection to the fuse ferrule, if a soldered construction is used. Other tests made on fuse wires soldered directly in printed circuit boards have also shown this tendency. For this reason, some fuses are assembled by welding rather than by soldering. The exact behavior of course depends on the specific metals used and the geometries of the fuses, so that we should not attempt to make sweeping generalities. Rather, we suggest that the empirical 25 percent derating practice, long used in power semiconductor applications, is also applicable to wire-type fuses used with a varistor. Fuses using more rugged construction, or less severe notching of the elements, such as motor-starting fuses, have been successfully applied with a 50 percent derating. The results on the ribbon type 10-A fuse reported here tends to confirm this rule. This conclusion was not obvious *a priori*, since the dynamics of wire melting, vaporizing, and breaking may differ when they occur in a few, rather than thousands of, microseconds. Eventually, we might see manufactures provide data comparable to the varistor pulse lifetime, for which surge current peak, waveform, and numbers of occurrences will be taken into consideration.

CONCLUSION

Guides on the surge environment in low-voltage ac power circuits, such as [3], can be used to generate a reasonable definition of the duty imposed on surge protective devices. Varistors can be selected and compared for predictable performance by combining their pulse lifetime characteristics with the surge environment characteristics. Fuses connected in series with surge protective devices and therefore subjected to repetitive current surges will exhibit some aging process; selection of a fuse for a particular application requires an appropriate derating. The rule of thumb of selecting fuses for an i^2t rating of three to four times the i^2t of the seconds-long surges seems equally applicable in cases of microseconds-long surges. Small fuses will require a four times derating; larger fuses might be applied with a three times derating only.

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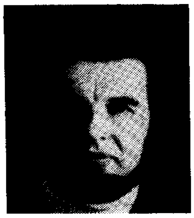

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