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Technical Report

Tony Nilsson

Protections Against HPM Front-Door Coupling -A Survey of Commercial Limiters

Sensor Technology
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Protections Against HPM Front-door coupling - A Survey of Commercial Limiters

Abstract (not more than 200 words)

This report provides a survey of commercial limiters. There is a number of different technologies that potentially can be used for circuit protection against HPM front-door coupling and other electromagnetical interferences. One of the aims with this report is to serve as the basis for deciding on which protection devices shall be purchased and tested regarding their potentials for protection against HPM. The other aim is to create a general survey of different technologies / types of limiters that can be used for HPM protection. Essential properties of the different limiter technologies have been investigated in order to sort out which ones can be of interest. The conclusion is that only a few limiters meets the demands for protection against HPM front-door coupling. These limiters are probably best used in a combination to achieve a good overall protection. Front-door protections can be used in a future network centric defence, where the systems for communications and sensors, has to be protected from harmful pulses.

Keywords
HPM, Front-door coupling, Protection Circuits, Limiter

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Skydd mot HPM framvägskoppling – En översikt av kommersiella skyddskretsar

Sammanfattning (högst 200 ord)

Denna rapport ger en översikt av kommersiella skyddskretsar. En mängd olika teknologier kan idag tänkas kunna användas för att skydda elektronik mot HPM framvägskoppling och andra elektromagnetiska störningar. Avsikten med denna rapport är dels att utgöra ett beslutsunderlag för inköp av kommersiella limitrar, avsedda att experimentellt utvärderas med avseende på deras eventuella skyddsfunktion mot HPM och dels att ge en god översiktsbild av vilka typer/teknologier som används eller kan tänkas användas som skydd. Egenskaperna hos de olika teknologierna har fastlagts för att utröna vilka limitrar som kan vara av intresse. Slutsatsen av undersökningen var att endast ett fåtal limitrar kan lämpa sig för skydd mot HPM framvägskoppling. Dessa limitrar har olika egenskaper vilket gör att man i praktiken förmodligen behöver använd olika limitrar i kombination för att få ett fullgott skydd. Framvägskopplingsskydd kan användas i ett nätverksbaserat försvar, där kommunikations- och sensorsystem måste skyddas mot skadliga pulser.

Nyckelord
HPM, skyddskretsar, framvägskoppling, limitrar

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Table of Contents

1 Aim

In today's society there are more and more electronic devices integrated into different applications, this makes our society more vulnerable to electrical interference. The question regarding protection of electronic systems has recently gained more importance. There are several devices for suppression of transient voltages available on the market today. The purpose of this report is to investigate the market for transient voltage suppression devices suitable for protection against microwave radiation of high intensity.

2 Introduction

2.1 Clamping and Crowbaring Devices

There are two main types of protection circuits, clamping devices and crowbaring devices. The clamping device limits the transient by changing its impedance, as soon as the threshold level is exceeded it starts to conduct and clamps the transient to a safe level. The voltage level of the transient is clipped off and clamped to a level near the nominal operating voltage. Diode limiters and MOVs (Metal Oxide Varistors) are examples of clamping devices.

Crowbaring devices uses a switching mechanism and starts to conduct when the transient exceeds the threshold level. When the device starts to conduct, the voltage level is dropped to a level way below the operating voltage. The device provides a low impedance path to ground and diverts the transient. The device returns to the off -state when the transient has passed. Crowbaring devices can in general handle larger voltages and currents without failure, compared to clamping devices, but on the other hand they usually have a longer recovery time [13]. Examples of crowbaring devices are gas discharge tubes, and spark gaps.

2.2 Passive and Active Protection Devices

As a way to further divide protection components into groups passive and active types of protection devices can be used.

More simplified one can say that a passive protection device is self-activated. It needs no external control signals or bias to perform its protective function. Most of the protection devices on the market are passive.

Active protective devices on the other hand need external control signals to perform their task. Active protection devices are often some kind of switch. The advantages of active devices are in general faster recovery times and that a very small amount of the energy is transmitted to the protected circuitry. The drawbacks of this type of protection circuits is that they give no protection when device is turned off and if the control signal fails there will be a malfunction of the protective device. To summarize one can say that passive devices are recommended, due to their reliability and fully automatic protection function. The passive devices will be functional even if the electrical equipment is turned off, which prevents damages to stored electrical equipment.

The further study of protective devices in this report will be focused on passive components, because this lies more in the interest of our needs.

2.3 Protection Specification

A possible component that is to be protected is a MMIC receiver front-end. In the receiver chain there are several sensitive circuits that needs protection from voltage transients. In order to protect smart skin antennas a tentative specification for the external threats is as follows:

Frequency, f_0	0,3-20 GHz
Field intensity	100 kV/m
Rise time	10 ns
Pulse burst length	1 to 10 seconds
Pulse length, τ	10 ns – 5 µs
Pulse repetition frequency	Single pulse to 1 kHz
Energy density	$\leq 10\ \mathrm{J/m^2}$

Figure 2.1 Description of expected HPM signal.

Given the external threat one also has to consider the sensitivity i.e. the failure level of the component (the load) that is to be protected. This can be expressed in terms of voltage (to avoid electrical breakdown) and power/energy (to avoid damage by heating of shorter pulses). The failure levels shall primarily be determined for different pulse lengths. An interesting component for tests is the integrated circuit (IC). The power handling capability of an IC made in GaAs is estimated to be around 20 dBm. The exact levels will depend on the features of the load and will be further investigated for front-end components in GaAs. Considering the high external threat level, the protection will generally have to be applied in more than one level in most cases.

2.4 Technical Terms

In order to get a better understanding of how limiters function, some technical terms related to limiter devices will be explained.

2.4.1 Threshold value

The threshold value is the specific level at which the protection function is triggered. At this level the limiter starts to operate in the on-state. This value varies a lot with different technologies. The threshold level is often measured in volts or power. A low threshold level can be important, even if the response time is fast, in order to protect the load from electrical breakdown.

2.4.2 Response time

The response time for a limiter is the time from when a surge hits the limiter until the clamping activity begins. This is a very important parameter, usually the response time should be as fast as possible. If the response time is to slow, a large part of the pulse energy will pass the limiter and reach the load.

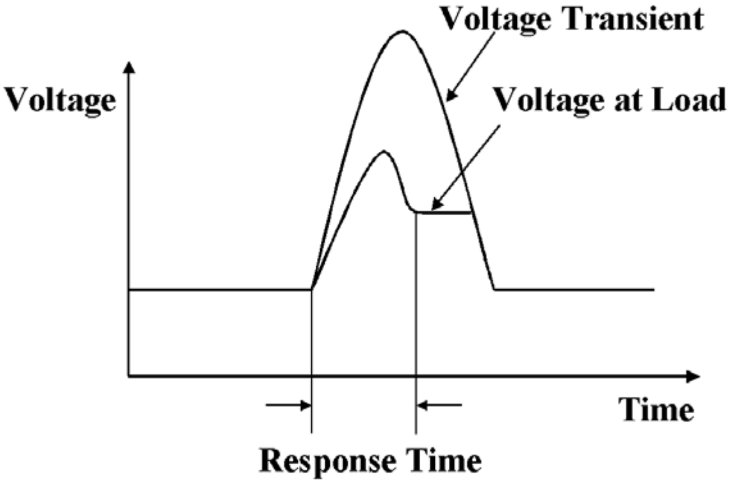


Figure 2.2 Definition of response time.

2.4.3 On-state

The on-state refers to the limiters way to operate, in this state it is activated. The limiter protects its load from potentially harmful high power signals. The high power signal is partly diverted, but it is mainly reflected.

2.4.4 Recovery time

To measure the recovery time the limiter is set to operate in the on-state, when the surge has passed, the limiter reacts with a transition back to the off-state. The recovery time is measured from where the input (the surge) has dropped to zero until the limiter returns within 3dB of its previous insertion loss value.

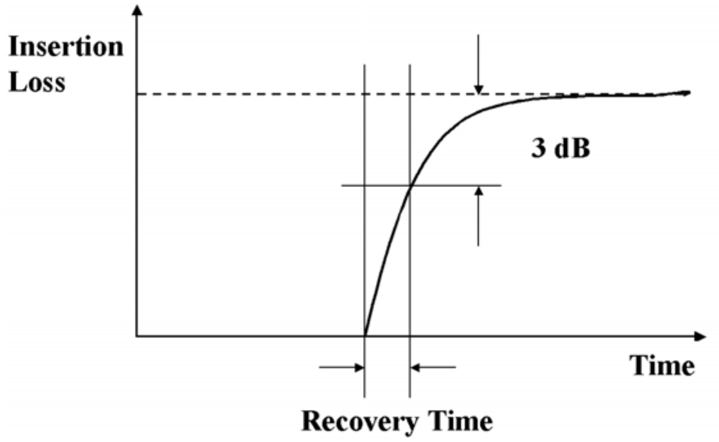


Figure 2.3 Definition of recovery time.

2.4.5 Off-state

This is the state where the limiter is not operating at all. In the off-state the limiter should be as transparent as possible, it should be well matched to the system and provide a very low noise figure.

2.4.6 Front-door coupling

The HPM radiation couples to equipment intended to communicate or interact with the external environment. Examples are antennas and sensors.

Front-door coupling, first order, is when the frequency of the HPM pulse coincides, at least partly, with the working frequency of the equipment. An example is a microwave target seeker, which as attacked in its pass band. Front-door coupling of the second order is when the frequency of the HPM pulse does not coincide with the working frequency of the equipment, but anyhow manages to couple through.

3 Front-door Protection Devices

Here follows a description of protective devices, which will be described regarding their performance. The components that are regarded as suitable for protection against HPM will later be further evaluated. These products will be purchased and measured in order to characterise their performance and ability to be integrated into array antennas or other systems.

3.1 Gas Discharge Tubes

Gas discharge tubes or GDTs are one of the most common protective devices against front-door coupling used in Radar and other RF applications. The working principle is based on electrical breakdown.

A GDT consists of two or more metal electrodes, which are hermetically sealed in a ceramic tube filled with gas. The gas is often a mixture of noble gases like neon or argon. The threshold level of the GDT can be controlled by adjusting the pressure of the gas or by changing the distance between the electrodes and by the selection of gas mixture.

When a transient with a sufficient amount of power occurs at the device, a potential is built up between the electrodes of the GDT. When the potential reaches the threshold level, ionisation of the gas is initiated. Once the gas is ionised breakdown occurs and a low impedance path to ground is formed. The transient is diverted away and the circuit is protected. The breakdown can be seen as an arc between the electrodes and the intensity of the light is proportional to the size of the current flowing between the electrodes. A GDT can handle very large peak currents (tens of kA) [5] and is therefore able to withstand high power transients. The advantages of a GDT are the low capacitance typically 0,5 to 2 pF [2], which enables it for use at higher frequencies and its relatively low price. The drawbacks of a GDT are the rather slow response time typically of the order of 0,5 μs [9] and the recovery time is also rather slow. In addition, once breakdown has been achieved, the arc may not be extinguished once the transient has passed. This effect can distort the normal signal. However the breakdown between electrodes can in some cases also be very fast, see section 3.2.

The lifetime of a GDT is finite and depends on the number of transients and the size of them. For large transients the GDT will only withstand a few cycles of successful protection. The gas discharge tube could be interesting to use in a combination with other types of limiters as a hybrid protection device. Primarily it could be suitable as a first stage in a protective circuit.

3.2 Air Gap Protection

The air gap protection consists of two metal electrodes, which are separated by a thin gap of air. The principle of operation for this device is much the same as for gas discharge tubes. When a transient with sufficient amount of power hits the air gap, a potential between the electrodes starts to build up. When the potential is high enough, the threshold voltage is reached and breakdown occurs. This kind of protective device is not hermetically sealed and is therefore working at atmospheric pressure and under the influence of different weather conditions. This leads to corrosion of the electrodes, which results in degradation of the overall performance of the air gap. The degradation is mainly seen as an increase of the threshold voltage and an increase of the response time. The response time can be as fast as 5 ps [17]. This type of limiter is not suitable for protection of low voltage circuits due to a too high threshold level. More information of this type of limiter can be found in [13].

3.3 Carbon Block Protection

The Carbon block protection is also one of the oldest forms for protection against voltage transients. It has usually been used as a primary protection. The principle of the carbon block is similar to the principle of gas discharge tubes. The carbon block consists of a pair of carbon elements, which is separated by a thin layer (~ 0.1 mm) of air. The carbon elements of the device are not hermetically sealed, which results in similar performance suffering as the air gap protection device.

When a transient reaches the carbon block a potential is built up between the carbon elements. When the potential reaches the threshold level a breakdown is triggered, and the transient is shunted to ground. One of the drawbacks for this component is that it is relatively unpredictable, the threshold level can vary between 400 to 570 Volts [20]. It is not suitable for protection of low voltage circuitry due to a too high threshold level.

3.4 Ferrite Limiter

The ferrite limiter is usually integrated in a waveguide. The ferrite material is mounted on the inside walls of the waveguide and is biased using permanent magnets. The limiter acts like a piece of dielectrically loaded waveguide in the off-state [14]. When in the off-state, the electrons of the ferrite are precessing around the magnetic field lines. This state is kept until a transient hits the limiter and the threshold value of the limiter is reached. Then the energy that is exceeding the threshold is coupled into the precession motion of the electrons. The energy is absorbed by the ferrite and converted to heat. The advantages are the unlimited life time and that this is an all solid state device.

The disadvantages of this type of limiter are that the insertion loss in the off-state is relatively high, it can only withstand medium power levels and it is relatively sensitive to temperature variations. More information on this component is to be found in [14].

3.5 Diode Limiters

There are a variety of different diode limiters available on the market. The diode limiter is a component which effectively clamps the transient over voltage, in particular transients with low currents and fast rise times. The threshold voltage of a diode can be adjusted by the level of doping and by introducing an intrinsic region between the P and N Regions. In order to use diode limiters for higher frequencies the PN-junction capacitance must be kept low, this results in a comparably small area. When a transient strikes, all of the shunted energy is forced to pass through the small junction of the doped areas. The energy is converted to heat, which can be very intense for transients with high energy. This lack of ability to handle high currents is the major limitation of the diode limiter. The diode limiter may be degraded or destroyed if it is exposed to current transient outside the specified working range. Typical power working range is up to a couple of Watts. There are two mechanisms of breakdown which are of interest: Avalanche breakdown and Zener Breakdown. More information can be found in [2], [14] and [18].

3.5.1 PN Diode Limiters

Zener breakdown is caused by an intense electric field at the PN-junction. The electric field causes the electrons to be torn out of its covalent bonds and accelerated to the N region which results in a current [14]. Zener breakdown occurs at low voltages (a few Volts), without triggering the avalanche mechanism.

The Zener diode limiter is an excellent component for clamping transients with very fast rise times and short duration, the response time is sometimes claimed to be less than 1 ps (theoretically) [21]. The threshold voltage is usually lower then 5 Volts [2]. The limiter has a small geometry and thereby a small junction capacitance which makes it suitable for protection of high frequency integrated circuits. Despite a small geometry the limiter is capable of protecting of 100-1500 W transients, depending on the shape of the transient. This type of components will be further investigated.

Avalanche breakdown involves impact ionisation of atoms and occurs at a higher voltage than Zener breakdown. The principle of avalanche breakdown is as follows, if an electron is in the transition region on its way to the N-side and if the electric field is large enough to give the electron sufficient kinetic energy to cause impact ionisation when it collides with a host atom, the impact releases an electron which is accelerated with the original electron causing further collisions. Hence we have an avalanche effect resulting in an increase of current [14].

The response time for avalanche diode limiters can be as low as a few ps [6].
When the avalanche diode is used as limiter, it is common to use two diodes in parallel, in a so called back-to-back connection, this way transients of both polarities can be shunted away. One of the disadvantages is the limited current handling capability. One advantage is the capability of protecting up to 6000 W transient. The threshold voltage of an avalanche diode limiter is 5-400 Volt. This component will be further investigated.

3.5.2 PIN Diode Limiters

PIN diode limiter got the name from its structure, it is an intrinsic region sandwiched between doped P- and N-regions. The intrinsic region is made of a material that has no intentional impurities and hence no defects in its lattice. The intrinsic region is important to the properties of the diode, by varying the thickness of the I-region the threshold voltage can be adjusted. The VPIN diode is vertically built PIN diode, seen in figure 3.1. The vertical structure minimizes the parasitic capacitances. The advantages of PIN/VPIN diode limiters are low insertion loss, fast response and recovery times in the order of ns and they can be made with a very wide bandwidth. The power handling capability is in the medium range, with peaks of 100 W. The PIN/VPIN diode is a suitable for protection of receiver circuits and will be further investigated.

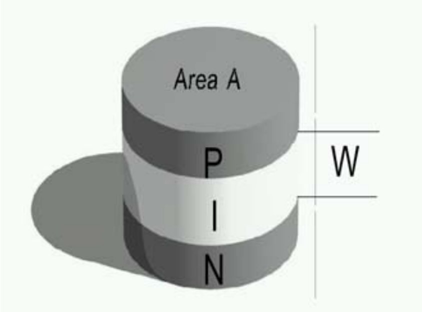


Figure 3.1 VPIN diode chip outline, taken from [18].

3.6 PUFET (Protectors against Ultra-Fast Electrical transients)

A PUFET [12] can be considered as a very fast electrical switch, it is based on the fast switching activity that occurs in thin amorphous semiconductors when they are exposed to high electric fields. This phenomena is called the Ovchinsky effect. The switching mechanism involves the resistance being affected and decreased by several orders of magnitude, thereby providing a short circuit to ground. When a transient strikes it is partly shunted away and partly reflected away. The response time of this mechanism is truly rapid 0.05 ns [12], the recovery time is somewhat slower, usually in the range of a few µs.

There are two different types of PUFET, The sandwich structured and the co-planar structured. Both the structures can be matched for use in a 50 Ω system and have a threshold voltage of 5 to 500 Volts. The bandwidth of the PUFET depends on how it is mounted. The bandwidth with a coaxial mounting is from DC to 12 GHz and if the Pufet is integrated as an integrated circuit it acquires a bandwidth of DC to 60 GHz [12]. The sandwich structured PUFET is designed to handle transients of 1 to 2 kVolts, with a rise time of 1 ns. The other type of PUFET, the co-planar structured is designed to withstand transients up to 1 kVolts, with a rise time of 0.3 ns. This type of PUFET is mounted in a coaxial transmission line. Both types of PUFET have the disadvantage of finite lifetime. The lifetime is dependent on the amount of energy the transient has and the number of transients. The availability and characteristics of PUFETs will be further investigated [12].

3.7 Metal OxideVaristor (MOV)

The metal oxide varistor is a semiconductor component where a metal oxide, usually zink oxide, is used as a voltage controlled resistance with a non-linear voltage/current dependence. This Limiter component has a very high resistance when operating in its normal working range, but when it is exposed to high voltage transients that exceeds the threshold voltage the resistance is rapidly decreased and the device provides a low impedance path to ground that diverts the transient away.

The response time from when the threshold voltage is exceeded, until the voltage is clamped can be as low as 0.1 ns [1]. Due to its construction the MOV clamps transients of both polarities. The capability of handling large voltages (tens of kV) and high currents (1 kA) is good.

The lifetime of the MOV is finite and depends on the size and number of transients, the larger transient, the fewer successful clamping actions. To extend the lifetime of a MOV, several MOVs can be connected in parallel, this way the energy from the transient is divided among the MOVs. The price for a MOV is relatively low. One disadvantage is that with increasing number of transients the electrical properties are degraded. It also has a moderate self capacitance (~100 pf or more), which can corrupt the signal. The properties of the MOV will be further investigated.

3.8 Thyristor Limiter

The Thyristor limiter can be used as protection against medium size voltage transients and it uses a crowbaring component based on the avalanche mechanism. The normal operating voltage starts at 12 Volts but devices are available with higher operating voltage, up to several hundreds of Volts. The capability of diverting currents depend on the size as well as structure of the component. Under normal operating conditions the limiter is as good as transparent. The breakdown voltage is 20% to 30% higher than the normal operating voltage level which is typically 12 volts or higher. When a voltage transient strikes the component is transitioned to the on-state, once in this state a current starts to flow that shunts the transient away. In order to return to the off-state the current through the device must drop below the minimum holding current. The advantages of the thyristor limiter are large current handling capability at a low threshold and that it has a low capacitance which makes it suitable for higher frequencies. The disadvantages on the other hand include a large variation of threshold level, vulnerable to high peak current. The Thyristor limiter will be further investigated. It could be suitable as a part in a hybrid limiter device. More information on the Thyristor limiter can be found in [10] and [11].

3.9 Selenium Cells

Selenium Cell transient suppressors use the technology of selenium rectifiers combined with a special process, this allows high breakdown current energy, without damaging the structure. The construction of a selenium cell is done by developing rectifiers on the surface of a metal plate substrate. This structure has the ability to dissipate heat well and withstand high energy transients. The selenium cell was once a popular surge protection device, but the clamping ability was not better than the MOV (Metal Oxide Varistor). Therefore the selenium cell was replaced in the 1960s by the more modern MOV (Metal Oxide Varistor) used today.

3.10 Breakdown in Antenna Slots

Breakdown in antenna slots is a limiting technique that is under development. The basic principle is that the air in the slot is ionised by high energy microwave pulses, see paragraph 3.1 and 3.2. The geometric features of the slot and the dielectric properties of the antenna substrate decides the threshold level. For more information see [3] and [15].

3.11 Research of Transient Protective Devices in GaAs MMIC

A GaAs MMIC shottky limiter has recently been designed at FOI. The circuits have been delivered to FOI and are soon to measured on and evaluated. Such a limiter device could easily be integrated with a receiver front-end design in GaAs MMIC. Depending on the properties of this limiter, it could be used as a last stage in limiter chain with other limiting devices. Similar devices for front-end protection have been ordered and will be investigated and characterised.

Also in this case the limiters has to be evaluated with respect to the external threat but also with respect to the failure levels of the GaAs MMIC circuit that is intended to be protected. These failure levels, e.g. in terms of energy as a function of pulse length, will be investigated experimentally.

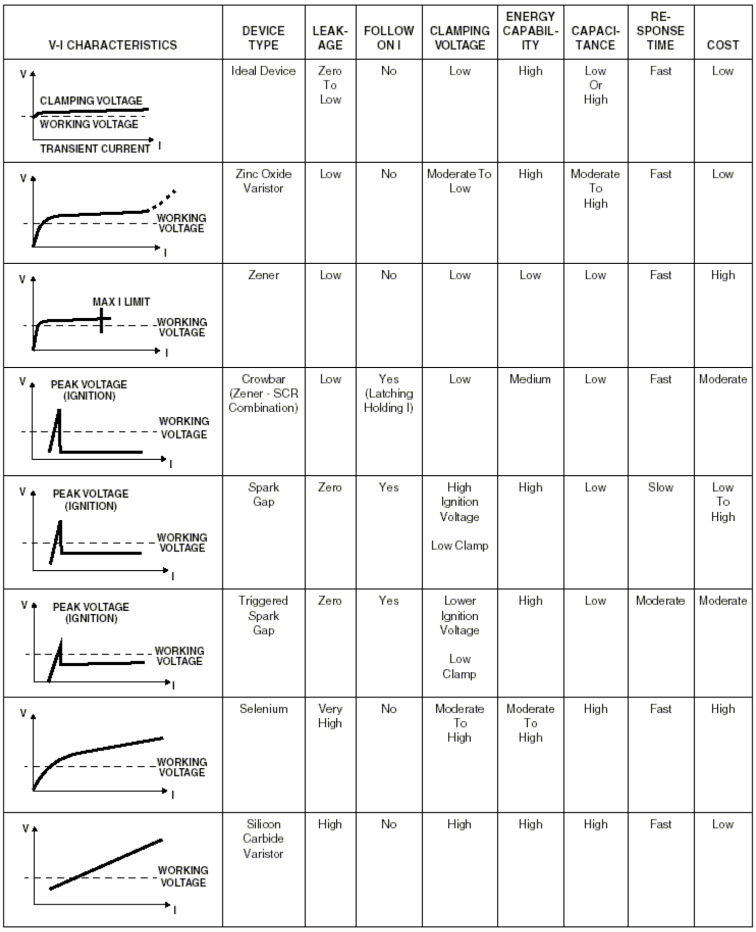
4 Selecting the Transient Voltage Suppressor

There are a few of the protective devices above that are of interest for protection against HPM. There are many considerations to take before selecting a proper protection technology. The decision to select the proper protection is based on the several criteria. One is what we are supposed to protect?

For example: An integrated circuit have a rather low nominal operating voltage, that narrows the choice of limiter in terms of threshold voltage and if the operating frequency of the circuit is wideband perhaps 2 to 18 GHz, this narrows the choices of limiter even further.

Other design criteria to be considered are what type of surge are we protecting against? The energy or power content of the surge as well as the duration needs to be estimated. Also size is important in order to integrate limiters into an antenna array. Rise times and repetitiveness of the surges are other important issues.

This has to be based on the external threat defined in paragraph 2.3 above together with the features pf primary protection devices such as slot discharges described in paragraph 3.10.



V-I CHARACTERISTICS	DEVICE TYPE	LEAKAGE	FOLLOW ON I	CLAMPING VOLTAGE	ENERGY CAPABILITY	CAPACITANCE	RESPONSE TIME	COST
V CLAMPING VOLTAGE WORKING VOLTAGE TRANSIENT CURRENT I	Ideal Device	Zero To Low	No	Low	High	Low Or High	Fast	Low
V WORKING VOLTAGE I	Zinc Oxide Varistor	Low	No	Moderate To Low	High	Moderate To High	Fast	Low
V MAX I LIMIT WORKING VOLTAGE I	Zener	Low	No	Low	Low	Low	Fast	High
V PEAK VOLTAGE (IGNITION) WORKING VOLTAGE I	Crowbar (Zener - SCR Combination)	Low	Yes (Latching Holding I)	Low	Medium	Low	Fast	Moderate
V PEAK VOLTAGE (IGNITION) WORKING VOLTAGE I	Spark Gap	Zero	Yes	High Ignition Voltage Low Clamp	High	Low	Slow	Low To High
V PEAK VOLTAGE (IGNITION) WORKING VOLTAGE I	Triggered Spark Gap	Zero	Yes	Lower Ignition Voltage Low Clamp	High	Low	Moderate	Moderate
V WORKING VOLTAGE I	Selenium	Very High	No	Moderate To High	Moderate To High	High	Fast	High
V WORKING VOLTAGE I	Silicon Carbide Varistor	High	No	High	High	High	Fast	Low

Figure 4.1 Comparison of different limiter technologies, taken from [21].

4.1 Hybrid Circuits

The hybrid circuit is a combination of two or more protection technologies. This is probably the most reasonable alternative. A single technology cannot provide the overall protection needed. A common combination is a mix of diode limiter and MOV technology. The avalanche diodes provide a very rapid response time to transients, while the metal oxide varistor gives the large current capacity needed in many applications. It is no less important to achieve acceptable noise figure and physical size for this combination, while providing a sufficient protection.

5 Future Work

The future work will consist in selecting and to purchase the most interesting limiters. These will then be measured, in order to properly characterise their behaviour. Using the experimental measurement set-up assembled by FOI's Olof Lundén, the limiters can be measured in the range of 0.5-18 GHz with insertion of power up to 30 W [16] see figure 5.1. This measurement set up allows measurement of coaxial mounted components and it is probably possible to measure also on surface mounted components using a fixture with coaxial connections. Mainly coaxial component will be purchased due to their ability to be easily be measured. The International standards [23] for measurements on limiter components will be considered. Parameters that are of major concern are response time, bandwidth, size, etc

It is also in our interest to investigate the properties of the load, in terms of what power/energy levels as a function of pulse length it can withstand without failure. This leads to the specification of leakage power for the limiter.

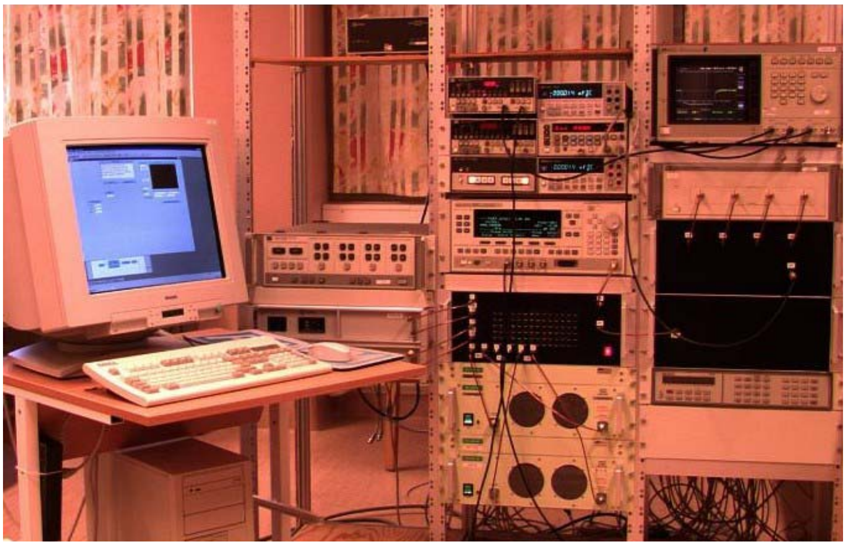


Figure 5.1 Picture of the experimental measurement set up.

6 Summary

An overview of protective devices is given in this report. There are a variety of devices used for protection of receivers and other sensitive components. Diode limiters can be used for protection against surges with fast rising edges, while gas discharge tubes (GDTs) and metal oxide varistors (MOVs) can be used against slower surges with higher amplitude. A combination of limiters with different characteristics is probably essential to get a good enough performance. For high frequency limiters it is important to have a low capacitance in order to minimize the insertion loss and noise figure, otherwise the overall system performance will be seriously degraded. The performance of different limiter will be experimentally investigated as well as failure levels of circuits aimed to be protected. In the near future, we intend to experimentally investigate the following types of protection devices:

- Gas discharge tubes

- Diode limiters

- Metal oxide varistors

- Thyristor limiters

- MMIC integrated limiters

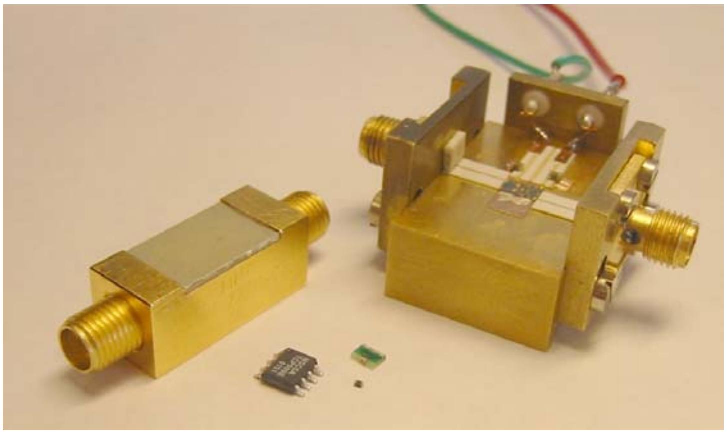


Figure 6.1 Picture of different limiters used for tests.

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Appendix

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Information from	[11]	Thyristor Surge Protective Device Application, page 33-35
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G.D.T application notes

Semitron GREENTUBE™ Gas Discharge Tubes (G.D.T.s) are manufactured using totally non-radioactive processes and are designed to perform to the stated characteristics of ITU (formally CCITT) K12.

OPERATION

The Gas Discharge Tube (G.D.T.) operates as a voltage dependent switch. When a voltage appears across the device which is greater than its breakdown voltage, known as the Sparkover Voltage, an arc discharge takes place within the tube which creates a low impedance path by which the surge current is diverted.

When this arc discharge takes place, the voltage level is maintained irrespective of the discharge current. When the transient has passed, the G.D.T. will reset to its non conducting state, providing the voltage of the system is below the Holdover Voltage of the G.D.T.

The ability to handle very high current surges, whilst limiting over voltages, is one of the most significant aspects of a G.D.T. performance, typically 5000 AMPS and up to 10,000 AMPS. This is defined as the Impulse Discharge capability.

The very low capacitance (typically 1-2pF) and very high insulation resistance (greater than 1GΩ) of the G.D.T. ensures that it has virtually no effect on the protected system during normal operating conditions.

Fail safe devices

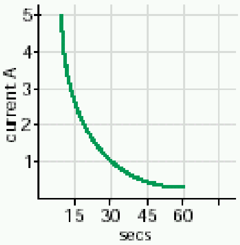
In normal operation, or when conducting short duration transients (spikes) the G.D.T does not generate any significent or detectable heat.

Under conditions of conducting mains electricity for extended periods (power cross), any G.D.T will generate excessive thermal energy, even to the point where its electrodes will glow `cherry red'. If a G.D.T is to be used in areas where this hazzard is a possibility then a failsafe can be fitted. These devices are spring loaded 'switches' which are normally insulated to ensure non conduction. When the G.D.T temperature rises, the insulation is destroyed allowing the device to create a short circuit between the G.D.T centre and line terminals. This short circuit is of low resistance and will conduct the fault current without generating any significant heat.

The operation of these devices are tested at the manufacturing facility in accordance with the test methods specified by British Telecom. The testing consists of applying mains electricity with current limiting to certain specified values. At each current value a maximum reaction time is specified.

Two types of failsafe are available. Select "F" for wrap-around type and "W" for wire slalom type. (Note: "W" is only available on the R pin configuration). Type "F" failsafe devices are not compatible for most wave soldering methods: hand soldering is possible with care.

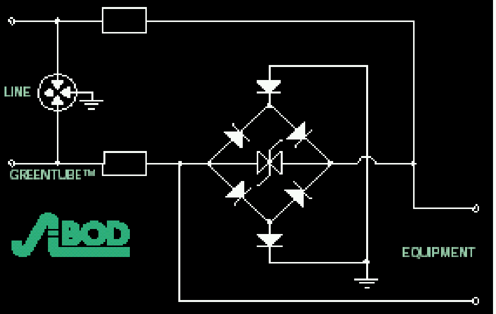
FAIL SAFE OPERATION
TIME vs AC CURRENT



All products are sold to the commercial specifications shown, for any additional reliability testing or extended parameters, please consult the factory.

Applications

Low Capacitance Protection

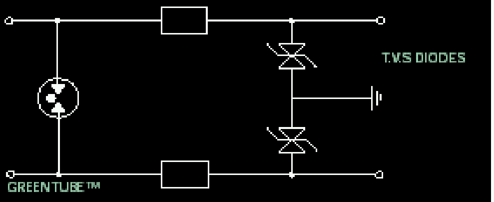


Telephone System:

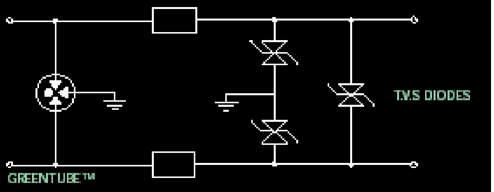
- MDF Protection
- PABX
- NTE

- Low capacitance
- Fast response

HDSL:



Telephone System:



Semitron hybrid applications

The Semitron Hybrid is an over voltage surge protection device utilising both gas tube and semi-conductor technologies, resulting in a package that delivers the high current handling capability of the GDT with the speed of a silicon device.

Compatible with standard gas tube arrester outlines it can be easily fitted or ex-changed into most board or magazine connection systems. eg Krone™ LSA - plus 5B and Quante 79126-506 00 magazines.

As electronic equipment becomes evermore complex, it has also now become more sensitive, and therefore prone to damage due to transients at lower voltage levels.

The hybrid series provides protection for sensitive electronic equipment where a standard GDT installation proves ineffective by allowing too much let through voltage against ultra fast transients. The precision matching of the GDT and the semiconductor TVS eliminates the dv/dt switching delay normally associated with GDT's giving lower clamping levels and better protection whilst maintaining its ability to divert high energy pulses, i.e 5KA 8/20µ sec.

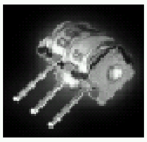
Already approved and trialed by BT, the hybrid - provides the ultimate in over-voltage circuit protection.

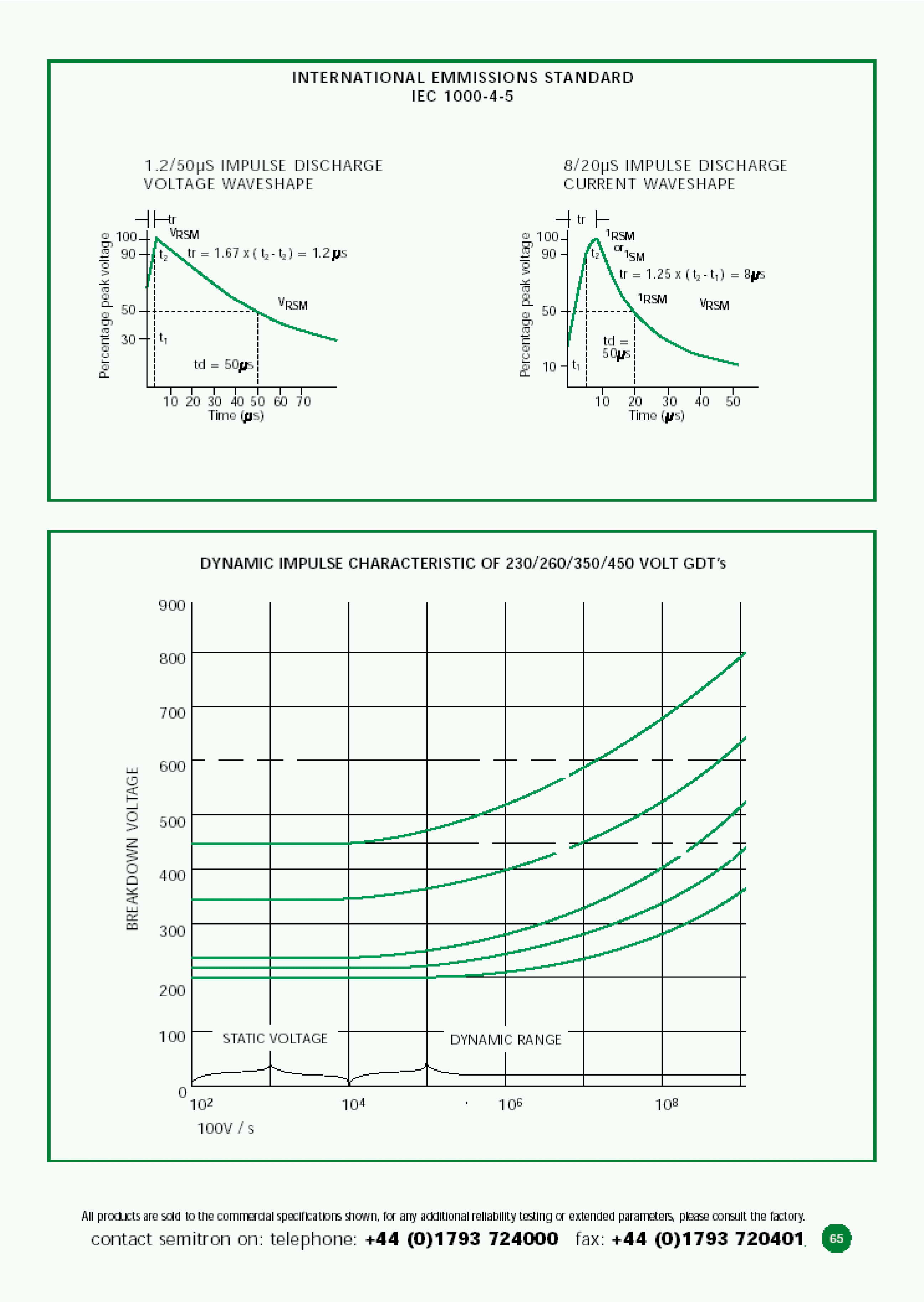
FEATURES

- Fast response, ie. no dv/dt switching delay
- High current handling capability, 5KA 8/20µs defined by IEC 1000-4-5
- High insulation resistance
- Typ Capacitance <100pF @ 1MHz
- No series resistive element for switching co-ordination
- Compatible with most GDT connection systems
- Approved for BT systems
- Integral failsafe

BENEFITS

- Increased level of protection for sensitive electronic equipment
- No need for separate primary and secondary protectors
- Low leakage current
- Can be used on most telecom and electronic applications
- No extra component cost
- No modifications of existing hardware
- Proven performance to the highest of standards
- Prevents hazardous temperature conditions





INTERNATIONAL EMMISSIONS STANDARD
IEC 1000-4-5

1.2/50µS IMPULSE DISCHARGE
VOLTAGE WAVESHAPE

8/20µS IMPULSE DISCHARGE
CURRENT WAVESHAPE

DYNAMIC IMPULSE CHARACTERISTIC OF 230/260/350/450 VOLT GDT's

All products are sold to the commercial specifications shown, for any additional reliability testing or extended parameters, please consult the factory.

contact semitron on: telephone: **+44 (0)1793 724000** fax: **+44 (0)1793 720401**

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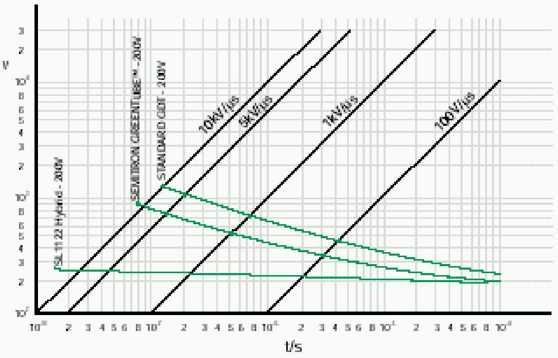
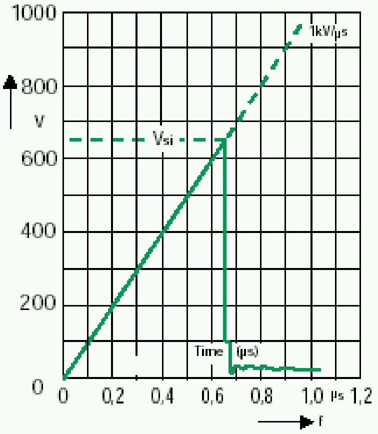
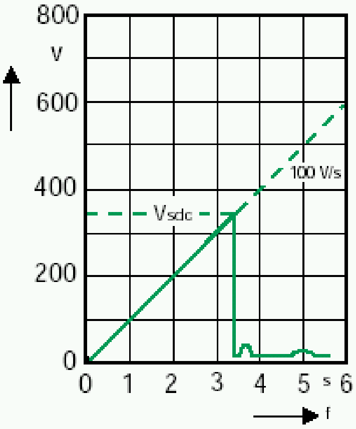
IMPULSE BREAKDOWN AGAINST VOLTAGE RAMP RATE





Impulse sparkover voltage referenced to a voltage with a rise time of dv/dt = 1kv/µsec



DC sparkover voltage is determined by applying a voltage with a low rate of rise dv/dt = 100V/sec

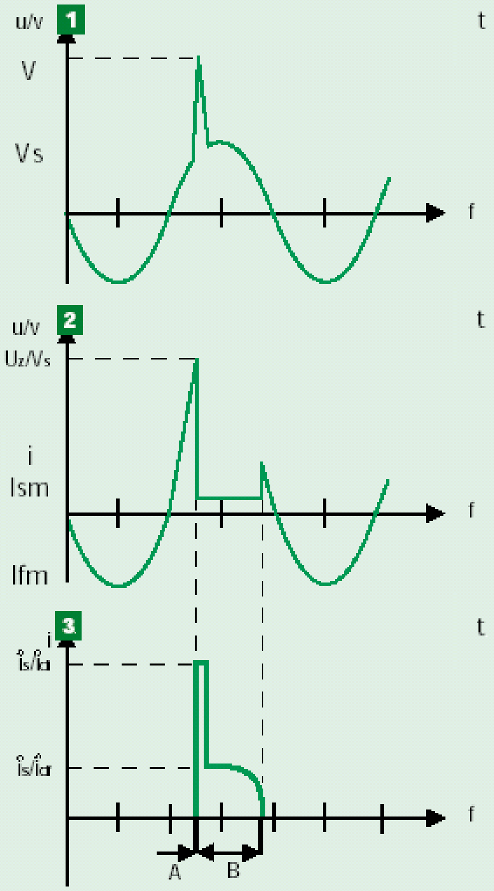


Figure 1
AC operating voltage and superimposed impulse voltage

Figure 2
Impulse voltage (Vsi) limited by a GREENTUBE™

Figure 3
Impulse discharge current (Ism) and follow-on current (Ifm), through the GREENTUBE™.

Glossary of terms

DC SPARKOVER

This is the voltage at which the arrester breaks down when subjected to a slow rising voltage, normally at a rate of 100V / second. The D.C Sparkover value maybe specified as an upper and lower limit or a nominal voltage with a tolerance, normally ± 20%, unless otherwise stated.

IMPULSE SPARKOVER

This is the voltage at which the arrester breaks down when subjected to a much faster rate than the D.C Sparkover. The rate of rise for the Impulse Sparkover is 1KV/µs. The specified value is the maximum voltage at which the breakdown can occur.

IMPULSE DISCHARGE CURRENT

This is the maximum value of current that the arrester can stand whilst remaining within the specified limits. This current maybe specified as 5KA or 10KA, depending on type. This current has a waveform of 8/20µs, (as specified by IEC 1000-5-5 formally IEC 801-5) and is applied to the arrester 5 times each polarity with 3 minute intervals. This test is termed as a destructive test and is designed to test the durability of the arrester.

ALTERNATING DISCHARGE

Like the Impulse Discharge Current, this is also termed as a destructive test. It is designed to simulate a condition where mains electricity comes into contact with the telephone line. The arrester is subject to a 1 second burst, 5 AMPS @ 50HZ. This is repeated 5 times each polarity with 3 minute intervals. After this test the arrester should stay within specified limits.

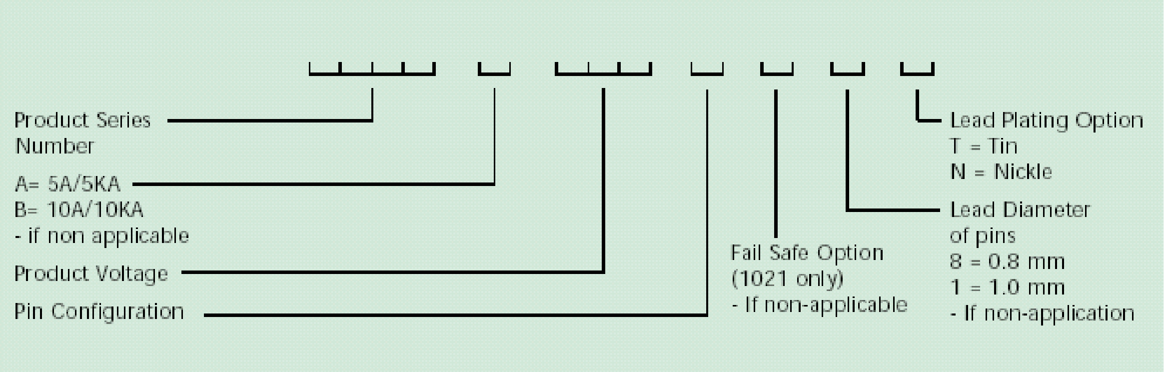
INSULATION RESISTANCE

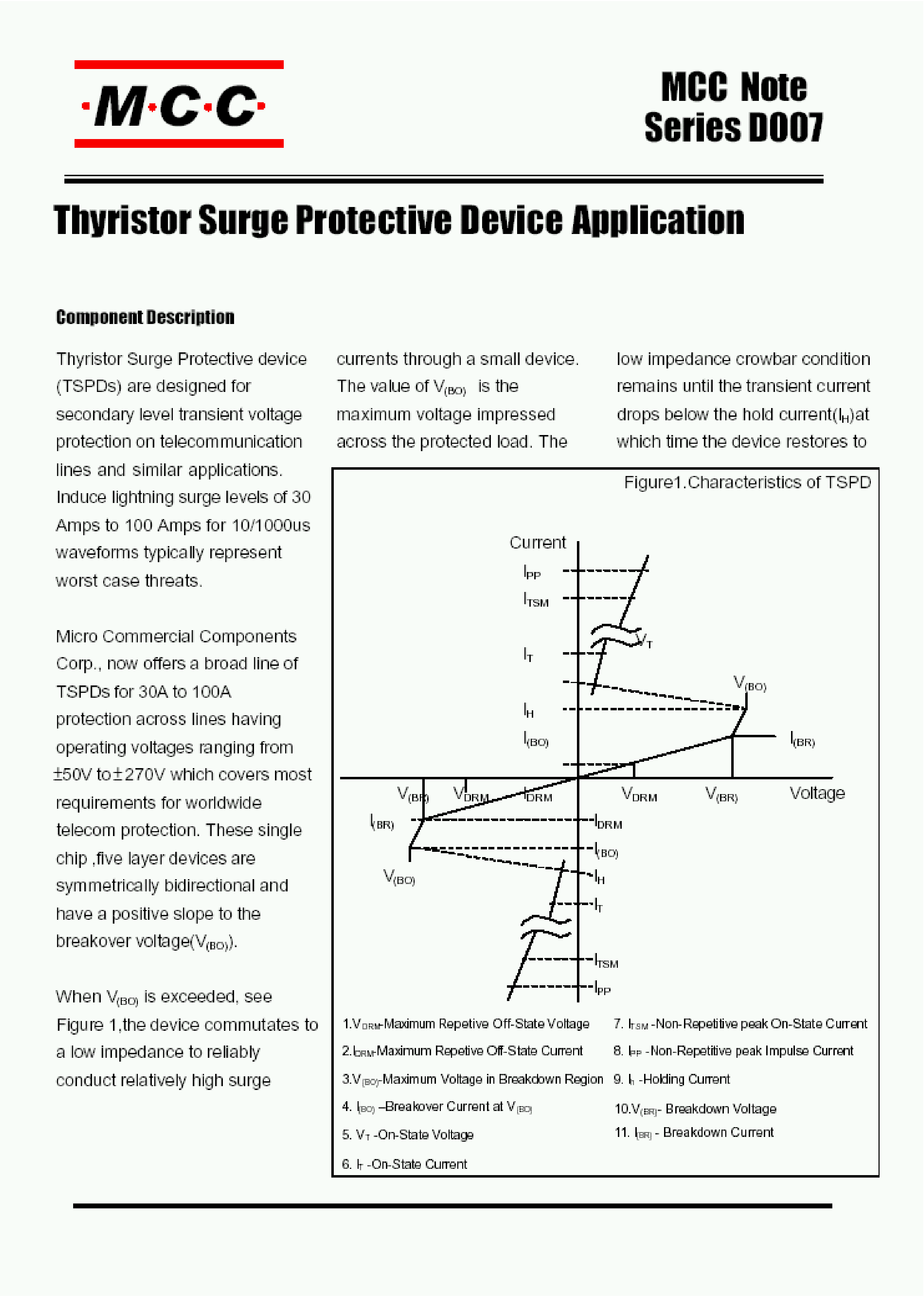
This is the measured resistance of the arrester at a given voltage, which is normally the voltage of the system it is designed to protect.

HOLDOVER VOLTAGE

Once the arrester has broken down due to a transient, it will remain in the low impedance arc mode until the voltage across it falls below a certain value, known as the Holdover Voltage. It is important when selecting an arrester that it has a Holdover Voltage in excess of the system voltage.

HOW TO ORDER





MCC Note
Series D007

Thyristor Surge Protective Device Application

Component Description

Thyristor Surge Protective device (TSPDs) are designed for secondary level transient voltage protection on telecommunication lines and similar applications. Induce lightning surge levels of 30 Amps to 100 Amps for 10/1000us waveforms typically represent worst case threats.

Micro Commercial Components Corp., now offers a broad line of TSPDs for 30A to 100A protection across lines having operating voltages ranging from ±50V to±270V which covers most requirements for worldwide telecom protection. These single chip ,five layer devices are symmetrically bidirectional and have a positive slope to the breakover voltage($V_{(BO)}$).

When $V_{(BO)}$ is exceeded, see Figure 1,the device commutates to a low impedance to reliably conduct relatively high surge currents through a small device. The value of $V_{(BO)}$ is the maximum voltage impressed across the protected load. The low impedance crowbar condition remains until the transient current drops below the hold current(I_H)at which time the device restores to

Figure1.Characteristics of TSPD

1.V_{DRM}-Maximum Repetive Off-State Voltage
2.I_{DRM}-Maximum Repetive Off-State Current
3.$V_{(BO)}$-Maximum Voltage in Breakdown Region
4. $I_{(BO)}$ –Breakover Current at $V_{(BO)}$
5. V_T -On-State Voltage
6. I_T -On-State Current
7. I_{TSM} -Non-Repetitive peak On-State Current
8. I_{PP} -Non-Repetitive peak Impulse Current
9. I_h -Holding Current
10.$V_{(BR)}$- Breakdown Voltage
11. $I_{(BR)}$ - Breakdown Current

·M·C·C·

MCC Note
Series D007

its nonconductive mode. The TSPD characteristic curve and electrical parameters are shown in figure 1.

MCC has intentionally Designed its TSPDs for positve resistance $V_{(BO)}$ to minimize false triggering of circuits. This can occur with low surge current levels that do not commutate TSPDs to their conductive mode. Positive resistance will also prevent partial turn-on or partial turn-off conditions in a negative resistance region reducing undesired oscillation effects.

A broad selection of packages is available including axial lead surface mount and chip for hybrid applications. Methods of specifying these configurations are described in the date sheet.

Device Nomenclature

The MCC part numbering system assists the user in choosing the appropriate part for his application. The first three to five characters identify the package style. The first two digits in the part number define the rated surge current at 10/1000us, 05 for 50 A and 10 for 100 A. The maximum operating voltage, V_{DRM} is derived from the last two digits, e.g., 05 identifies a 50V part, 14 for 140V.

For example in selecting a surface mount device for a 240 volt application with 50 Amp surge capability, "TSMBJ" designates the surface mount package, 05 defines the 50 A rated surge current and 24 indicates the operating voltage of 240V.The assembled part number becomes TSMBJ0524C with the C suffix designation bi-directional electrical parameters.

Protective Applications

MCC TSPDs are qualified to UL497B," Protectors for Data Communication and Fire Alarm Circuits," as further referenced by General spec UL1459 for Telecommunication circuits. Package encapsulate meets the flame retardant requirements of UL 94VO. On a telecom twisted pair, surges occur in the differential mode (metallic; line-to-line) and common mode (longitudinally: line to ground). The least severe are metallic surge, specified in FCC Part 68 as 800V, 100A Peak with a 10/560us waveform. Figure 2 illustrates protection in this mode.

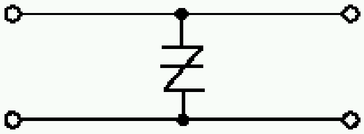


Figure 2. Configured for Metallic Surge Protection.

Here, only one TSPD is required. the voltage rating of the device will depend on the application, typically a 50V to 60V rated off-state voltage part for data on non-ringing communication lines and a 240V to 270V rated device where ringing voltages are present. This is an approximate for US applications; however, requirements vary with national codes and designs. For additional protection, series resistance can be added to the incoming lines for surge current reduction. Fuses or positive temperature coefficient (PTC) devices can also be placed in series with the incoming line for severe overstress conditions. Protection from the more severe longitudinal surges, 1500V, 200A 10/160us,along with metallic Surges, also requires a TSPD from each line-to-ground as

MCC Note
Series D007

shown in Figure 3.The devices used must have an operating voltage equal to the circuit voltage.

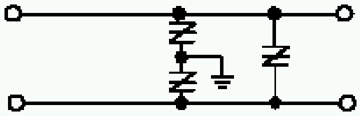


Figure 3. Metallic & Longitudinal Transient Protection.

Depending on the circuit requirements, resistance may be added to increase the surge impedance thus lowering the delivered surge current.Also a fuse or PTC device may be added for supplementary protection from follow current.

Another option for providing both metallic and longitudinal transient protection is illustrated in figure 4. In this configuration, each device is rated at one-half of operating voltage as the voltage is impressed across two devices in series. For example, a 240V operation circuit would use 120V rated parts as their individual operation voltage are additive.

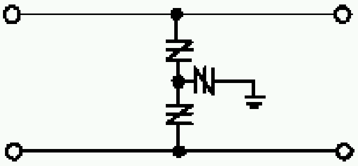


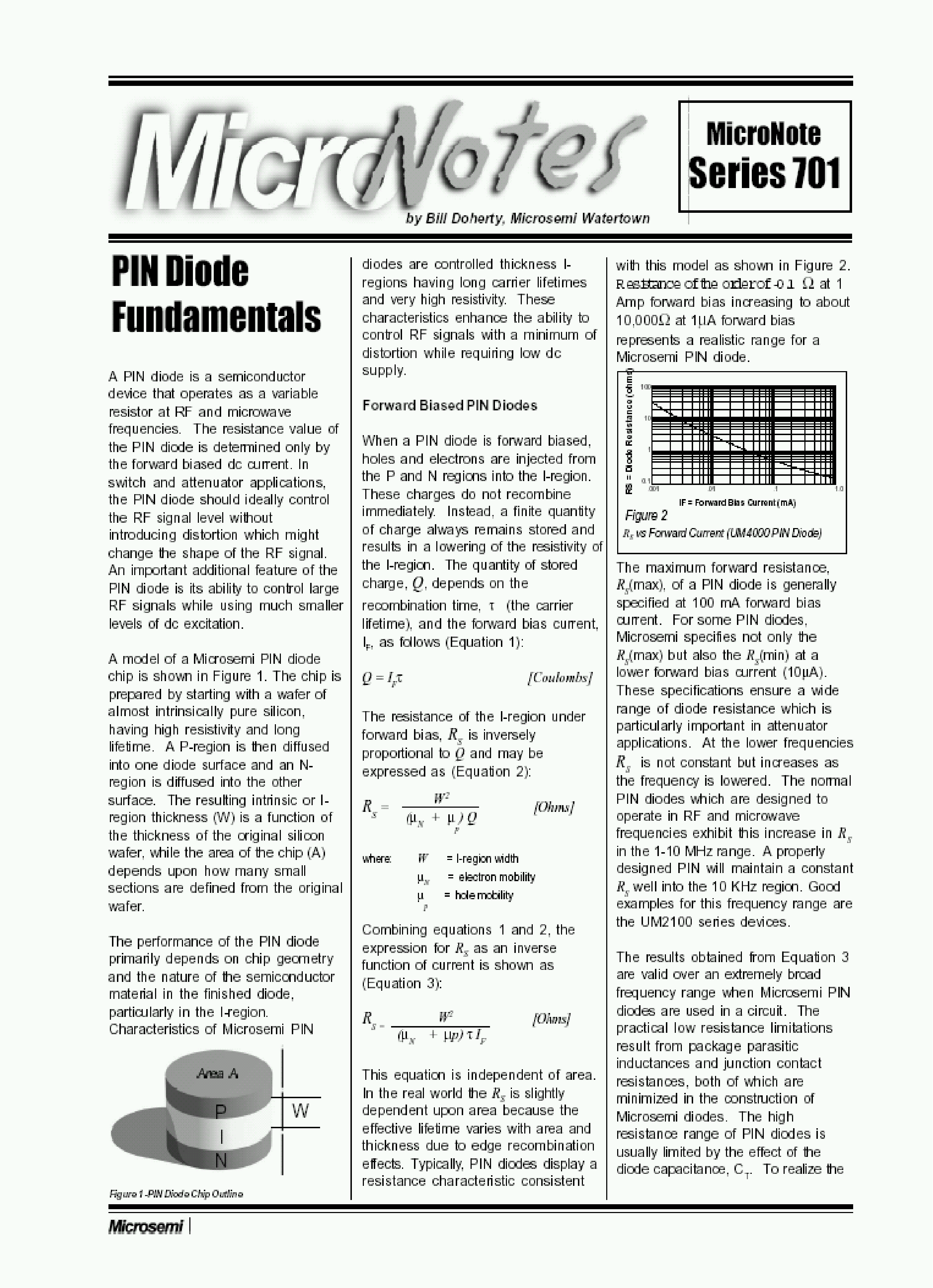
Figure 4. Alternative Protection Method for Metallic and Longitudina Surges.

TSPD Crowbar Suppressors Compared to Avalanche TVSs

Regardless of the operating voltage, whether 50V or 270V, TSPDs in a given family will withstand the same current because devices over the entire rang commutate to the same low impedance state during conduction. Thus power disspation during . conduction is the same for each device over the entire voltage range.

TSPDs are applicable only where the source impedance or " load line" has a sufficient level to permit the normal operating current to again drop below the minimum holding current (I_H) after a surge event allowing the device to restore to the nonconduction mode.

By comparison, the maximum surge current (I_{PP}) capability of a pn junction TVS of any specifiedoperating voltage level is limited by its power issipation, (clamping voltage times surge current). Thus the surge current is inversely proportional to the voltage and decreases as the perating voltage increases. These pn junction TVSs are largely used for low-level surge protection in iow voltage circuits. They also provide excellent protection from fast rising electrostatic discharge threats. High source impedance load lines are not required to ensure turn-off.



MicroNotes

MicroNote Series 701

by Bill Doherty, Microsemi Watertown

PIN Diode Fundamentals

A PIN diode is a semiconductor device that operates as a variable resistor at RF and microwave frequencies. The resistance value of the PIN diode is determined only by the forward biased dc current. In switch and attenuator applications, the PIN diode should ideally control the RF signal level without introducing distortion which might change the shape of the RF signal. An important additional feature of the PIN diode is its ability to control large RF signals while using much smaller levels of dc excitation.

A model of a Microsemi PIN diode chip is shown in Figure 1. The chip is prepared by starting with a wafer of almost intrinsically pure silicon, having high resistivity and long lifetime. A P-region is then diffused into one diode surface and an N-region is diffused into the other surface. The resulting intrinsic or I-region thickness (W) is a function of the thickness of the original silicon wafer, while the area of the chip (A) depends upon how many small sections are defined from the original wafer.

The performance of the PIN diode primarily depends on chip geometry and the nature of the semiconductor material in the finished diode, particularly in the I-region. Characteristics of Microsemi PIN diodes are controlled thickness I-regions having long carrier lifetimes and very high resistivity. These characteristics enhance the ability to control RF signals with a minimum of distortion while requiring low dc supply.

Figure 1 -PIN Diode Chip Outline

Forward Biased PIN Diodes

When a PIN diode is forward biased, holes and electrons are injected from the P and N regions into the I-region. These charges do not recombine immediately. Instead, a finite quantity of charge always remains stored and results in a lowering of the resistivity of the I-region. The quantity of stored charge, Q, depends on the recombination time, τ (the carrier lifetime), and the forward bias current, I_F, as follows (Equation 1):

$$Q = I_F \tau \qquad [Coulombs]$$

The resistance of the I-region under forward bias, R_S is inversely proportional to Q and may be expressed as (Equation 2):

$$R_S = \frac{W^2}{(\mu_N + \mu_P)\,Q} \qquad [Ohms]$$

where: W = I-region width
μ_N = electron mobility
μ_P = hole mobility

Combining equations 1 and 2, the expression for R_S as an inverse function of current is shown as (Equation 3):

$$R_S = \frac{W^2}{(\mu_N + \mu p)\,\tau\, I_F} \qquad [Ohms]$$

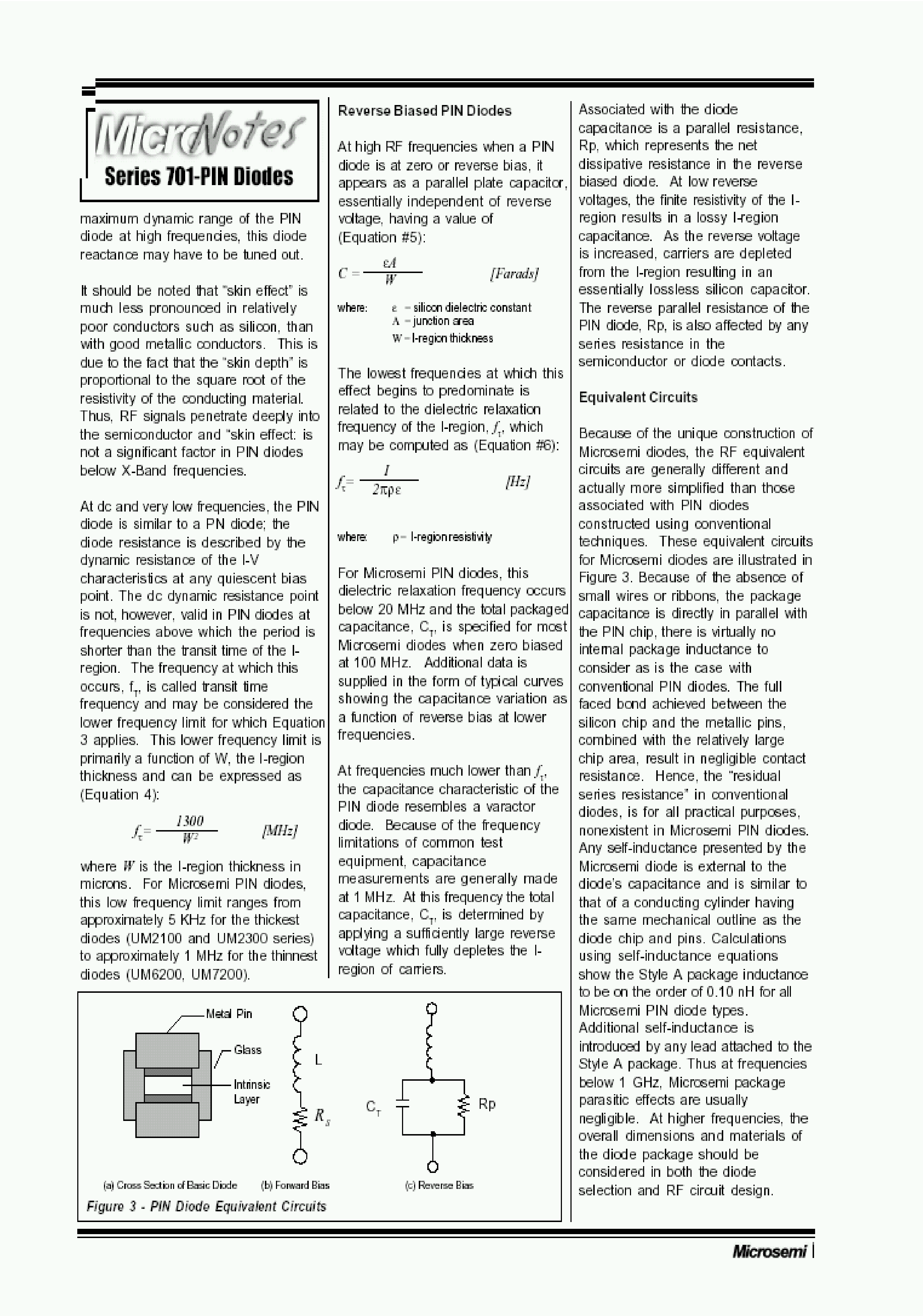
This equation is independent of area. In the real world the R_S is slightly dependent upon area because the effective lifetime varies with area and thickness due to edge recombination effects. Typically, PIN diodes display a resistance characteristic consistent with this model as shown in Figure 2. Resistance of the order of .01 Ω at 1 Amp forward bias increasing to about 10,000Ω at 1μA forward bias represents a realistic range for a Microsemi PIN diode.

Figure 2
R_S vs Forward Current (UM4000 PIN Diode)

The maximum forward resistance, R_S(max), of a PIN diode is generally specified at 100 mA forward bias current. For some PIN diodes, Microsemi specifies not only the R_S(max) but also the R_S(min) at a lower forward bias current (10μA). These specifications ensure a wide range of diode resistance which is particularly important in attenuator applications. At the lower frequencies R_S is not constant but increases as the frequency is lowered. The normal PIN diodes which are designed to operate in RF and microwave frequencies exhibit this increase in R_S in the 1-10 MHz range. A properly designed PIN will maintain a constant R_S well into the 10 KHz region. Good examples for this frequency range are the UM2100 series devices.

The results obtained from Equation 3 are valid over an extremely broad frequency range when Microsemi PIN diodes are used in a circuit. The practical low resistance limitations result from package parasitic inductances and junction contact resistances, both of which are minimized in the construction of Microsemi diodes. The high resistance range of PIN diodes is usually limited by the effect of the diode capacitance, C_T. To realize the

Microsemi



MicroNotes
Series 701-PIN Diodes

maximum dynamic range of the PIN diode at high frequencies, this diode reactance may have to be tuned out.

It should be noted that "skin effect" is much less pronounced in relatively poor conductors such as silicon, than with good metallic conductors. This is due to the fact that the "skin depth" is proportional to the square root of the resistivity of the conducting material. Thus, RF signals penetrate deeply into the semiconductor and "skin effect: is not a significant factor in PIN diodes below X-Band frequencies.

At dc and very low frequencies, the PIN diode is similar to a PN diode; the diode resistance is described by the dynamic resistance of the I-V characteristics at any quiescent bias point. The dc dynamic resistance point is not, however, valid in PIN diodes at frequencies above which the period is shorter than the transit time of the I-region. The frequency at which this occurs, f_T, is called transit time frequency and may be considered the lower frequency limit for which Equation 3 applies. This lower frequency limit is primarily a function of W, the I-region thickness and can be expressed as (Equation 4):

$$f_T = \frac{1300}{W^2} \qquad [MHz]$$

where W is the I-region thickness in microns. For Microsemi PIN diodes, this low frequency limit ranges from approximately 5 KHz for the thickest diodes (UM2100 and UM2300 series) to approximately 1 MHz for the thinnest diodes (UM6200, UM7200).

Reverse Biased PIN Diodes

At high RF frequencies when a PIN diode is at zero or reverse bias, it appears as a parallel plate capacitor, essentially independent of reverse voltage, having a value of (Equation #5):

$$C = \frac{\varepsilon A}{W} \qquad [Farads]$$

where: ε = silicon dielectric constant
A = junction area
W = I-region thickness

The lowest frequencies at which this effect begins to predominate is related to the dielectric relaxation frequency of the I-region, f_T, which may be computed as (Equation #6):

$$f_T = \frac{1}{2\pi\rho\varepsilon} \qquad [Hz]$$

where: ρ = I-region resistivity

For Microsemi PIN diodes, this dielectric relaxation frequency occurs below 20 MHz and the total packaged capacitance, C_T, is specified for most Microsemi diodes when zero biased at 100 MHz. Additional data is supplied in the form of typical curves showing the capacitance variation as a function of reverse bias at lower frequencies.

At frequencies much lower than f_T, the capacitance characteristic of the PIN diode resembles a varactor diode. Because of the frequency limitations of common test equipment, capacitance measurements are generally made at 1 MHz. At this frequency the total capacitance, C_T, is determined by applying a sufficiently large reverse voltage which fully depletes the I-region of carriers.

Associated with the diode capacitance is a parallel resistance, Rp, which represents the net dissipative resistance in the reverse biased diode. At low reverse voltages, the finite resistivity of the I-region results in a lossy I-region capacitance. As the reverse voltage is increased, carriers are depleted from the I-region resulting in an essentially lossless silicon capacitor. The reverse parallel resistance of the PIN diode, Rp, is also affected by any series resistance in the semiconductor or diode contacts.

Equivalent Circuits

Because of the unique construction of Microsemi diodes, the RF equivalent circuits are generally different and actually more simplified than those associated with PIN diodes constructed using conventional techniques. These equivalent circuits for Microsemi diodes are illustrated in Figure 3. Because of the absence of small wires or ribbons, the package capacitance is directly in parallel with the PIN chip, there is virtually no internal package inductance to consider as is the case with conventional PIN diodes. The full faced bond achieved between the silicon chip and the metallic pins, combined with the relatively large chip area, result in negligible contact resistance. Hence, the "residual series resistance" in conventional diodes, is for all practical purposes, nonexistent in Microsemi PIN diodes. Any self-inductance presented by the Microsemi diode is external to the diode's capacitance and is similar to that of a conducting cylinder having the same mechanical outline as the diode chip and pins. Calculations using self-inductance equations show the Style A package inductance to be on the order of 0.10 nH for all Microsemi PIN diode types. Additional self-inductance is introduced by any lead attached to the Style A package. Thus at frequencies below 1 GHz, Microsemi package parasitic effects are usually negligible. At higher frequencies, the overall dimensions and materials of the diode package should be considered in both the diode selection and RF circuit design.

(a) Cross Section of Basic Diode (b) Forward Bias (c) Reverse Bias

Figure 3 - PIN Diode Equivalent Circuits

Transient Voltage Surge Suppression (TVSS) Component Technology

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This document contrasts Metal Oxide Varistor (MOV) and Silicon Avalanche Diode (SAD) technologies used in modern hard-wired TVSS designs. Both MOV's and SAD's have been in use for many years as surge mitigation components. There are proper and improper performance at the component level, much progress has been made in recent years in the correct application and design of these components in built-up TVSS systems.

The favored application for SAD's is at the Printed Circuit Board (PCB) level as a final stage of surge suppression. The SAD has a very tight voltage clamp characteristic, a very fast response speed, but very low energy (surge current) capability. Due to the short lead lengths possible in PCB applications, SAD's ideally take advantage of their speed and voltage clamping characteristics. When used as final stage in surge suppression, the low SAD surge current capability is not a problem. SAD's will survive at the PCB level when downstream of more robust surge suppression.

MOV's provide an excellent compromise of voltage clamping, response time, and energy handling capability. Perhaps this is why MOV's are used in over 95% of hard-wired TVSS designs either exclusively or in hybrid with other components. At the component level, an MOV will not clamp as low nor as fast as an SAD. When these components are assembled into a TVSS system, the difference between MOV and SAD performance is lost. This results from the impedance in the electrical connections between the component or group of components and the electrical distribution system. In a real-world, TVSS installations there must be several inches or several feet of cable or buss bar as well as overcurrent protection separating the surge suppression components from the power line surge. Since overvoltage surges are of high frequency, the connection impedance acts to slow the response and raise the clamping of the connected suppression component. This results in a very similar system performance for both MOV and SAD hard-wired TVSS. The high energy handling capability of MOV's, however, allows them much greater survivability in a power distribution system.

Hybrid systems using both MOV's and SAD's in parallel are perceived as having "the best of both worlds". In hard-wired TVSS, due to the connection impedance, this is often not the case. In fact, the weakest link of the hybrid is the SAD, resulting in an increase in overall TVSS system failure!

Liebert offers a series / parallel filter TVSS combination, the Active Tracking Filter System, which outperforms any parallel TVSS design. This is a hybrid of MOV's with inductive and capacitive filter elements.

Many hard-wired TVSS designs use several components connected together in parallel to achieve higher energy handling capability

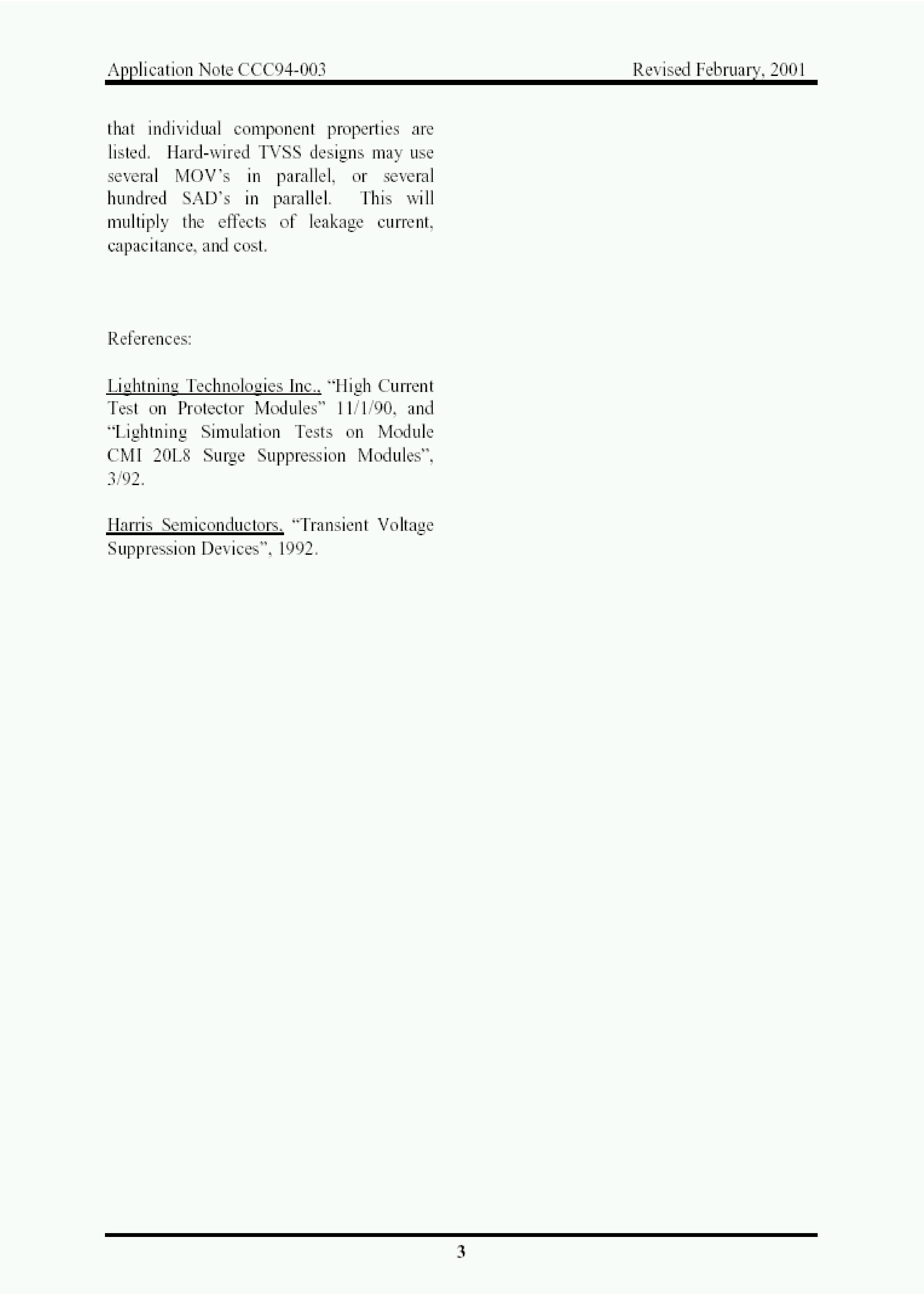
and lower surge impedance. Paralleling of components works if done properly. There are many factors to consider, such as overcurrent protection, tolerance, and uniformity of components, uniformity of lead length, and manufacturing quality control. The more components used in parallel the more these factors will add to or detract from anticipated performance. Only a few MOV's in parallel will approach the energy handling capability of a spark gap device. Many SAD's, often in the hundreds, are required to approach the energy handling capacity of a single MOV!

TVSS overcurrent protection is the most important (and often overlooked) aspect of reliability and safety. Any TVSS component can fail, open or shorted, due to surge voltage stress or Temporary Over Voltage (TOV) stress. This TOV stress causes many more TVSS failures than actual transient surges. TOV stress often causes a component with on fuse (or breaker) may not clear this type of failures. The result may be smoke, fire, or explosion. This occurs regularly in real-world TVSS installations. Even if a main overcurrent protective device safely clears the failure, all the surge protection is lost on a phase or the entire system. The answer to this dilemma is component level fusing. Done properly, this fusing will interrupt excessive continuous current through the component, interrupt available utility fault current, but pass transient current. Component level fusing in a TVSS can provide a fail-safe system preventing catastrophic failure or complete loss of protection. Individual component level fusing of SAD's is difficult because of the great number of SAD's required for hard-wired TVSS. SAD's are normally group fused whereas MOV's can be individually fused.

The Liebert TVSS design utilizes carefully matched and balanced MOV's, each individually fused. The fuse links will interrupt a high impedance MOV failure of a few amperes continuous. The fuse links are UL tested to interrupt up to 300KA of available utility fault current in the event of a short circuit failure. The fuse links will not interrupt rated surge current, however. Each MOV used in a Liebert TVSS is individually tested at the factory. MOV's are matched to within one volt at two points on the V-I curve. Over 10% of MOV's purchased are discarded. Through careful MOV matching, balancing, and quality control, Liebert achieves consistently high surge current ratings. These ratings are conservatively derived from independent laboratory testing. Please refer to the Lightning Technologies, Inc. test reports. With component level fusing, the Liebert TVSS is fail safe, only a fraction of the surge protection will be lost. Failed MOV's are cleared in a fair safe manner - without smoke, fire, explosion, or interruption of critical load power. Any failed MOV is apparent immediately because of continuous integrity monitoring of all components.

Hard-wired SAD TVSS designs require large quantities of components. This presents both an up front higher cost, as well as a long term maintenance / replacement expense. MOV designs are a lower cost up front. When modularly constructed, long-term maintenance costs are minuscule. Liebert offers a five year parts warranty as standard at no extra cost.

For an in depth MOV and SAD analysis, please refer to the Harris Semiconductor "Transient Voltage Suppression Devices" handbook, Chapter 2. Table 2.1 offers and excellent comparison of TVSS components. MOV's are listed as "Zinc Oxide Varistors". SAD's are listed a "Zeners". Please note



that individual component properties are listed. Hard-wired TVSS designs may use several MOV's in parallel, or several hundred SAD's in parallel. This will multiply the effects of leakage current, capacitance, and cost.

References:

Lightning Technologies Inc., "High Current Test on Protector Modules" 11/1/90, and "Lightning Simulation Tests on Module CMI 20L8 Surge Suppression Modules", 3/92.

Harris Semiconductors, "Transient Voltage Suppression Devices", 1992.