EVALUATION OF SOLID-STATE CROWBARS AND GAS-DISCHARGE TUBES IN CATV SURGE SUPPRESSION APPLICATIONS

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Abstract

Gas-discharge surge arrestor tubes and the recently-introduced solid-state AC crowbars perform identical surge suppression functions in CATV systems, but each operates on very different principles and possesses different performance limitations. CATV equipment must withstand two distinctly different types of surge phenomena, and each surge suppression device is uniquely suited to protect from the effects of a particular type and level of surge. Analysis of both equipment failure and field test data is used as a guide in the selection of appropriate surge protection devices, which are then tested to determine their relative strengths.

INTRODUCTION

"Outages" are a major issue for the CATV industry, and the primary cause of service outage is equipment damage (or blown fuses) from exposure to surge voltages and/or currents in excess of design limits. Bonding, grounding, and equipment ruggedness have increased significantly, but no matter how much the design limits are improved, surge suppression devices are required to suppress surges in excess of the limits. With the move towards elimination (or up-sizing) of fuses, the surge suppression devices have become the "weak link" in the system.

Meanwhile, the primary protective devices have improved performance and ruggedness. Solid-state devices have advanced from their secondary role so that they now rival the performance of traditional primary devices. Unfortunately, the devices have fundamentally different characteristics and limitations, and direct comparison of device capabilities has been difficult because the device performance is stated under different conditions. The purpose of this work is to compare the performance of the different types of surge protection devices under conditions which are appropriate to CATV applications.

SURGE CHARACTERISTICS

While the electrical term "surge" is most often meant to define a potentially damaging temporary increase in circuit voltage, the term "power surge" is more accurate in defining this condition as it relates to CATV equipment.

This is because any surge protection device that does not function by disconnecting the protected equipment causes an increase in circuit current and power as the voltage is clamped to an acceptable level. (While a "disconnecting" type of surge protector would be desirable, such devices are too slow and/or not suitable for use in RF circuits.)

Electrical surges may be divided into three general groups based on duration and amplitude. The most common type of surge is of relatively low amplitude, and in most CATV applications, any surge that does not result in a voltage increase of more than 50% may be disregarded. Surge events that cause voltage increases over 50% will be defined as either long or short duration, with a dividing line of 1 milli-second.

Short-duration surges (also known as "impulses") due to lightning strikes and switching transients are well-known and have been characterized by the IEEE for various applications, which unfortunately do not include CATV. The "IEEE Guide for Surge Voltages in Low-Voltage AC Power Circuits," (ANSI/IEEE C62.41-1980, formerly designated IEEE Std 587-1980) establishes standards for devices connected to 120 VAC power, and their location category "B" (for major indoor feeders and short branch circuits) appears to be a worst-case for CATV applications.

Two impulse waveshapes are defined by the IEEE, a 100-kHz oscillatory wave of .5 micro-second rise time decaying by 60% every 10 micro-seconds, and a uni-directional impulse of 1.2 micro-second rise time with 50 micro-second decay ("1.2 x 50 uS") for high-impedance loads and 8 micro-second rise time with 20 micro-second decay ("8 x 20 uS") for low-impedance discharge current. Amplitudes for these waveshapes are defined as 6000 Volts for 100 kHz and 1.2 x 50 uS high-impedance waves, 3000 Amps for the 8 x 20 uS low-impedance wave, and 500 Amps for the 100 kHz low-impedance wave. While power dissipation in a surge protector can be quite high (up to 900 kW peak), total energy is low (about 10 Joules) due to the short duration of the surge.

Long-duration surges due to imbalances in distribution system powering range upwards from 1 milli-second to many hours. While the 60 VAC cable power system would appear to be isolated from the effects of power distribution fluctuations by the regulating qualities of the line power supply's ferroresonant transformer, Herman and Shekle showed how current sharing between the power company's neutral conductor and the CATV system's cable sheath can cause significant increases in cable voltage. The power company uses primary fuses and circuit breakers to interrupt high-amplitude imbalances and overloads over 200 Amps, but these devices can take up to 11 cycles to activate. Power dissipation in a surge protector can be moderately high (over 60 kW), but total energy (10,000 Joules over 11 cycles) can be tremendous.

FIELD EXPERIENCE

It is possible to deduce a significant amount of information regarding the type and magnitude of CATV surge phenomena by studying field failure patterns and equipment failure modes. Over a two-year period, the equipment failures were concentrated near the ends of powered segments (normally the lowest voltage points), and even oversized Metal Oxide Varistors (MOVs) experienced catastrophic failures at these points. Since many failures occurred during clear weather, they did not appear to be statistically coincidental with lightning storms (although the study areas were located in high-lightning portions of the country).

When the CATV system's DC power supplies were ruggedized to withstand peak input voltages of 400 and 500 Volts (up from 150 Volts), failure rates were substantially reduced even when other types of surge protection was removed. Often, MOVs would fail in the open condition with no other failures in the ruggedized equipment. As will be shown, MOVs offer good protection from short-duration surges, but do not provide appropriate protection against long-duration surges. All the data pointed away from the short-duration impulses, strongly implicating the long-duration surges as the major cause of equipment damage.

While equipment ruggedization resulted in substantial reductions in failure rates, an opportunity for further study occurred at a site experiencing a unique failure mode (multiple instances of circuit conductor destruction at a single location) along with a higher than normal overall failure rate. An "RMU" (Remote Monitor Unit) commercial surge monitoring device was obtained, and a custom interface was constructed to facilitate its use in CATV systems. The equipment, which was intended to measure short- and long-duration surge voltages on the 120 VAC power line along with voltage differences between line neutral and safety ground, was selected specifically for its small size, low power consumption, and unattended operating capability.

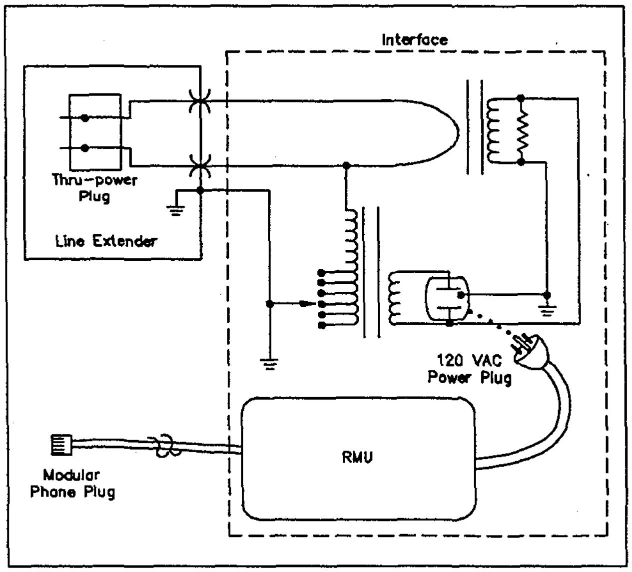

Figure 1.
Remote Monitoring Interface for CATV

The CATV interface enclosed the RMU, allowed it to be powered by (and to monitor) the cable system's 40-60 VAC power with negligible loading effects, and adapted the neutral-to-ground feature to measure center conductor current surges. A detailed functional diagram of the configuration is shown in Figure 1. The only non-cable connection to the device was a local telephone line, connected to the RMU's internal modem. The RMU contained an internal battery backed-up memory, and was polled several times a week for a period of 7 months from June 1989 through January 1990.

The RMU was installed at the "problem" location, a line extender in a residential section of Cleveland, Mississippi near a cotton processing facility. This location had experienced repeated outages (some of which were not related to severe weather), and had suffered damage to internal AC circuits on two occasions. The nominal AC cable power at this location was 47 VAC with less than 1 Amp through-current to one following line extender on the feeder. The through-current carrying conductors were ruggedized to prevent further damage (no damage occurred during the test). The line extender was equipped with its normal complement of two medium-duty "gas tubes."

The RMU was programmed to log the time, duration and maximum RMS value of each long-duration voltage surge over 50 Volts, the time and maximum peak amplitude of each short-duration impulse over 80 Volts, and the time and peak amplitude of each current surge over 14 Amps. While the current surge measuring subsystem did not possess sufficient bandwidth or resolution to measure short-duration impulse currents, current surges over 1 mS were logged with 16 mS (one-cycle) resolution. The logging thresholds were intentionally set relatively low to avoid losing data associated with other surges, since the RMU's firmware was designed to treat each surge type individually.

Over the seven-month period, 67 "events" were logged. An "event" is herein defined as any surge or series of surges within a 1-second period. In 16 cases, power was lost for periods ranging from 1 second to 30 seconds, and in one case, power was lost for a period of 7 minutes following a single 66 Amp current surge. In all but one event, one or more surges were logged in conjunction with the power loss.

Short-duration voltage surges were relatively rare and of low amplitude, but one event exceeded the 800 Volt measurement capability of the RMU. The >800 Volt measurement was accompanied by the highest amplitude current surge sequence measured throughout the test: 5 cycles ranging from 306 to 408 Amps peak, followed by a loss of power for 2 seconds. According to the system engineer, the weather was clear all day on the day of this event. A total of 14 surge events included short-duration voltage surges, and in all but four, at least one (usually two or more) current surge was logged in conjunction. More than one impulse was logged in a total of five events. During one event, six individual impulses were logged within 1 second (the highest was 382 Volts, which was also the 2nd highest overall). Sixty-four percent of the short-duration impulses were between 100 and 382 Volts.

The long-duration voltage surges were relatively low in amplitude at this location, with a maximum of 88 Volts for 140 mS. While they were often associated with other surge types, long-duration voltage surges were logged alone in 15 out of 31 events. During one large lightning storm, four individual long-duration voltage surge events were logged within 70 minutes, with only one other surge event (a 16-Amp current surge) that day.

Current surges were logged in 48 events, with a total of 113 surges and as many as eight in a single event. Of these, only five events contained a surge over 100 Amps, while 33 events were entirely below 50 Amps. In 25 events, current surges were logged alone (not in conjunction with other surge types), with none of the 25 over 100 Amps and all but four under 50 Amps. Only two events contained surges between 200 and 300 Amps, and the five highest individual surges (in order: 408, 306, 322, 318, and 322 Amps) were all within the single event previously mentioned. This single event is of great interest, since it also contains the highest impulse measured (over 800 V) followed by a 2-second power loss, all under clear skies. This event may have been associated with a major power fault at the nearby processing plant, but it is difficult to explain the high-amplitude impulse under clear skies.

PROTECTIVE DEVICES

Three basic types of protective devices are commonly used for protection of consumer and telecommunication devices: the Metal Oxide Varistor (MOV), the gas-filled surge arrestor ("gas tube"), and various types of silicon-based devices such as ruggedized zener diodes ("Tranzorb" is a common trademark) and thyristors. (SIDACs, SCRs, and TRIACs are members of the thyristor family.) Of these, the MOV and the zener diode are simple voltage-limiting devices, while gas tubes and thyristors are "crowbars" which clamp the circuit voltage to a low value when activated by a higher "trigger" voltage.

MOVs

Voltage-limiting devices are fundamentally restricted in that for equal surge current levels, power dissipation is 100 to 1000 times higher than for the various "crowbar" devices. While the MOV makes up for this limitation by spreading the dissipation over the largest area, the zener diodes have a very small active area. By clamping circuit voltage to a low value, crowbar devices reduce dissipation and, therefore, reduce surge energy.

MOVs are available in a wide range of voltage and energy ratings. They are widely used for protection against the impulses defined in the IEEE guide because they are inexpensive and generally perform well. Energy ratings for devices of manageable dimensions vary from 10 to 70 Joules, with maximum current ratings of up to 6500 Amps. MOVs have been well-characterized for their impulse-suppression application, and are known to degrade significantly over time when subjected to events near their maximum ratings. MOVs are not recommended as protection against the long-duration surges due to the

MOV's limited energy ratings. While they are used for "secondary protection" inside CATV power supplies and some modules, MOVs are not suitable as sole protection.

Gas Tubes

More accurately described as gas-filled surge voltage protectors, gas tubes are crowbar devices which have been used for surge suppression in telecommunications applications for many years. They are triggered at relatively low voltages by a gas ionization process similar to that of neon "glow tubes" and cold-cathode displays. When current flow increases beyond about 100 mA, their terminal voltage drops to around 20 Volts as an arc forms. Gas tubes in CATV applications have been ruggedized so that the heavy-duty types have over 100 times the ratings of early telecommunications types. While some have traditionally exhibited limited life due to the formation of internal debris during high-current surge conditions, recent versions have been developed with specially-coated electrodes to eliminate debris formation.

Special gas tubes developed for CATV use exhibit "follow current" ratings over 400 Amps. The "follow current" rating is that current for which the device will immediately return to its normal high-impedance state following a surge. Gas tubes are the only surge protection devices which are specifically characterized for suppression of long-duration surges, and the heavy-duty types now used in some CATV equipment are rated at 20,000 Amps impulse current. This is by far the highest rating of the devices considered here, exceeding the ANSI/IEEE specification by a large factor. Unfortunately, no manufacturer's data relating to service life is available for high-amplitude, long-duration current surge applications.

Zener Diodes

Due to their limitations, all but the largest ruggedized zener diodes are used only in sensitive low-voltage circuits for which the only concern is the short-duration transient, and for which the circuit impedance limits the maximum current. In this application, zener diodes are a very effective "last line of defense" against short-duration pulses due to their ultra-fast response time. Peak power ratings for typical devices are 1200 Watts for 1 milli-second, or 1.2 Joules. Larger versions rated for up to 15 kW are available, but besides being too large and expensive for CATV applications, they fall far short of requirements.

SIDACs

SIDACs are solid-state members of the thyristor family. These small devices emulate many of the electrical characteristics of gas tubes, but the SIDACs have limited energy dissipation capabilities. While SIDACs are recommended by their manufacturers as "line transient clippers" and for other AC line uses, their maximum rating of 20 Amps (for 16 mS) restricts their use in low-impedance circuits. SIDACs are ideal triggers for other thyristors (SCRs and TRIACs) in crowbar circuits. Some manufacturers have combined SIDACs and TRIACs into monolithic components designed specifically for surge suppression, but these devices are equivalent only to the light-duty gas tubes.

SCRs and TRIACs

With their continuous current capacity, low terminal voltage, and seemingly limitless service life, high-power thyristor devices such as SCRs and TRIACs appear to be ideally suited for use in "crowbar" applications. Crowbar circuits containing them have been successfully tested for several years in CATV power inserters, and these circuits have successfully completed testing in accordance with the ANSI/IEEE standard.

However, close scrutiny of the manufacturer's notes and specifications relating to all SCRs and TRIACs raises many questions relating to their suitability for use in surge suppression applications. Thyristors are not characterized for high-current impulses below 1 mS, and the technology specifically limits maximum dI/dt (relating to rapid changes in current) to values well below those required by the ANSI/IEEE standard.

While the published non-repetitive peak surge current specifications for some thyristors are quite high, they are considered to be overloads. One reputable manufacturer notes that "Usually only approximately 100 such current overloads are permitted over the life of the device," and goes on to state that "... neither off-state nor reverse blocking capability is required on the part of the thyristor immediately following the overload current." (This constitutes a limitation similar to the "follow current" gas tube rating.) Thyristor "AC-crowbar" applications in past linear CATV power supplies have not been very reliable. Although thyristors have long been used as DC-crowbars at power supply outputs, such applications are not subject to more than one or two surges over the life of the power supply.

In all fairness, none of the devices considered here has ever been fully tested under the entire range of surge conditions measured, and there has long been questions relating to device service life in CATV applications. Given the limited life of light-duty gas tubes in some severe CATV applications, it has been surmised that the lifetime of a device may be significantly limited by rapid sequences of surges similar to those which were logged in the field measurements described above. However, little if any data was available relating to reliability under rapid-sequence conditions, and a comparative testing program was suggested. Since no equipment is available for the type of testing needed, it was necessary to construct equipment which could generate (under controlled conditions) the repetitive current surge recorded most frequently in the field.

LAB TESTS

The initial strategy was to test at least five devices of each type to failure using as many combinations of current and duration as possible, under conditions similar to CATV applications (with 60 VAC applied). The equipment had to generate a variable current surge with controllable duration and sufficient power to cause immediate failure of the most rugged devices, and had to be able to record current and voltage waveforms during and immediately following the surge. Generating up to 1000 Amps for 11 cycles (176 mS) with sufficient voltage to trigger the protective device (at least 200 Volts) proved to be the most difficult challenge.

TEST SETUP

Due to the substantial power requirements, special facilities were required. Power Technologies Inc. of Schenectady, NY, professional consultants to the power distribution industry, suggested the use of a site normally used to test high-voltage transmission lines. The site was powered by a dedicated primary branch line from a major power company substation, and was capable of delivering over 1000 Amps with an open-circuit voltage of 500 Volts.

Figure 2 shows the test set-up in which 208 VAC from the main power panel connects through an adjustable reactor to the secondary of a standard 50 kVA distribution transformer, providing an isolated 4160 VAC source to a step-down transformer delivering 442 VAC (open circuit). A high-speed contactor delivers timed test current pulses adjustable from 1 to 11 cycles to the device under test, which is connected across a conventional 60 VAC ferroresonant CATV line power supply to simulate the CATV environment. The adjustable reactor limits the maximum surge current to values between 140 and 1000 Amps, and the 60 VAC (quasi-squarewave) line power supply is powered by a small generator to keep the surges isolated from the rest of the power system. A digital storage oscilloscope captures the surge event through current and voltage transformers (for isolation), and the oscilloscope display is downloaded to a computer for permanent storage.

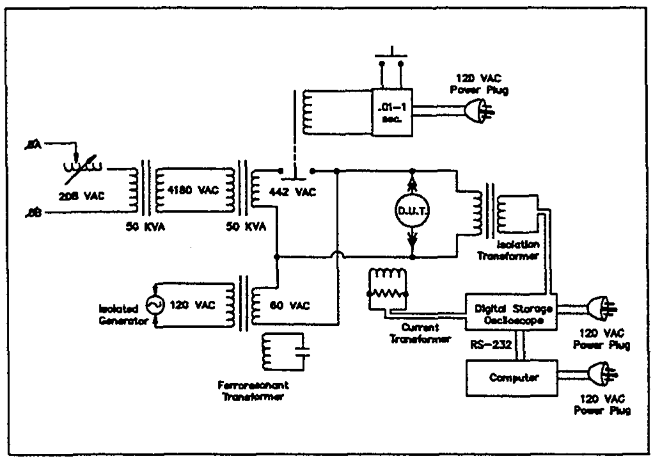

Figure 2.
High-Energy Surge Testing System

Initially, short-circuit surge currents were recorded for each reactor tap, yielding an available range of 140 Amps to 640 Amps (plus 1200 Amps without the reactor). Test results appear below in tabular form, with gas tubes listed separately from SCR-based crowbar circuits for easy reference. (While the actual testing sequence tested gas tubes and SCRs together for setup consistency, the results are numbered and grouped for clarity.) All devices were tested with surges of 5 cycles duration at 60 Hz (80 mS), and were allowed to cool (typically 15 to 30 seconds, depending on device and current) between surges. All currents are given in peak amperes. Figures 3-5 can be referenced as examples of device behavior.

TESTING GAS TUBES

The first six gas tubes were tested to determine the maximum level that they would withstand.

Tube #1	Survived 1 surge at 400 Amps Failed shorted during a second surge at 640 Amps
Tube #2	Survived 2 surges at 640 Amps Failed opened during a third surge at 640 Amps
Tube #3	Survived 1 surge at 640 Amps Failed shorted during a second surge at 640 Amps
Tube #4	Survived 1 surge at 600 Amps Failed shorted during a second surge at 600 Amps
Tube #5	Survived 3 surges at 600 Amps Failed shorted during a fourth surge at 600 Amps
Tube #6	Failed shorted during the first surge at 600 Amps

Figure 3 shows typical gas tube performance at 600 Amps, with current on the top trace and voltage on the bottom: At the beginning, the voltage trace shows the 60 VAC, which drops to 20 VAC as the surge current begins. Following the completion of 5 cycles, the surge current is interrupted, and the 60 VAC resumes with no evidence of "follow current."

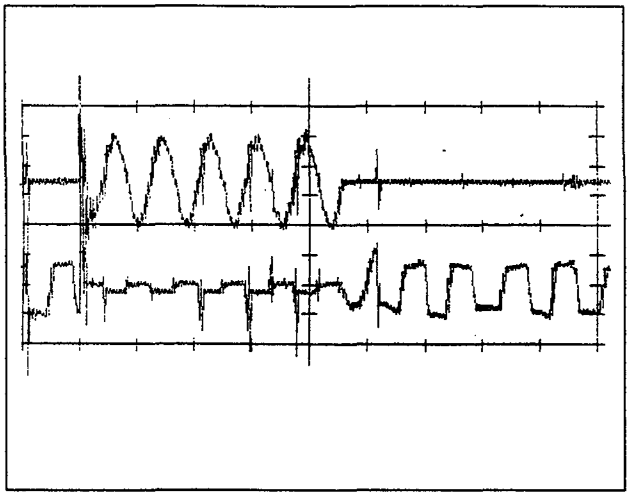

Figure 3.
Typical Gas Tube at 600 Amps

Of the six failed devices, all but one failed in the shorted condition as shown in Figure 4 (gas tube #1), where continuous "follow current" (barely visible at about 20 Amps) follows the completion of the 640 Amp surge.

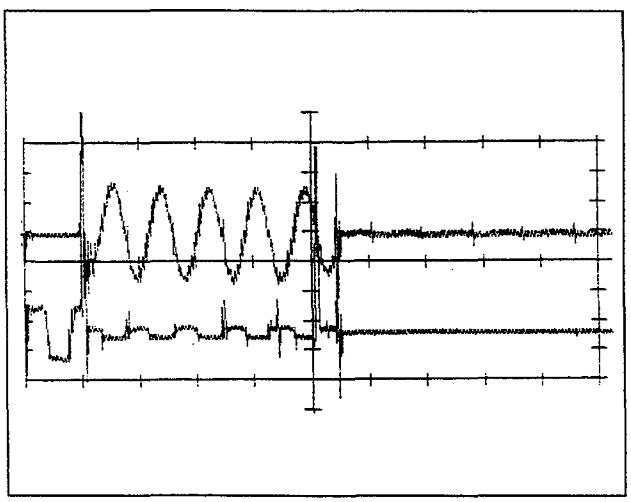

Figure 4.
Gas Tube Failure at 640 Amps

Gas tubes #7 through #11 were tested for ruggedness at reduced current levels, and although the final five gas tubes could not be tested to failure (due to time limitations), they provided statistical data for comparison with the SCR-based devices.

Tube #7	Survived 18 surges at 320 Amps Failed opened during surge #19 at 320 Amps
Tube #8	Survived 117 surges at 320 Amps Failed opened during surge #118 at 320 Amps
Tube #9	Survived 419 surges at 320 Amps Failed opened during surge #420 at 420 Amps
Tube #10	Survived 55 surges at 320 Amps Failed opened during surge #56 at 320 Amps
Tube #11	Survived 161 surges at 320 Amps Failed opened during surge #162 at 320 Amps
Tubes #12-#16	Functioning normally after 100 surges each at 255 Amps

Based on the performance of gas tubes #8, #9, and #11, it is reasonable to estimate that one or more of devices #12-#16 could have survived over 1000 surges at the 255-Amp level, if time had allowed.

TESTING SOLID STATE "CROWBAR" CIRCUITS

These first seven solid-state SCR-based circuits were tested to determine the maximum level that they would withstand. The 340-Amp tests were performed under the same conditions which provided 320 Amps in the gas tube tests, with the difference caused by the difference in terminal voltage (20 Volts for the gas tubes vs 2 Volts for the SCRs). NOTE: In three cases, the surge exceeds the manufacturer's specification: Itsm =

500 Amps (peak 1-cycle), and a table implies a maximum of over 300 Amps (peak) for 5 cycles.

SCR #1 Failed opened during the first surge at 600 Amps

SCR #2 Survived 1 surge at 340 Amps
Failed opened during a second surge at 400 Amps

SCR #3 Failed opened during the first surge at 400 Amps

SCR #4 Survived 6 surges at 340 Amps
Failed opened during a 7th surge at 340 Amps

SCR #5 Survived 3 surges at 340 Amps
Failed opened during a 4th surge at 340 Amps

SCR #6 Survived 2 surges at 340 Amps
Failed opened during a 3rd surge at 340 Amps

SCR #7 Survived 5 surges at 308 Amps
Failed shorted during a 6th surge at 308 Amps

Figure 5 shows SCR-based solid-state crowbar circuit #1 failing at the 600-Amp level, where the SCR increased resistance (note the simultaneous decrease in current and increase in voltage) and then blew up (opened) after only 1.5 cycles of the first 5-cycle surge. The odd-looking waveform in the remainder of the plot is characteristic of the ferroresonant transformer output following a high voltage un-clamped surge. (It settles back to normal after about 5 to 10 cycles.)

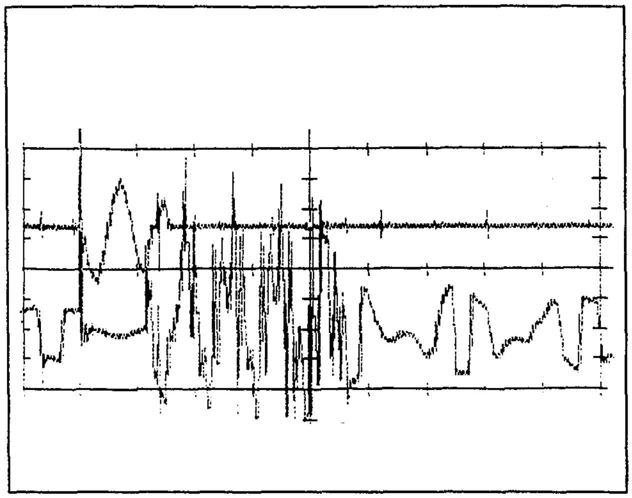

Figure 5.
SCR Failure at 600 Amps

The next six solid-state devices were tested at a reduced current level for ruggedness comparison to the gas tubes. The tests were performed under the same conditions which provided 275 Amps in the gas tube tests, with differences due to device characteristics as noted above.

SCR #8 Survived 24 surges at 288 Amps
Failed opened during surge #25 at 288 Amps

SCR #9 Survived 36 surges at 288 Amps
Failed shorted during surge #37 at 288 Amps

SCR #10 Survived 25 surges at 288 Amps
Failed shorted during surge #26 at 288 Amps

SCR #11 Survived 5 surges at 288 Amps
Failed opened during surge #6 at 288 Amps
(circuit PCB trace failed; SCR later tested OK)

SCR #12 Survived 29 surges at 288 Amps
Failed opened during surge #30 at 288 Amps

SCR #13 Survived 49 surges at 288 Amps
Failed shorted during surge #50 at 288 Amps

SCRs #9, #10, #12, and #13 all showed the "follow current" effect starting at about the 18th surge. Typically, this "follow current" lasted 3 and 6 cycles following the surge.

SUMMARY & CONCLUSIONS

Field testing has shown that not only do long-duration current surges dominate the totals, they usually accompany short-duration impulses, and can exceed 100 mS duration. While many of the long-duration events are moderate (under 100 Amps), the extreme amplitudes which were recorded require serious consideration.

Given the amplitudes and durations of the most serious long-duration current surges, most of the devices which are traditionally used for surge protection are not appropriate for most CATV applications. Common devices such as MOVs and "Tranzorbs" are suitable only in secondary applications, where primary protection is provided by clamp-type ("crowbar") devices such as high-power thyristors and gas-filled surge arrestors.

Although high-power thyristor circuits have performed well in limited field and laboratory testing, their manufacturer's specifications and application notes cast considerable doubt on their use as surge protectors.

The long-duration surge testing illustrated the limitations of both gas tubes and thyristors, and proved that the modern heavy-duty gas tubes offer significantly superior performance overall.

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