The effect of repetitive swells on metal-oxide varistors

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Significance - 2004 perspective
Part 7 – Protection techniques

Neither the effects of repetitive swells on metal-oxide varistors, nor the natural occurrence of swells had been documented in the literature. The paper briefly described a laboratory system capable of generating arbitrary swells and applying them to test varistors. A statistical experiment on five lots of varistors was performed and preliminary results reported. Effects of amplitude, duration, and number of swell occurrences were assessed, using as a criterion the change in varistor nominal voltage from before to after the swell sequence.

The factors that affect the varistor response are the amplitude of the swell, the duration of the swell, and the number of swells experienced in the life of the varistor. It seems that failure by thermal runaway occurs quickly when amplitude or duration settings are large. Failure caused by gradual aging (the classic 10% limit quoted by industry) appears to require a larger number of swells than those applied in the experiments conducted in what was intended to be the first phase of a continuing investigation.

While these results suggested an agenda for additional research, limited NIST resources prevented further investigation of the effect. We had encouraged all interested parties to contribute support and share new information on the subject, which might have provided significant information on the issue of varistor ageing/degradation, for which industry consensus has not yet been reached fourteen years later.

THE EFFECT OF REPETITIVE SWELLS ON METAL-OXIDE VARISTORS

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Abstract *— Neither the effects of repetitive swells on metal-oxide varistors, nor the natural occurrence of swells have been documented in the literature. The paper briefly describes a laboratory system capable of generating arbitrary swells and applying them to test varistors. A statistical experiment on five lots of varistors has been performed and preliminary results are reported. Effects of amplitude, duration, and number of swell occurrences are assessed, using as a criterion the change in varistor nominal voltage from before to after the swell sequence.*

MOTIVATION FOR A SWELL EFFECTS STUDY

Metal-oxide varistors, introduced in the early seventies, are used extensively as the basic nonlinear element in surge arresters built for electric utilities and in 'surge suppressors' for end-use protection at utilization voltage levels. These devices operate by diverting the surge currents away from sensitive loads and, in combination with the source impedance of the surge, limit the voltage across their terminals by a 'clamping' action. Thus, the prime function of the varistor is to offer a low (but not zero) impedance to surge currents, resulting in power being dissipated in the bulk material. For surges of short duration, the peak power can be high but the total energy deposited in the material during one typical surge event remains low enough to keep the material from reaching excessive temperatures.

Another power system disturbance involves a temporary overvoltage at the power frequency, with amplitudes ranging from a modest increase in the rms value of the line voltage to slightly less than twice the system voltage. The term 'swell' was proposed to describe this type of disturbance, and has now received acceptance in the U.S. engineering community [ANSI/IEEE C62.41]. Occurrences of swells have not been documented as much as occurrences of surges, but some data are now being collected and published [Hairabedian, 1992]. A question then arises on the possible effect that these small but long swells could have on varistor life, compared with the effect of short but large surges.

It is known that conducting high-peak current surges can cause a progressive degradation of the varistor material. Manufacturers of electronic-grade varistors have recognized this process, and publish "Pulse Rating" charts describing the permissible stress [Harris, 1990]. These pulse rating charts present a set of permissible values of the amplitude, duration, and number of occurrences of surges that will not produce a change of more than 10% in the varistor nominal voltage (the voltage corresponding to a 1 mA dc current).

Figure 1 shows a typical Pulse Rating chart, with pulse duration, pulse amplitude and number of allowable pulses before the varistor reaches the criterion of expended rating, that is, a 10% change in characteristics. The surges are understood to be repeated events with cooling between repetitive surges. The surge duration covered by the charts provided by the manufacturers ranges from 20 to 10 000 μs, and amplitudes from a few amperes to a few kiloamperes.

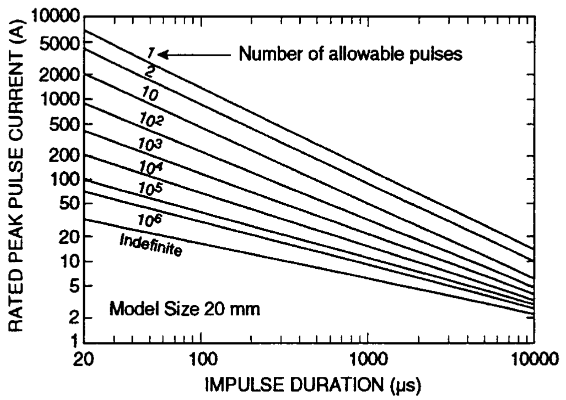

Figure 1
Pulse Rating chart for 20-mm dia. metal-oxide varistors

Armed with this information, designers can select a varistor size commensurate with the expected level of surges in the application of interest [Martzloff, 1985]. Nevertheless, anecdotes of unexplained varistor failures occurring in the absence of accurately documented high-energy surges are sometimes heard.

One of several possible explanations would be that varistors selected with a relatively low clamping voltage will be subjected to greater stress than varistors with a relatively higher clamping voltage when swells occur in the power system [Martzloff & Leedy, 1987]. The effect of repetitive swells on the durability of varistors is not discussed in the information provided by manufacturers.

Therefore, we speculate that an aging mechanism, perhaps similar to that characterized by the pulse rating charts, might be induced by the stress associated with repetitive swells applied during the lifetime of a varistor. Rather than identifying the aging mechanism itself — a task we leave to those versed in varistor physics or ceramics — we seek to establish an empirical but predictable relationship

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between, on the one hand, the amplitude, the duration, and the number of occurrences of swells, and, on the other hand, the aging of the varistor.

In keeping with the practice of the low-voltage varistor industry, we use as aging criterion the change in the nominal voltage. We have also considered measuring the power dissipation at the nominal ac system voltage, but have not implemented the more complex insertion of a wattmeter in the instrumentation sequence.

Ultimately, the duration-amplitude-number relationship for repetitive swells might be described by extending the pulse rating lines of Figure 1 to longer durations and lower amplitudes, or by creating an entirely new chart. Our purpose is to provide an initial set of generic data, based on several brands of varistors, that might motivate varistor manufacturers to provide their customers with a complete set of data. Combined with results of ongoing power-quality surveys that will give new data on the occurrence of swells, these swell rating charts, just like the existing pulse rating charts, would result in greater reliability in the application of metal-oxide varistors.

Another result of our work will be the in-house capability of producing well-controlled, arbitrary power-line disturbances of any waveform. These disturbances may be repetitive or single events. This capability will allow investigation of the effects of disturbances on end-user loads other than varistors.

STATISTICAL EXPERIMENT DESIGN

The objective of the experiment is to develop an empirical model relating the percentage change in nominal varistor voltage before and after application of the swell (called a response and labelled y) to the voltage amplitude (percentage above nominal line voltage), swell duration (number of cycles) and number of swells applied. The last three variables are called factors and are labelled x_1, x_2 and x_3, respectively. The technique of statistically designed experiments [Box et al., 1978] was used to generate valid experimental data. This technique uses a systematic approach to generate data which yield unambiguous results at minimum cost and time.

Changes in the varistor nominal voltage were measured in both the forward and reverse directions, giving nearly identical values. The analysis for the forward direction is presented here. The factor settings to be studied are given in Table 1.

For each lot a 2x3x3 full factorial design was run. This design consists of all combinations of settings of the three factors and hence has 18 (= 2x3x3) runs. Since the test rack can hold 20 varistors, two control varistors (no applied swell) were also included from the same lot.

Table 1
Factors and settings for the first experiment

Hits (Number of swells)	Duration (Number of cycles)	Amplitude (% above nomimal)
1	3	35
		45
		52
	10	35
		45
		52
	30	35
		45
		52
10	3	35
		45
		52
	10	35
		45
		52
	30	35
		45
		52

The 20 varistors were randomly sampled from a given lot. This was done for each of the five lots and hence 5 lots containing 20 varistors each were run for a total of 100 varistors in one experiment. The order of applied swell conditions was randomized to reduce the potential confounding of factor effects with any time drift effect.

Some care should be taken when making inference from these experiments to the population of varistors in the world. When we acquired approximately 200 varistors from each of 5 manufacturers, neither the manufacturers nor the varistors themselves were chosen at random or to be representative of their respective populations. Rather, we were given what was readily available from local distributors. This approach was simply motivated by the idea of expanding the data base to more than one source and thus obtain more general information. An additional motivation was to avoid the possibility of working with specimens specially selected by the manufacturer. Had we wanted to make inference, we would have selected manufacturers at random from all varistor manufacturers, and we would have selected varistors at random from several lots from each manufacturer.

Therefore, although the random sampling we do from our pool for each experiment allows us to make inference to the rest of the pool, we cannot safely make inference beyond that group in any formal way.

IMPLEMENTATION OF A SWELL SYSTEM

The swell system used in our experiment is a computer-controlled power source designed to deliver well-defined sinusoidal waveforms to large dynamic loads. A regulated ac source provides the nominal 120 V source to maintain the varistors energized before and after the swell. The swell itself is generated by momentary addition of a 60-Hz signal to a steady 60-Hz signal. The composite signal is then fed to a precision 3 kW amplifier capable of delivering 300 V swells at 10 A. Varistors to be tested are connected to the swell circuit by computer-controlled relays that apply the sequence of scheduled tests, including the initial and post-swell determination of the varistor nominal voltage.

The software allows the operator to define, for a given group of specimens, the three characteristics of swells as they would be defined by the results of power-quality surveys: voltage amplitude, duration, and number of occurrences. On the other hand, the stress in the varistors is likely to be associated with the current flowing in the varistor, which is determined by the relative voltage amplitude of the swell and the rated voltage of the varistor. Thus, the analysis of the experiment needs to focus on swell current rather than swell voltage.

By characterizing the nominal voltage of each specimen varistor before applying the swell, the system can introduce a scaling factor that will adjust the generated swell voltage to obtain a predictable swell current, which is the desired parameter for the statistical experiment. In this manner, the parameters of the experiment become the amplitude of the current (peak), the duration (number of cycles), and the number of applied swells (hits).

Figure 2 shows a block diagram of the swell generator. Several distinct subsystems operate to produce the controlled swells: a master control computer, a steady-state voltage source, a swell source (signal generator and amplifier) and a relay-controlled test rack. The parameters of the swell are recorded by instrumentation actuated by the controller. We give a brief description of the system, starting from the final stage – the varistors to be subjected to the swells and are installed in a test rack – and proceeding upstream to the other elements of the complete system.

Test rack and test sequence

The test rack allows the connection of up to 20 varistors to the various power sources and instruments involved in the measurements and application of the swell(s). These connections are performed by a set of relays actuated by the master controller. The test sequence involves the several stages described below. Before starting the test sequence involving the varistors, a self-test sequence is performed by the controller.

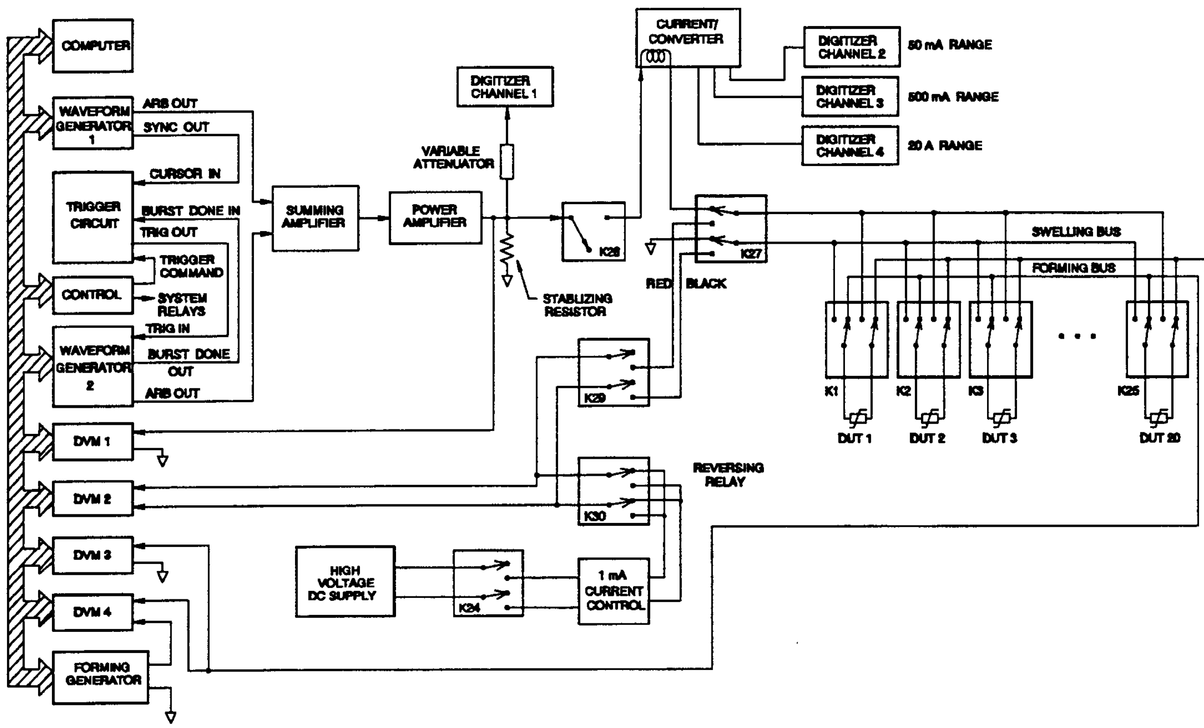

Figure 2
Block diagram of the swell system

A detailed description of the self-test sequence is beyond the scope of this paper. A brief description of the tests applied to the varistors will serve to provide information on the conditions of the experiment. The varistors, selected at random from one lot, are subjected to a steady 120-V stress that stabilizes their standby condition, an operation often called 'forming'. The varistors remain connected in parallel to the 120-V forming bus until subjected to a swell. The sequence, driven by the controller, unfolds as follows:

1. Disconnect the varistors from the forming bus, one at a time, to insert the varistor in a circuit capable of injecting a controlled 1 mA dc current (both directions) through the varistor. Record the voltage across the varistor at a fixed time after applying the dc voltage, to establish the nominal voltage of the varistor. Return the varistors to the forming bus.
2. Disconnect the varistor selected for swell application from the forming bus, and insert it in the swelling bus.
3. Compare the measured nominal voltage of that varistor with the average nominal voltage of the five lots (obtained from an initial characterization of the varistors), and let the controller compute the adjusted value of the swell amplitude to be applied to that particular varistor.
4. Apply the swell with the amplitude just computed, and a duration (number of cycles) preset by the experiment design. Record and store (digitally) the instantaneous values of voltage across the varistor and current through the varistor, for later processing.
5. As an option (selected before the test sequence is initiated), display on the computer monitor the voltage and current waveforms during the swell.
6. If the experiment design calls for repeated swells, allow a fixed cooling time for the varistor to return to room temperature (Figure 3), then apply the next swell called for by the experiment design.
7. Reconnect the varistor just tested to the 120-V forming bus, and start the swell-application sequence for the next varistor.
8. When the last swell of the sequence has been applied to the last varistor on the test rack, repeat step 2 to record the post-swell voltage at 1 mA dc.
9. Using the data stored during the application of the swell, initiate the computation of several parameters of the swell event, such as total energy deposited in the varistor, total coulombs transferred, percent change in nominal voltage, etc.
10. Initiate plotting of hard copies for the voltage and current during the swell, including the results of the computations, for each of the applied swells, followed by printing a summary sheet of the test data.

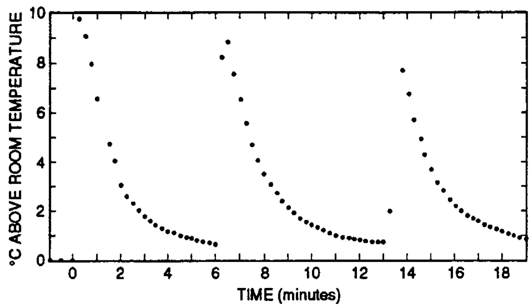

Figure 3
Temperature profile during repetitive swells

Power sources

Three power sources are involved in the swell system: the 120-V forming supply, the 1 mA dc source, and the swell generator. The 120-V ac forming supply is provided by a commercial calibrator that supplies a regulated sinewave to the bus of the test rack. The fixed 1 mA dc used for the measurement of the nominal voltage is obtained from an operational amplifier with sufficient voltage compliance to drive the 1 mA current at the varistor nominal voltage.

The swell generator consists of two parts: a pure sinewave generator and an arbitrary waveform generator that produces a sinewave of programmable value, synchronized with the first generator. The two low-level (10 V) sinewaves are added, producing a swell waveform. A linear power amplifier delivers the voltage waveform at the desired level, that is, 120 V rms before and after the swell, and peaks up to 300 V during the swell. The power amplifier is capable of delivering up to 15 A of peak current as the varistor responds to the swell according to its power law characteristic

$$I = A\ V^{\alpha} \qquad (1)$$

where:
V is the voltage applied to the varistor,
I is the resulting current through the varistor,
α is the characteristic exponent of the varistor material, and
A is a factor reflecting the dimensions of the varistor disc.

Instrumentation

Figure 4 shows a typical recording of a swell as printed after the test (step 9 of the sequence). Note the 120-V rms sinevawe before and after the swell, and the occurrence of the swell at the peak of the 120-V waveform. The timing of the beginning of the swell has been selected at the 90° point of the wave to avoid an offset in the transient response of the output transformer of the amplifier. The current has the typical peaked waveform of the highly nonlinear response of a varistor to an applied sinewave voltage. The plot program includes identification of the test number and results of computation of the parameters of the varistor response.

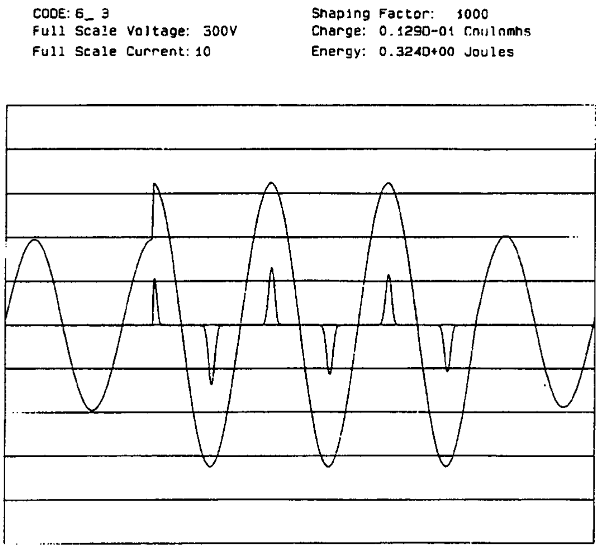

Figure 4
Typical record of a swell

The varistor current has a wide dynamic range, from milliamperes to amperes, while the desired plot has a linear scale. To obtain adequate resolution over this wide range, the instrumentation includes three current sensors in series, with a maximum range of respectively 50 mA, 500 mA, and 20 A. Each sensor has a digital output channel which is fed to the four-channel data acquisition card. The controller detects any saturation in the output of a channel, and automatically selects the next higher level channel to perform the plot and the various computations.

Controller functions

The functions of the controller are performed by an AT type computer with an IEEE-488 interface to provide the waveform parameters to the swell generator, drive the sequencing relays of the test rack, receive inputs from the voltage and current sensors, and provide an output to drive a laser printer. The controller is programmed in BASIC, providing a dialogue with the operator to select the test program according to the parameters defined in the statistical experiment design. This software allows a simple set of commands to initiate a test sequence that can involve tens of hours of test time for a set of 20 varistors to be subjected to many repetitive swells. The program also allows access to its 2000 lines of custom-developed code if modifications are desired in the options or operation of the system.

After a sequence has been completed, all the voltage and current data are stored in the hard-disk memory of the computer. These data can also be transferred onto diskettes so that the plotting can be performed through another computer with remote data processing capability.

The controller computer is then free to run another experiment while the printing of the plots — which can take several hours for a sequence involving printing out individual records of repetitive swells — can proceed without interference. Thanks to this custom program, the result of a long evolution of hardware and software development, we have been able to perform overnight test sequences, unattended, and find the results ready the next day. Running an experiment on a group of varistors is almost anticlimactic after the long series of experiments that were conducted during the development of the system. Now that the system is fully operational, we intend to run several more experiments to explore the range of possible swells and their effects. So far we have been able to conduct one experiment on five sets of 20 varistors, and obtain preliminary data on a second set with parameters close to the failure point for some combinations, as described in the next section.

ANALYSIS OF EXPERIMENTAL DATA

The objective of this analysis is to develop an empirical model relating percentage change in varistor nominal voltage (y) to amplitude (x_1), swell duration (x_2) and number of swells (x_3) and ultimately to identify swell conditions producing a 10% change in nominal voltage. First we perform a graphical analysis. Graphical analysis permits detection of outlying data points and allows the data to suggest an appropriate model form, rather than relying on prior assumptions about the form of the model. Once a candidate model is identified, the model is fit to the data by least squares regression [Neter et al., 1990]. The model is then validated. This validation involves checking that the assumptions made in fitting the model are reasonable. If they are not, the model is modified in an appropriate fashion and the entire process is repeated. This analysis approach is used for each lot of varistors. We will describe in some detail the analysis for one lot and present a summary of the results for the remaining lots.

Figure 5 gives a 3 x 3 matrix of scatter plots. The first row gives plots of nominal voltage change versus amplitude (x_1), duration (x_2) and number of swells (x_3). In each plot the vertical lines cover the range of data at the given x setting and the lines intersecting these vertical lines connect the mean at each x setting. These plots are used for detecting outlying data and checking in advance the assumptions required for least squares regression. The four assumptions of least squares regression are:

1. correct model
2. constant variation in each set of measurements
3. independent data
4. normality of the residuals

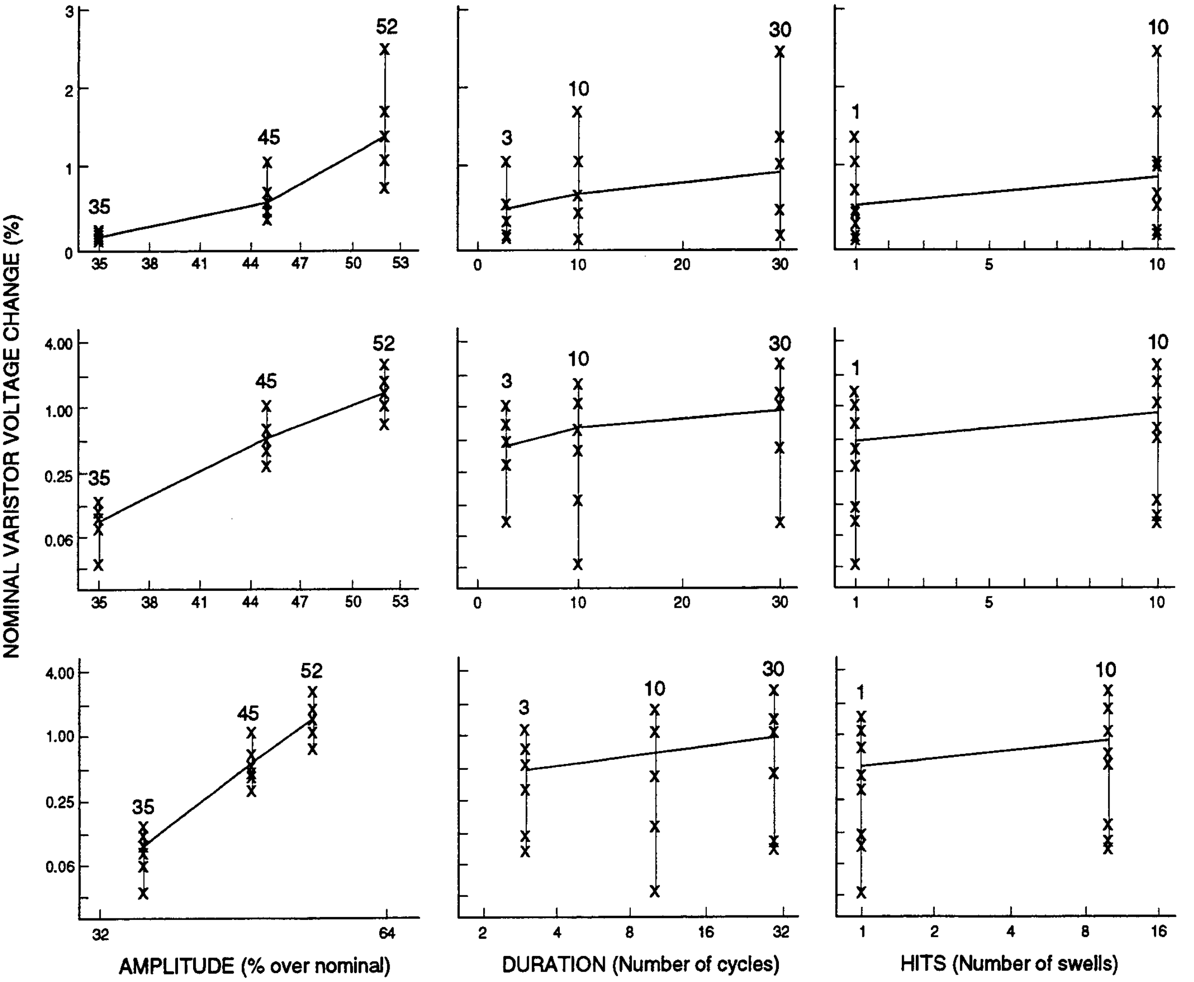

Figure 5
Plots of nominal voltage change versus factors (first row), log [voltage change] versus factors (second row) and log [voltage change] versus log [factors] (third row)

The fourth assumption is required only for performing statistical inference (such as hypothesis tests, confidence intervals, ...). From the first row of plots in Figure 5 we can see that the second assumption is violated. Variation in nominal voltage change is not constant, in fact it increases as amplitude or duration or number of swells increases.

There are several ways to correct this problem. One particularly effective way is to identify a transformation of the y's such that the transformed y's have constant variation. When the variation in y increases as x increases, a log transformation of the y's often yields transformed data having constant variation. The second row in Figure 5 gives plots of the log (y) versus the three factors. The log (y) clearly satisfies the assumption of constant variation better than the original y's. From this second row of plots we observe curvature in the plot of y versus amplitude and y versus duration (there were only two settings of number of swells, so curvature, even if present, cannot be detected). A second use of transformations is to simplify the relationship between the y's and x's. The bottom row gives plots of log (y) versus the log (x). We see that log (y) is now a linear function of log (x_1) and log (x_2). These plots lead us to postulate the following empirical model

$$y^* = \beta_0 + \beta_1 \log x_1 + \beta_2 \log x_2 + \beta_3 \log x_3 + \varepsilon \quad (2)$$

where $y^* = \log(y)$. (For lots C and E, $y^* = \log(y+0.1)$, since a few small negative values were recorded.) The term ε represents the combined effect of all x's that affect y, but have not been included in the model, and is called a "random error" term. By taking the exponential of both sides of equation (2), we obtain equation (3), a power model in the original units,

$$y = \beta_0^* \, x_1^{\beta_1} \, x_2^{\beta_2} \, x_3^{\beta_3} \, \varepsilon^* \quad (3)$$

where

$$\beta_0{}^* = e^{\beta_0} \tag{4}$$

and $\varepsilon^* = e^{\varepsilon}$. We fit the model (2) using least squares regression.

Note that this postulated model is linear in the log (x). It is entirely possible that a better model is obtained by including cross-product terms. We considered such models and concluded that they were not an improvement over model (2). The details in performing such tests can be found in [Neter, 1990].

The fitted model is given in equation (5)

$$\hat{y}^* = b_0 + b_1 \log x_1 + b_2 \log x_2 + b_3 \log x_3 \tag{5}$$

The terms b_0, b_1, b_2 and b_3 are least squares estimates of the parameters β_0, β_1, β_2 and β_3, respectively. The term $\hat{y}^*$ is the y value predicted by the fitted model at x_1, x_2 and x_3. The values $y^* - \hat{y}$ are called residuals. The model is then validated by a thorough graphical analysis of these residuals. Residuals without structure indicate a satisfactory model. This analysis was performed for each lot, see [Neter, 1990] for details on this type of analysis. The least squares estimates for the fitted model (5) for each lot are given in Table 2.

Table 2
Least square estimates for model (5) for five lots

LOT	Response variable	b_0	b_1	b_2	b_3	Residual standard deviation
A	log(y)	-13.4	3.09	0.09	0.29	0.46
B	log(y)	-12.04	2.98	0.08	0.18	0.19
C	log(y+0.1)	-24.55	5.99	0.28	0.29	0.31
D	log(y)	-27.48	6.86	0.17	0.22	0.31
E	log(y+0.1)	-18.77	4.48	0.25	0.28	0.35

In Table 2, the residual standard deviation is given for each fitted model and indicates how closely the model predicts the original data. We observe that the coefficient of amplitude (b_1) is substantially larger than that for duration or number of swells.

Once the empirical model is validated, we can interpret it. An effective way of interpreting such models is by contour plots. A contour plot displays "traces" (contours) which have equal values of the response, y, as a function of two x variables. Since we have three x variables, we generate contour plots for each setting of a third variable. Since x_3 (number of swells) has only two settings, 1 and 10, we generate two contour plots, one for each setting of x_3. Figure 6 gives two such plots for lot D.

The contours of nominal voltage change are plotted over the experimental region (amplitude 35 to 52% and duration 3 to 30 cycles). The maximum nominal voltage change contour over this region for 1 swell is 1.18% and for 10 swells is 1.95%. These fall well short of the desired change of 10%. The shape of the contour lines indicate that nominal voltage change increases more rapidly when amplitude is increased rather than duration (or number of swells) and therefore, to reach 10% nominal voltage change most rapidly, we should increase the amplitude.

The swell generator, however, has an upper limit of 15 A peak for the current it can deliver. For some specimens with low I-V characteristic, this limit is almost reached with a 52% voltage level and, therefore, the amplitude cannot be increased.

Since we are interested in applications of one to thousands of swells, we need to increase swell duration if the criterion of 10% change is to be reached after only a few swells. Informal tests were run at longer swell duration to determine the duration required to identify the point at which a 10% change occurred or the varistor burned out. This point was identified and a second experiment was planned in this region.

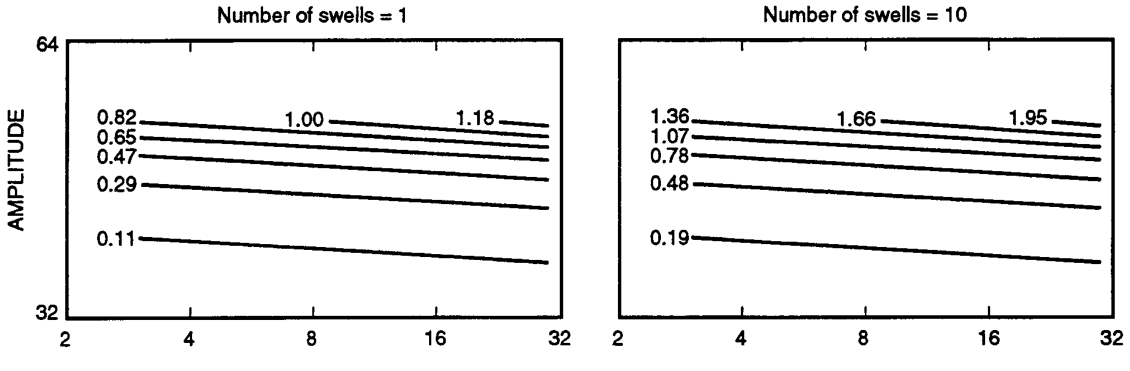

Figure 6
Contours plots of amplitude versus duration with nominal voltage change contours for 1 and 10 swells

Since nominal voltage changed very little at 35% amplitude, this setting was dropped, and a third setting of number of swells (30) was added. Also, the duration now depends on the number of swells. For example, 30 swells of 600 cycles each could be too severe and 1 swell of 6 cycles too mild. A 2x3x3 full factorial design with two controls was planned for each lot, similar to the first series, but with the new settings, as shown in Table 3.

Table 3
Factors and settings for the second experiment

Amplitude (% Above nomimal)	Hits (Number of swells)	Duration (Number of cycles)
45	1	60
		180
		600
	10	18
		60
		180
	30	6
		18
		60
52	1	60
		180
		600
	10	18
		60
		180
	30	6
		18
		60

Tests on new varistors from the same five lots were performed with the new settings shown in Table 3. A thorough statistical analysis is currently underway. However, inspection of the test results already provides interesting information.

First, the point of failure, which was not reached in the first experiment, was reached for three lots. Several varistors failed in short-circuit mode, indicating that the new settings might be within range of significant change.

Second, none of the five sets of lots had degradation close to 10%. Most varistors tested degraded less than 2%, while a few completely failed. A graphical analysis of the data for one lot indicates that the failures that did occur were for settings of long duration and high amplitude (Figure 7). However, no quantification of this apparent phenomenon has been done at this time. In the discussion below, we offer some speculation on what may be the cause of this behavior.

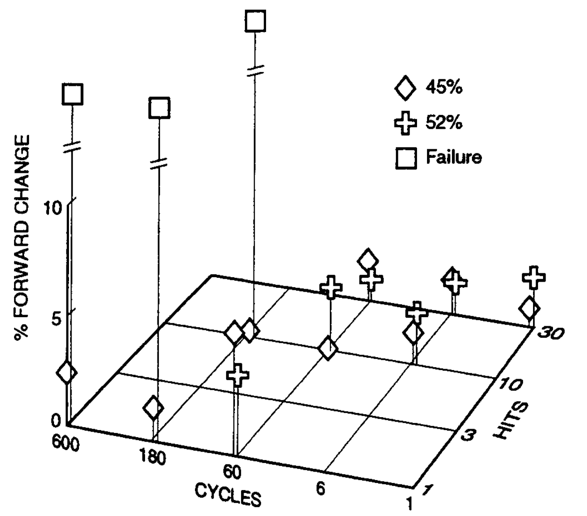

Figure 7
Three-dimension plot of failure distribution for two swell amplitudes: 45% and 52% - shifts and failures

DISCUSSION AND DIRECTION OF FUTURE WORK

Test results

The results obtained in the two experiments reported here are the beginning of a more comprehensive series of experiments from which more general conclusions will be drawn. Nevertheless, we can make several observations that will guide us toward the next series.

From the first experiment, we obtained statistical confirmation that the most powerful factor for change is the amplitude of the swell (the high value of coefficient b_1 in Table 2). Given the nonlinear response of the varistors, we can expect this finding. The other two factors, duration of the swell and number of swells, were found quite smaller and of comparable magnitude.

This statistical finding that duration and number of swells have comparable effect must be reconciled with intuitive expectations. We would expect a difference in the behavior of varistors exposed to a few long-duration swells versus varistors exposed to many short-duration swells. We can readily accept that the longer the swell, the higher the temperature reached in the body of the varistor [Martzloff & Leedy, 1987]. To validate this expectation, we applied a sequence of 10 swells of 60 cycles each (a total of 10 seconds), allowing the varistor to cool between swells. That test is illustrated in the profile shown in Figure 3. The highest temperature rise of the surface was less than 10 °C, and the actual temperature returned to room temperature before application of the next swell. Then, we applied to the same varistor, with the same swell amplitude, an uninterrupted swell of 10 seconds. In that second test, the temperature rise at the surface reached 45 °C.

Varistor aging considerations

Not knowing the physics of varistor aging, we can speculate that the internal temperature of the varistor body (higher than the measured surface temperature) plays a dual role in the process. On the one hand, the accumulation of small temperature rise events — repetitive 'benign' swells — may be the aging mechanism that we are attempting to accelerate by our laboratory tests. On the other hand, a single, large temperature rise caused by a large swell may launch a thermal runaway of the varistor, without involving much aging.

Examination of the plot of Figure 7 shows two distinct behaviors of the test varistors. Among those that failed catastrophically, two were exposed to a single long duration swell, one failed during a sequence planned for 10 swells. The data stored by the computer include all the swell history for each application; by searching through the records we will be able to pinpoint the time of failure within one exposure to the swell(s) and refine the statistical analysis.

Looking at the pattern of voltage changes for varistors that did not fail, we see only a maximum of 4% for one, the rest being less than 2%. That behavior may be genuine aging, as opposed to catastrophic failure caused by thermal runaway. These varistors might have aged further if a greater number of swells had been applied.

Our software system includes the acquisition and storage for time, voltage, and current. From these data, the total energy deposition (joules) and total charge transfer (coulombs) are computed for each swell. A statistical analysis of these parameters might reveal a stronger correlation for one of those energy or charge parameters, pointing toward a hypothesis on the nature of the effect.

In summary, increasing the amplitude of the swells could produce faster aging, as long as the temperature rise during a single swell will not reach the thermal runaway threshold. Increasing the duration of the swell does bring the varistor quickly to this threshold. That situation could point toward short swells of high amplitude, but our system does not produce these high swell currents. Furthermore, a 1-cycle (16 ms) swell current amplitude of more than 10 A begins to look very much like a 16-ms *surge*, a stress defined on the long time range (10 000 μs) of the pulse rating chart of Figure 1.

Therefore, our next direction will be toward increasing the number of swells. We will apply those amplitudes and durations in the ranges used during the second experiment that did not produce failure, but substantially increase the number of swells and observe whether the changes increase beyond the present 2-4% range.

An alternative approach might be to accelerate the process by conducting the experiment at higher ambient temperatures, on the assumption that some Arrhenius-type relationship could be found. The manufacturers' data show such a relationship for aging under exposure to rated line voltage [Harris, 1990]. However, to make this demonstration, several ambient temperatures must be applied to allow extrapolation, introducing the risk of modifying the failure mechanism. Therefore, with the limited resources available at this point of the investigation, we prefer conducting the experiments at room temperature, rather than introduce one more variable in the process.

ACTION ITEMS

Just as we are seeking new knowledge on the effects of repetitive swells on varistors, we clearly need to find out more about the occurrence of swells in practical applications. When the two bodies of information will have matured, then it will be possible for application engineers to consider the aging effects of swells, as they do now for the pulse ratings. Therefore, we can define an agenda for future work, inviting the surge-protection engineering community to participate:

1. Characterize swells as they occur in power systems

- How often do swells occur?
- How long are these swells?
- How large are these swells?

Several organizations are currently conducting surveys of power quality on low-voltage power systems. Some of these have been published [Hairabedian, 1992], while others remain unheralded or proprietary. In the past, emphasis was often given to characterization of surges. More recently, characterization of harmonics has become a subject of intense interest. To these disturbances, we now add swells as a subject that needs more attention, in view of the anecdotes of varistor failures. Sharing information on the data collection is a must, if the situation is to be corrected.

2. Conduct further experiments on aging caused by swells

- Increase the number of swells in a sequence
- Investigate acceleration by ambient temperature
- Extend the range of specimen collection
- Correlate aging with joules and coulombs

We intend to conduct further research on these items, but also invite other researchers to join in the quest, and share the results.

3. Investigate the physics of aging caused by swells

As non-specialists in this field, we refrain from making any suggestion, but invite a dialogue with interested parties.

4. Combine, share, and recommend

These three areas of research, if pursued aggressively, reported candidly, and shared openly, will serve as the basis for a new consensus on varistor applications.

CONCLUSIONS

1. Applying swells produced by a computer-driven system is a practical method for subjecting varistors to repetitive swells under controlled conditions.

2. The factors that affect the varistor response are the amplitude of the swell, the duration of the swell, and the number of swells experienced in the life of the varistor.

3. It seems that failure by thermal runaway occurs quickly when amplitude or duration settings are large. Failure caused by gradual aging (the 10% limit quoted by industry) appears to require a larger number of swells than those applied in our current experiments.

4. These results suggest an agenda for additional research. We encourage all interested parties to contribute and share new information on the subject.

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