# Electromagnetic Pulse and the Radio Amateur - Part 2

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# Electromagnetic Pulse and the Radio Amateur

## ***Part 2:*** This month, we present the method and results of the first of two series of tests of EMP/transient-protection devices.†

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The inherent weakness of solid-state components to damaging transient electrical energy has stimulated the electronics industry to develop a large variety of transient-protection devices. In order to identify low-cost, commercially available devices capable of protecting Amateur Radio equipment, an extensive market search was made and a representative number of protective devices were purchased. The protection devices purchased were the most current types available for use with Amateur Radio equipment where it connects to power lines, antenna systems, communications lines and other potential transient sources. The test program was divided into two stages: First, the protection devices, then the Amateur Radio equipment.

### Test Objectives

No common test procedure existed for determining the effectiveness of different types of protection devices. Therefore, we sought to develop a common test procedure to ascertain the average performance of a wide variety of devices against the fast-rising and powerful transient pulses that are generated by lightning and EMP. Three standard electromagnetic pulses were used to simulate the expected transient waveforms associated with ac power connections, short interconnecting wires and long exterior conductors that are found in the typical Amateur Radio installation.

Protection devices that allowed a voltage spike to exceed their rated clamping voltage by 100% (6 dB), or exhibited a significant delay in response time, were rejected. The 6-dB overload level was selected because it is common to design electronic circuits to withstand such an overload for short durations. Those devices that suppressed the initial voltage spike to an acceptable level, less than twice the clamping voltage, were accepted for further testing.

**Table 3**
**Peak Voltage and Current Values vs Conductor Type**

| *Conductor* | *Peak Voltage (Volts)* | *Peak Current (Amperes)* | *Test Class* |
|---|---|---|---|
| Power Connections | 600 | 120 | A |
| Box interconnections | 600 | 20 | B |
| Exterior Conductors | 4500 | 1000 | C |

### Test Program

#### Threat Definition

Other than in the case of a direct lightning strike, EMP is generally considered a more stringent threat to electrical systems than lightning. Consequently, the test pulses approximated the characteristics of EMP, rising to full strength in approximately 10 ns and decaying exponentially in about 1 µs. The waveform that is frequently used in unclassified work was used for this test; it is expressed as:

$$E(t) = 5.25 \times 10^4 \exp(-4 \times 10^6 t) - \exp(-4.76 \times 10^8 t) \qquad \text{(Eq 1)}$$

where
E is volts per meter
t is time in seconds

The transient threat to electrical hardware does not come directly from the free field, but from the interaction of the electric and magnetic fields with electrical conductors. Current peaks in excess of thousands of amperes are predicted as a response to EMP. Similarly, voltage levels may reach hundreds of kilovolts. In practice, however, the physical dimensions and characteristics of the conductors themselves tend to limit current and voltage amplitudes, although not always without physical damage to the conductors. For example, it has been proposed that the highest transient voltage transmitted through a residential power-distribution breaker box would be limited by air-discharge breakdown. Conversely, in an Amateur Radio station, the transients experienced, if limited at all, would be determined by the lengths and configurations of conductors exposed to the fields, and the dielectric strength.

The peak values shown in Table 3 were used in the protective-device qualification tests for this program. These peak values were used because they are representative of the transient pulses expected in a typical Amateur Radio system, and they could be readily reproduced in a laboratory test environment.

To test for insulation breakdown of the protective devices, the highest pulse level obtainable in the laboratory (25 kV) was used. Each protective device was subjected to ten equal pulses in order to ensure that protection was not circumvented by the first transient received. A cooling time of approximately one second was allowed between pulses.

#### Direct Testing

Direct device testing consisted of driving the device terminals with a differential-mode signal from a pulse generator. The test was conducted once with a source impedance appropriate to the voltages and currents listed in Table 3, and once with the tabulated voltage and a source impedance of 50 ohms. This impedance was chosen because it is encountered most commonly in house wiring and antenna circuits. The input- and output-pulse magnitudes were recorded photographically. A comparison was made of the input and output voltages with and without the device in the circuit,

†Part 1 appears in Aug 1986 *QST*. Part 3 will appear in a subsequent issue.

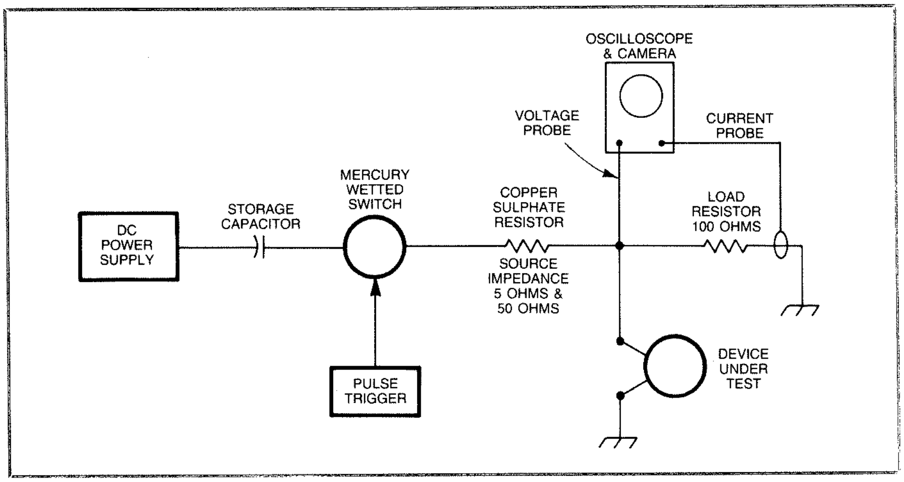

Fig 8—Low-voltage pulser; below 5 kV.

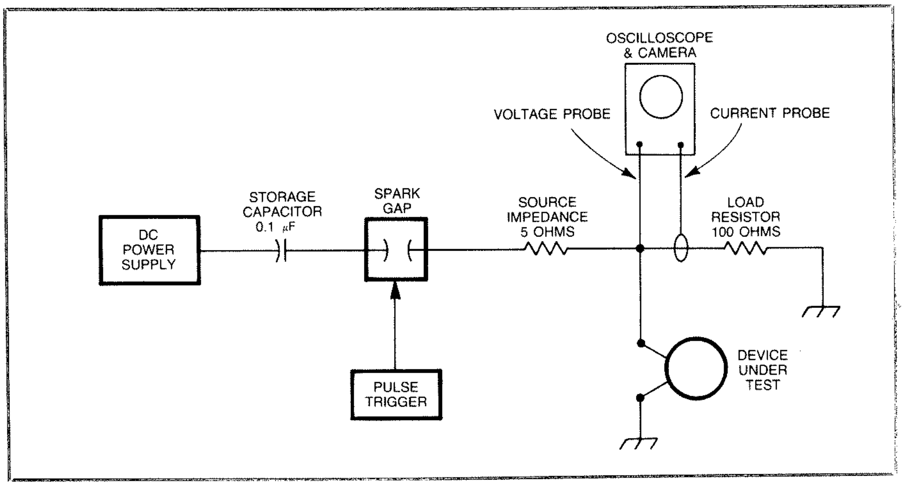

Fig 9—High-voltage pulser; above 5 kV.

and a transient-rejection ratio (in decibels) was calculated using the relationship:

$$RR\ dB = 20 \log_{10} \frac{\text{peak signal in}}{\text{peak signal out}} \quad \text{(Eq 2)}$$

From one to 15 devices of each type were tested. When 10 identical devices of any one type had been tested with forward and reverse polarity, the data were statistically analyzed to determine if further testing was required. For statistical analysis, 10 items were considered to provide a representative sample of the device's performance, since the devices performed consistently.

### Test Equipment

Two pulse generators were used. One provided pulses below 5 kV (600-V and 4.5-kV tests), the other produced pulses above 5 kV (25-kV test).

### Pulses Below 5 kV

Transient pulses for this test were generated by manually firing a mercury-wetted switch to discharge a storage capacitor through a copper-sulphate source resistance of the appropriate size to generate the desired current pulse (see Fig 8). The capacitor was charged to the desired voltage level by a quick-recovery, high-voltage power supply. Transients were fired across a 100-ohm load resistor protected by the device under test.

Data were recorded by photographing a properly calibrated oscilloscope display. For repeated pulse requirements, the camera shutter was held open to record all (nominally 10) of the pulses of one polarity, and then, after removal of the device under test, to record the applied transient with the same exposure. Reverse-pulse measurements were obtained by reversing the leads of the device under test and repeating the photographic sequence.

### Pulses Greater Than 5 kV

Transient pulses for this test were generated by manually firing a 2-inch spark gap to discharge a 0.1-µF storage capacitor through a 5-ohm copper-sulphate source resistance to generate the desired current pulse (see Fig 9). The capacitor was charged to the desired voltage level by a quick-recovery, high-voltage power supply. The transients were fired across a 100-ohm load resistor protected by the device under test.

Again, data were photographically recorded. Current and voltage were recorded for the initial pulses of each device. The voltage probe was attenuated by a flexible copper-sulphate resistance of suitable value. For repeated pulse requirements, the camera shutter was held open to record five of the pulses and the reference in a manner similar to that of the lower-voltage measurements described previously. The polarity of the second set of five pulses was not reversed, and the current trace was usually omitted from the second data set.

### Small-Device Tests

For physically small devices, test measurements were conducted inside a metal enclosure. Penetrations of the enclosure were made by the high-voltage lead from the mercury-wetted switch, the system ground and the voltage probe. Currents were measured by a sensor on the system ground, but were not regularly recorded as part of the test data. The voltage probe was run in solid-sheath coaxial cable to the metal enclosure, and the internal probe was shielded by a metal braid to within a few millimeters of the probe tip.

Shunt-protective devices were connected between the high-voltage input terminal and system ground. The voltage probe and load resistor were also connected to the same terminals. For device combinations containing series elements, the line side of the device was connected to the input terminal, and the voltage probe and load resistor connected between the load side terminal and ground.

### Large Devices

For devices with special connectors too large to fit within the test chamber, connecting adapters were made of straps and braid to provide the lowest-impedance circuit available. In many cases, however, the inductance of the connection did affect the measurement, particularly in the case of determining the reference grounds.

### Ac Power Tests

To test the ability of the devices to function when connected in a 117-V ac circuit, ac was provided by an isolation transformer connected to the device through a large inductance. If the device continued to arc or pass current after the pulse, the transformer was manually disconnected (but not always before the device had melted).

### Test Results

A total of 56 different devices were tested. All of the devices substantially suppressed the test pulses. However, not all of the devices suppressed the test pulse to an acceptable voltage level on every test.

Twenty-six of the 56 devices passed the low-impedance drive tests and 40 passed the high-impedance drive test. To pass the particular test, the device had to suppress the peak-voltage pulse to less than two times its published, designed clamping

## Table 4
### Devices with Acceptable Clamping Voltages Low-Impedance Drive Tests

| Manufacturer and Device | Designed Maximum Clamping Voltage (MCV) (Volts) | Average Measured Peak Clamping Voltage at 600 V and 4.5 kV (APV) (Volts) | Acceptable Clamping Voltage (APV = <2 MCV) |
|---|---|---|---|
| *Fischer* | | | |
| FCC-120-P | 300 (1) | 200 | 300 |
| FCC-250-300-UHF | 300 | 1333 | |
| FCC-250-300-UHF | 350 | 1633 | |
| FCC-450B-75-BNC | 75 | 670 | |
| FCC-250-150-UHF | 150 | 1700 | |
| FCC-250-120-UHF | 120 | 1700 | |
| FCC-450-120-UHF | 120 | 800 | |
| *Joslyn* | | | |
| 2027-23-3B | 230 | 600 | |
| 2027-35-B | 350 | 1940 | |
| 1270-02 | 190 | 400 | |
| 1250-32 | 350 | 2300 | |
| 1663-08 | 66 | | |
| 2027-09-B | 90 | 1820 | |
| 2027-15-B | 150 | 1620 | |
| 2022-44 | 250 | 1460 | |
| 2031-23-B | 230 | 1560 | |
| 2031-35-B | 350 | 1360 | |
| *General Electric* | | | |
| V39ZA6 | 76 | 132 | 76 |
| V82ZA12 | 147 | 230 | 147 |
| V180ZA10 | 300 | 428 | 300 |
| V8ZA2 | 20 | 120/690 | 60 (3) |
| V36ZA80 | 63 | 120 | 63 (3) |
| *PolyPhaser Corporation* | | | |
| IS-NEMP | 200 (2) | 380 | 200 |
| IS-NEMP-1 | 200 (2) | 380 | 200 |
| IS-NEMP-2 | 200 (1) | 600 | |
| *TII* | | | |
| Model 428 | 280 | 350 | 280 |
| *Siemens* | | | |
| S10K11 | 40 | 120/690 | |
| S20K25 | 80 | 131/720 | 80 |
| S14K50 | 125 | 220/620 | 125 |
| S10K60 | 160 | 265/710 | 160 |
| S14K130 | 340 | 464/1050 | 340 |
| B1-C75 | 75 (2) | 600/910 | |
| B1-C90/20 | 90 (2) | 600/938 | |
| B1-C145 | 145 (2) | 600/880 | |
| B1-A230 | 230 (2) | 600/960 | |
| B1-A350 | 350 (2) | 632/1020 | |
| S8-C150 | 150 (2) | 600/4500 | |
| T61-C350 | 300 (2) | 672/990 | |
| *Alpha Delta Communications, Inc (4)* | | | |
| LT | 635 (1) | 4500 | |
| R-T | 635 (1) | 400 | 635 |
| *General Semiconductor* | | | |
| 587B51 | 650 | 290 | 650 |
| ICTE-5 | 7.1 | 112/560 | 60 (3) |
| ICTE-15 | 20.1 | 116/580 | 60 (3) |
| ICTE-8C | 11.4 | 119/510 | |
| LCE-6.5A | 11.2 | 239/780 | |
| LCE-15A | 24.4 | 158/590 | |
| LCE-51 | 91.1 | 188/770 | |
| LCE-130A | 209 | 270/830 | 209 |
| PHP-120 | 319 | — | — |
| GHV-12 | 8 | 155/590 | 80 (3) |
| GSV-101 | 0.85 | 115/500 | 60 (3) |
| GSV-201 | 1.7 | 120/570 | 60 (3) |
| *Electronic Protection Devices, Inc* | | | |
| Lemon | 300 (1) | 380 | 300 |
| Peach | 300 (1) | 350 | 750 (3) |
| *S. L. Waber* | | | |
| LG-10 | 300 (1) | 550 | 300 |
| *Archer (Radio Shack)* | | | |
| 61-2785 | 300 (1) | 90 | 300 |

(1) Estimated or calculated
(2) Dc break-down voltage
(3) Acceptable above 2 MCV
(4) Alpha Delta recently released new versions of their Transi-Trap™. These units are the Model R-T and LT having an "EMP" suffix. In these units, the EMP clamping level is three times lower than previous designs.

voltage, or exhibit an acceptable response waveform.[4] The manufacturer of the protection device normally establishes the maximum clamping voltage using a much slower pulse (8 µs rise time and 20 µs decay time) than the expected electromagnetic pulse and the test pulse (10 ns rise time and a 1 µs decay time). In some cases, the dc breakdown voltage is used as the reference clamping voltage. Therefore, the measured clamping voltage of the devices was expected to be higher than the published figure. During the tests, these higher clamping voltages were found with few exceptions.

### Low-Impedance Testing

The low-impedance test was conducted at two different voltage levels (600 V and 4.5 kV). The devices were tested with positive- and reverse-polarity pulses. There was no significant difference in response caused by the different polarity pulses, with the exception of certain General Semiconductor TransZorbs®.

Twenty-six devices were considered to have acceptable pulse-suppression characteristics. The most consistent performer was the metal-oxide varistor (MOV)[5]. Varistors suppressed the leading edge of the pulse wave to less than two times the designed clamping voltage. Table 4 shows those devices that have acceptable clamping performance. The accepted devices have rejection ratios that range from 0.75 dB to 16.47 dB for the 600-V test pulse, and from 13.06 dB to 21.47 dB for the 4.5-kV pulse.

Gas-discharge tubes and devices containing only gas-discharge tubes did not respond well to the 600-V pulse. The rise time (10 ns) and the low voltage level were not sufficient to cause the tube to ionize and conduct the test pulse to ground within the rise time. With 10 pulses being injected at a 1-second injection rate, the gas-tube ionization was delayed for periods of up to 4000 ns for each pulse, and in some cases, the measurements were off the observable scale. This slow response time makes the gas-discharge tube an unacceptable device to use as the sole protection unit for a low-voltage pulse with a slow rise time such as experienced with the 600-V pulse that had a rise time of only 60 V/ns.

Twenty devices were considered to have acceptable measured clamping voltages on the low-impedance test. Six other units had a satisfactory response waveform and were accepted although their clamping voltage was over two times their published or design clamping level. Not all of the devices were tested at the 600-V level. Of the ones that were, the varistors and the ac power-line protection devices were the best performers.

### High-Impedance Testing

This test was conducted only at the 4.5-kV level. The devices were tested with positive- and reverse-polarity pulses. Again, no significant response differences were noted with the different polarity pulses, except with the TransZorbs. The 4.5-kV, 50-ohm test pulse is considered to be the most accurate simulation of the expected EMP energy that will be impressed on the ac power and coaxial-cable

[4] Notes appear on page 26.

**Table 5**
**Devices With Acceptable Clamping Voltages High-Impedance Drive Test**

| *Manufacturer and Device* | *Designed Maximum Clamping Voltage (MCV) (Volts)* | *Average Measured Peak Clamping Voltage at 4.5 kV 50 Ohms (APV) (Volts)* | *Acceptable Clamping Voltage (APV = <2 MCV)* |
|---|---|---|---|
| *Fischer* | | | |
| FCC-120-P | 300 (1) | 420 | 300 |
| FCC-250-300-UHF | 300 | 393 | 300 |
| FCC-250-300-UHF | 350 | 260 | 350 |
| FCC-450B-75-BNC | 75 | 210 | |
| FCC-250-150-UHF | 150 | 220 | 150 |
| FCC-250-120-UHF | 120 | 240 | 120 |
| FCC-450-120-UHF | 120 | 120 | 120 |
| *Joslyn* | | | |
| 2027-23-3B | 230 | 310 | 230 |
| 2027-35-B | 350 | 366 | 350 |
| 1270-02 | 190 | 600 | 500 (3) |
| 1250-32 | 350 | 940 | |
| 1663-08 | 66 | 90 | 66 |
| 2027-09-B | 90 | 378 | |
| 2027-15-B | 150 | 242 | 150 |
| 2022-44 | 250 | 294 | 250 |
| 2031-23-B | 230 | 336 | 230 |
| 2031-35-B | 350 | 291 | 350 |
| *General Electric* | | | |
| V39ZA6 | 76 | 254 | 150 (3) |
| V82ZA12 | 147 | 254 | 147 |
| V180ZA10 | 300 | 388 | 300 |
| V8ZA2 | 20 | 174 | 100 (3) |
| V36ZA80 | 63 | 170 | 100 (3) |
| *PolyPhaser Corporation* | | | |
| IS-NEMP | 200 (2) | 140 | 200 |
| IS-NEMP-1 | 200 (2) | 150 | 200 |
| IS-NEMP-2 | 200 (1) | 160 | 200 |
| *TII* | | | |
| Model 428 | 280 | 410 | 280 |
| *Siemens* | | | |
| S10K11 | 40 | 186 | 100 (3) |
| S20K25 | 80 | 190 | 150 (3) |
| S14K50 | 125 | 234 | 125 |
| S10K60 | 160 | 232 | 160 |
| S14K130 | 340 | 436 | 340 |
| B1-C75 | 75 (2) | 220 | |
| B1-C90/20 | 90 (2) | 210 | |
| B1-C145 | 145 (2) | 200 | 145 |
| B1-A230 | 230 (2) | 218 | 230 |
| B1-A350 | 350 (2) | 230 | 350 |
| S8-C150 | 150 (2) | | |
| T61-C350 | 300 (2) | 250 | 300 |
| *Alpha Delta Communications, Inc (4)* | | | |
| LT | 635 (1) | 700 | 635 |
| RT | 635 (1) | 720 | 635 |
| *General Semiconductor* | | | |
| 587B51 | 650 | 600 | 650 |
| ICTE-5 | 7.1 | 134 | |
| ICTE-15 | 20.1 | 146 | |
| ICTE-8C | 11.4 | 124 | |
| LCE-6.5A | 11.2 | 250 | |
| LCE-15A | 24.4 | 200 | |
| LCE-51 | 91.1 | 220 | |
| LCE-130A | 209 | 210 | 209 |
| PHP-120 | 319 | 400 | 319 |
| GHV-12 | 8 | 218 | |
| GSV-101 | 0.85 | 168 | |
| GSV-201 | 1.7 | 174 | |
| *Electronic Protection Devices, Inc* | | | |
| Lemon | 300 (1) | 580 | 300 |
| Peach | 300 (1) | 1000 | 750 (3) |
| *S. L. Waber* | | | |
| LG-10 | 300 (1) | 600 | 300 |
| *Archer (Radio Shack)* | | | |
| 61-2785 | 300 (1) | 300 | 300 |

(1) Estimated or calculated
(2) Dc break-down voltage
(3) Acceptable above 2 MCV
(4) Alpha Delta recently released a new version of their Transi-Trap™. This unit has an EMP suffix. In these units, the EMP clamping level is three times lower than previous designs.

interfaces to the amateur's equipment. Therefore, the results of this test were expected to be the most significant of the program. The devices tested are listed in Table 5.

### Varistors

Varistors performed adequately during the test. The General Semiconductor, General Electric and Siemens varistors performed consistently. The varistors tested had clamping voltages ranging from 0.85 V to 350 V. The average measured varistor clamping voltage ranged from a low of 168 V to a high of 436 V. Nine out of 12 varistors were found to have acceptable clamping voltages. Three varistors exceeded their designed clamping voltage, but performed consistently and could be used at a higher voltage level if desired.

### Gas-Discharge Tubes

The advantage of using a gas-discharge tube is in its ability to handle large power transients for short periods.[6] One of the disadvantages of gas tubes is that once they begin to conduct, a continuous ac or dc operating voltage of the proper level will keep the tube in the conductive state after the pulse has passed. This characteristic can result in the destruction of the tube, as was experienced during another phase of this test program. Several gas tubes were destroyed when attached to an isolated ac power source and then exposed to a 25-kV pulse. The pulse started the tube's conduction and the ac power sustained the tube's ionization and conduction until the tube was destroyed.

In a special test, two gas tubes were connected in series between the pulse source and system ground. An ac voltage was impressed across the source circuit and then through a 100-ohm resistor to ground. The gas tubes did not begin to conduct until they were pulsed. When pulsed, the tubes ionized and conducted the pulse to ground, then shut off. The applied ac power did not sustain the ionization across the series-connected tubes.

Similarly, a gas tube and a varistor were connected in parallel to ground with an ac current in the circuit. When pulsed, the tube ionized and conducted the transient current to ground while sharing the current with the varistor, then shut down without being destroyed. It was concluded that gas tubes could be used for their high power handling capabilities, but only when used at the proper voltage levels or with another device to cut off the tube. This design adaptation is found in commercial ac-power protection devices and RF devices using gas tubes.

### Coaxial-Line Protectors

Eleven RF protection devices from three suppliers were tested. These devices are designed to be placed in the coaxial transmission line. All of the units, with the exception of the one with the lowest clamping voltage, were accepted. This exception, the Fischer FCC-450B-75-BNC, is rated to clamp at 75 volts. It did suppress the 4.5-kV pulse to an average of 210 V and was given a rejection ratio of 26.62 dB, still very good performance.

The measured clamping voltages ranged from a low of 120 V (for a device rated at 120 V) to a high of 720 V (for a unit rated at 635 V). The coaxial-line protectors exhibited a very high rejection ratio to the 4.5-kV high-impedance pulse, starting at a low of 16.15 dB for the Alpha Delta Transi-Trap R-T to a high of 30.14 dB for the Polyphaser IS-NEMP devices. The Fischer FCC-250-350-UHF clamped 90 V below its rated clamping voltage of 350 V. This was not considered to be a problem, but a lower clamping voltage potentially could interfere with the transmitted RF signal.

### Power-Line Protectors

There are numerous ac power-line protection devices available, but our selection was limited to the lowest-cost devices. Ten devices from seven sources were tested. All of the units, with the exception of the Fischer FCC 120 F-P, Joslyn model 1250-32 and the General Semiconductor models 587B051 and PHP 120, could be plugged directly into an ac wall outlet.

Internally, the devices consist of a combination of gas-discharge tubes, varistors or other protective circuitry. All except one were found to be acceptable. The published clamping voltages ranged from a low of 190 V to a high of 650 V. For several devices, the designed clamping voltage was not known, so a 300-V level was assigned to them for purposes of comparison. The measured clamping voltages ranged from a low of 300 V to a high of 1 kV.

### TransZorbs

Seven units from General Semiconductor were checked in an effort to find a device that would clamp at a very low voltage level. The one with the lowest-rated clamping voltage is the ICTE-5 (7.1 V); the unit with the highest-rated clamping voltage is the LCE-130A (209 V). Average measured clamping voltages ranged from a low of 124 V to a high of 250 V. Only one of the units was accepted — the LCE-130A. Rated at 209 V, it had an average clamping voltage of 210 V. All of the other TransZorbs conducted only at levels considerably above their ratings.

### Test to Failure

The larger of the two pulse generators was used to generate a 25-kV pulse at 4 kA for 1 μs. This provided a total energy output of 100 J. Up to five each of the 36 devices were tested with only three of them approaching failure. The three ac power-line protection devices experienced excessive internal arcing, although they did not fail completely. All of the other devices survived the 10 pulses and suppressed the voltage transient voltage without failure.

### Conclusions

Of the 56 devices tested, there are many that have acceptable transient-voltage suppression capabilities and can be used for the protection of Amateur Radio equipment. These include ready-made units for direct connection to the ac power lines and coaxial antenna lines as well as smaller devices that can be used alone (varistors) or in combinations (gas-discharge tube/varistor) to protect other points.

[Editor's Note: This series of articles is condensed from the National Communications System report (NCS TIB 85-10) *Electromagnetic Pulse/Transient Threat Testing of Protection Devices for Amateur/Military Affiliate Radio System Equipment*. A copy of the unabridged report is available from the NCS. Write (no SASE required) to Mr Dennis Bodson, Acting Assistant Manager, Office of Technology and Standards, National Communications System, Washington, DC 20305-2010, or call 202-692-2124 between the hours of 8:30 AM and 5 PM Eastern.]

### Notes

[4] The published clamping voltage of a device is the average voltage level where the device will change from a nonconducting state to a conducting state.

[5] Varistors are voltage-dependent devices that behave in a nonlinear electrical manner similar to back-to-back Zener diodes. When subjected to high-voltage transients, the varistor's impedance changes over a large range from a near open circuit to a highly conductive circuit, thereby switching the transient voltage to ground or some other point. Varistors are designed for a large assortment of switching (clamping) voltages.

[6] The tubes tested are sealed gas-discharge tubes consisting of two or three electrodes properly separated by insulators and filled with a rare gas. These tubes are designed to switch rapidly at a specific voltage level from a nonconductive to a conductive state (arc mode) when subjected to a fast-rising voltage transient. When the voltage across the tube's electrodes is increased, ionization of the inert gas occurs and the tube conducts across the electrode gap. The breakdown-voltage level is determined by the design of the tube's electrode spacing and the gas pressure.