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Characterization of Triggered Vacuum Switches for High Current Operation

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Abstract—Triggered Vacuum Switches show promise for use in high-power, high-current and high-frequency conversion and switching circuits. Their specific power and power density ratings are well above silicon devices. TVS are robust devices that can survive faults that would destroy other types of switching devices. In addition, TVS are capable of fast recovery. However, there is not much performance data at high current and frequency and TVS are unable to recover reliably under reversing current and voltage conditions after passing a peak current greater than 20 kA. This paper describes the results of tests performed to obtain a wide variety of characteristics, including V/I characteristic, ability to share current, and ability to recover when a reverse voltage is applied.

INTRODUCTION

Triggered vacuum switches (TVS) show promise for use in very high-power, high-current and high-frequency conversion and switching circuits. Their specific power and power density ratings are well above those of silicon devices. TVS are extremely robust devices that can survive over-voltage, over-current, and reverse-current faults that would destroy other types of switching devices. TVS are also capable of extremely fast recovery. As a result, they can be used in higher frequency circuits than large diameter, high-voltage SCR that require several hundred microseconds to recover. In addition, the TVS' low cost per kilowatt make it attractive for use in switching circuits that would otherwise require the use of large series and parallel arrays of silicon devices.

The main difficulties in designing with TVS are the relative lack of performance data at high current and frequency and the apparent inability of the TVS to recover reliably under reversing current and voltage conditions after passing a peak current greater than 20 kA.

This paper describes the results of tests performed to characterize the TVS under a wide variety of operating conditions, including high frequency (0.5 to 2 kHz) V/I characteristic, ability to share current when connected in a parallel switch array, and ability to recover when a reverse voltage is applied following current zero of a sinusoid.

PRIOR RESEARCH ON TVS RECOVERY CHARACTERISTICS

Several researchers have investigated the performance of the TVS in a variety of test conditions. Most of this work has been at either low peak current, low frequency, or low reverse recovery rate. Lauer [1] reported TVS recovery at a peak current of 75 kA and a di/dt of 5 kA/ μ s, however recovery rates were relatively low (between 40 and 380 V/ μ s). Rich [2] reported successful recovery up to 5 kV/ μ s for very low current (<1 kA) and low frequency. Dethlefsen [3] performed tests on the TVS-40 and reported reliable recovery up to near 45 kA, with a current fall rate near 220 A/ μ s and a voltage recovery rate of 10.8 kV/ μ s. In addition, successful recoveries were achieved in the 90 kA range, however the recovery probability was below 50%.

Some researchers have investigated the use of circuit elements to aid the TVS in recovery. Anderson [4] used saturable and linear inductors in series with the TVS to aid recovery; however peak current was only 10 kA. Gorman [5] applied a magnetic field parallel to the axis of the switch, but reported recovery at 24 kA with a low recovery rate of 90 V/ μ s.

DESCRIPTION OF THE TEST CIRCUIT

The test circuit, shown in Fig. 1, was designed to simulate one phase of a multiphase generator. The switch tester consists of two 1.2 to 9.7 mF capacitor banks and two 0 to 17.5 μ H inductors. Both can be varied to apply a wide variety of switch stresses to the device under test (DUT). The tester's maximum charge voltage is 11 kV, and it is capable of producing a maximum output current of 500 kA. In its present configuration, one bank is charged while the other bank acts as the load. This configuration produces a half sinusoid while applying reverse voltage to the DUT as soon as it begins to clear. A typical data set collected from a test is shown in Fig. 2. The DUT, in this case an unassisted TVS-40, recovered following current zero.

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Fig. 1 Simplified test circuit.

Fig. 2. Typical response of the test circuit with a recovering switch.

CHARACTERISTICS OF THE TVS-40

The triggered vacuum switch used in all tests was the Russian TVS-40 that is marketed in the US by Maxwell Laboratories, Inc. That device is closely based on a switch developed by GE in the late 1970's [6]. The device is a multiple-rod-electrode TVS designed to operate in the diffuse arc mode. Its recommended peak operating parameters are 100 kA and 25 kV at 60 Hz [3].

Over 600 tests were completed to characterize the behavior of the TVS-40. Data compiled include current/voltage characteristics over a variety of frequencies, current sharing characteristics at different anode voltages, and recovery characteristics under various conditions.

V/I Characteristic

The voltage-current characteristics of the TVS-40 are shown in Fig. 3. The current and voltage were both taken at the time of peak current ($di/dt=0$). The data includes tests

Fig. 3. Voltage-current characteristics of the TVS-40.

using three different TVS-40. The manufacturer's published characteristic is shown for reference [3]. The other curves are linear fits of data taken in test. The manufacturer's data shows the voltage increasing nearly linearly with current to approximately 50 kA, then becoming flat at about 105 V through approximately 130 kA. No data in this test set is below 20 kA, so the increase from zero is not shown. In addition, the data taken in these tests did not flatten between 50 and 130 kA, but instead sloped upward at a rate that appears to be dependent on time to peak current. Another difference from the manufacturer's data is the magnitude of the voltage drop. The data closest to the manufacturer's is that taken from tests where the time to reach current peak was 500 μ s. Tests with times-to-peak shorter than 500 μ s exhibited markedly higher voltage drops. Tests at shorter times were repeated several times to verify the result. This result is significant because a converter designed to operate on a line with a fundamental frequency of 600 Hz will be subjected to times to peak current of 250 μ s or less, particularly when the converter is under phase control or is inverting. One researcher has observed this high voltage drop at high di/dt and suggested that the impedance of the switch remains high until the injected and generated plasma completely fills the volume of the switch and the gap capacitance is drained [7]. If the rising current outruns the turn-on process of the switch, then the voltage drop is high. Once the TVS has had time to completely turn on, the voltage drop is reduced, as can be seen in Fig. 2.

Current Sharing

A series of tests was performed to measure the current sharing characteristics of the TVS. The circuit was different from that described above. Less capacitance was used and the circuit elements were designed for near-critically damped opera-

tion. In addition, three TVS-40 were connected in parallel with bus work carefully designed to ensure minimal effect on current sharing characteristics. Typical results of those tests are shown in Fig. 4 and 5. Fig. 4 shows the currents resulting from a 1 kV discharge. The worst current mismatch is 40% from nominal. However, at low anode voltage, the total circuit current is likely to be small, so designing a parallel array so that no one device carries excess current would not be a problem.

Fig. 4. Current sharing after low initial anode voltage.

Fig. 5. Current sharing after high initial anode voltage.

Fig. 5 shows three TVS-40 sharing current from a 2.8 kV discharge. The applied anode voltage is only 9% of the rated voltage, yet the three devices share current nearly equally. Clearly, the self-correcting nature of the TVS' positive voltage characteristic helps to force sharing, particularly at higher anode voltage.

Reverse Recovery

The ability of the TVS to clear and recover its voltage withstand capability is extremely important to the design of a high-frequency, high-power converter. Two hundred and fifty tests were performed to apply different currents, recovery voltages, di/dt and dv/dt to the TVS. The recovery data for these tests is plotted in Fig. 6. The data is marked according to the range of peak current and whether or not the TVS recovered. Closed symbols indicate successful reverse recovery; open symbols indicate failed reverse recovery. In addition, the manufacturer's data for recovery is shown as solid lines that represent regions of recovery probability.

The data from test correlated well with the manufacturer's data in the less than 50% and the 50% recovery probability regions. However, in the 90% and 99% regions, the recovery success was less than predicted. The recovery rate in the 90% region was 60%, and the recovery rate in the 99% region was 85%.

The data suggest that peak current carried prior to current reversal plays a role in recovery. In fact, low current tests skew the data somewhat because one-third of the tests had a peak current of 20 kA or less. All of those discharges resulted

Fig. 6. Recovery data for TVS-40 operated singly.

in successful recovery. Furthermore, note the grouping of six unsuccessful data points just above the 200 A/ μ s mark at low dv/dt. These tests had a peak current of 72 kA to 75 kA. There is a corresponding set of eight closed triangles also at approximately 200 A/ μ s in the same current range (but at a much higher rate of voltage rise). In addition, there are groupings of successful recoveries at lower peak currents but similar rates of current fall in the 90% successful recovery range. Table 1 illustrates this trend by showing the successful recovery percentage by peak current range when operating within the predicted 99% and 90% recovery probability regions.

Fig. 7 shows two recovery traces, one successful and one unsuccessful. The conditions of the successful recovery were 72 kA, -205 A/ μ s, and -6.4 kV/ μ s. If the recovery time is defined as the time from the beginning of the buildup of reverse voltage to the time when the peak voltage is reached, then the recovery time for this test was 1.7 μ s. This time is typical of all of the recovered tests. Including all successful recovery tests, the average recovery time was 1.6 μ s.

Table 1. Recovery rates by range of peak current

Peak Current Range (kA)	Successful Recovery (%)
0 – 20	100
20.1 – 40	95
40.1 – 80	75
80.1 – 100	50

Fig. 7. Reverse voltage measured across a TVS-40.

Although recovery times ranged from 0.7 μ s to 2.8 μ s, most of the times were near the average. The standard deviation was only 0.3 μ s. The time to peak recovered voltage before collapse in the failed recovery test was 1.2 μ s. It appears from the plot that if recovery had proceeded successfully, then the recovery time for this test would have been nearly the same as the previous test. The parameters of this test were 72 kA, -202 A/ μ s, and -6.5 kV/ μ s. While peak current and recovery rates do have an effect on recovery probability, they do not seem to affect recovery time.

The rate of re-application of voltage does not seem to have as large an effect on recovery as do di/dt and I_{pk} . The ranges of reapplied voltage for successful and unsuccessful recovery were the same (0.5 kV/ μ s to 11 kV/ μ s). This includes data from recovery tests performed under current sharing conditions, shown in Fig. 8. However, there is a difference in the ranges of the rate of current fall. For successful recoveries, the di/dt range was 20 A/ μ s to 550 A/ μ s. For unsuccessful recoveries, the range was 118 A/ μ s to 1000 A/ μ s. The highest di/dt recovered by peak current range is shown in Table 2, and the lowest di/dt not recovered by current range is shown in Table 3. The divisions for current ranges are the same as those used in Table 1.

This observation seems to be supported by the results reported in [3]. In an effort to improve recovery performance, snubbers were added to the TVS to limit dv/dt but resulted in only a marginal improvement in recovery. In addition, two TVS were connected in series in order to divide dv/dt. Once again, the improvement in recovery performance was small.

Fig. 8. Recovery data for two TVS-40 connected in parallel.

Table 2. Highest di/dt recovered by current range

Peak Current (kA)	Rate of Current Fall (A/ μ s)
20.1	133
40.1	257
76	300
99	550
Currents at top of range	

Table 3. Lowest di/dt not recovered by current range

Peak Current (kA)	Rate of Current Fall (A/ μ s)
21	26
44	118
81	230
Currents at bottom of range	

The recovery performance of the TVS when two were connected in parallel was markedly worse than the performance of a single device. Successful recovery was defined as reverse voltage sustained by both devices following current zero. Successful recovery occurred in only 10% of the tests. The recovery data is summarized in Fig. 8. The reason for the very high rates of current fall for some tests is that often one switch would block voltage while the other continued to carry current. In these tests, the main current was commutated into the failing device, so di/dt doubled.

CONCLUSION

The poor recovery performance of the TVS at high current would seem to preclude its use in high-power converters. However, its other attributes, when compared to other switching devices, are very attractive. The recovery performance can be enhanced greatly through the use of recovery-assist components such as saturable reactors, active magnetic assist, series diodes, and a switched parallel branch that allows the TVS to recover under favorable conditions.

The use of saturable reactors to improve the performance of TVS has been attempted by at least three researchers [3],[4],[7] with mixed results. In addition, the amount of magnetic material needed to provide the required volt-second rating may be quite large. Active magnetic assist (the application of a Lorentz force to the arc particles to force gap clearing) has been proved in principle and requires further development [5]. In addition, research into other recovery assist methods is expected to result in devices that can be used successfully in very high power converters.

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