OVERVOLTAGE PROTECTION

Most semiconductor devices are intolerant of overvoltage transients in excess of their voltage ratings. Even a microsecond overvoltage transient can cause a semiconductor to fail catastrophically or may result in severe stress, reducing the useful life of the equipment. Overvoltage transients in electrical circuits result from the sudden release of previously stored energy. Some transients may be created in the circuits by inductive switching, commutation voltage spikes, and so on. Other transients may be created outside the circuit and then coupled into it. These can be caused by lightning, capacitor-bank switching at the substation, or similar phenomena. This article discusses overvoltage protection in terms of the following three categories:

1. Overvoltage transients
2. Overvoltage protection devices
3. Overvoltage protection for switch-mode power supplies

OVERVOLTAGE TRANSIENTS

Overvoltage transients in a low-voltage (600 V or less) ac power circuit originate from two major sources: system switching transients and direct or indirect lightning strikes on the power system. A sudden change in the electrical condition of any circuit will cause a transient voltage due to the stored energy in the circuit inductance or capacitance. Switching-induced transients are a good example of this; the rate of change of current (di/dt) in an inductor (L) will generate a voltage

$$V = -L di/dt \tag{1}$$

The transient energy is equal to

$$E = 1/2 L i^2 \tag{2}$$

This energy exists as a high-power impulse for a relatively short time ($J = Pt$). Consider an example as shown in Fig. 1. If load 2 is shorted, load 1 and/or the diode rectifier will be subjected to a voltage transient. As load 2 is shorted, the fuse will open and interrupt the fault current. The power supply will produce a voltage spike equal to Eq. (1) with an energy

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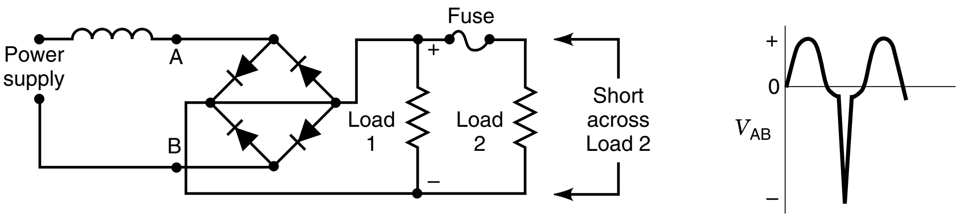


Figure 1. Overvoltage transient due to change of current in an inductor.

content of Eq. (2). This transient may be beyond the voltage limitations of the diode rectifiers and/or load 1. Switching out a high-current load will have a similar effect.

Energizing a Transformer Primary. When a transformer primary is energized at the peak of the supply voltage, the coupling of this voltage step function to the stray capacitance and inductance of the secondary winding can generate a transient voltage with a peak amplitude up to twice the normal secondary voltage. Figure 2 shows a circuit in which the secondary side is a part of the capacitive divider network in series with the transformer interwinding capacitance (C_S). This stray capacitance has no relation to the turns ratio of the transformer, and it is possible that the secondary circuit may see a substantial fraction of the applied primary peak voltage.

Deenergizing a Transformer Primary. The opening of the primary circuits of a transformer generates extreme voltage transients in excess of ten times the normal voltage. Interrupting the transformer magnetizing current, and the resulting collapse of the magnetic flux in the core, couples a high-voltage transient into the transformer's secondary winding, as shown in Fig. 3. Unless a voltage-limiting device is provided, this high-voltage transient appears across the load.

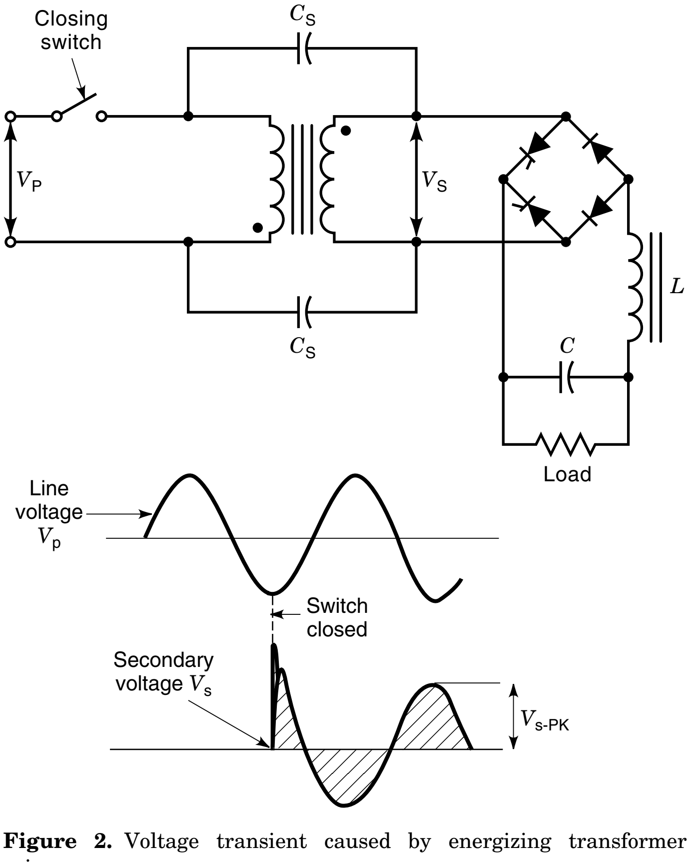


Figure 2. Voltage transient caused by energizing transformer primary.

Switch Arching. When the current in an inductive circuit, such as a relay coil or a filter reactor, is interrupted by a contactor, the inductance tries to maintain the current by charging the stray capacitance. Similar behavior can occur during closing if the contacts bounce open after the initial closing, as shown in Fig. 4. During the opening and closing of the electromechanical switches, the bouncing action of contacts can result in high-frequency overvoltage transients.

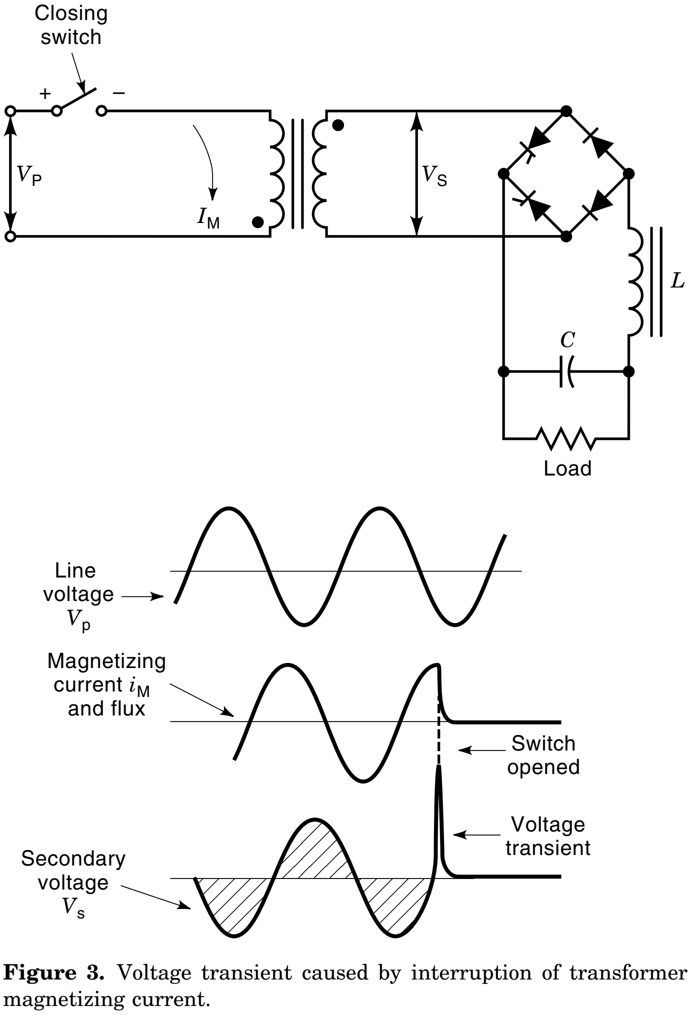


Figure 3. Voltage transient caused by interruption of transformer magnetizing current.

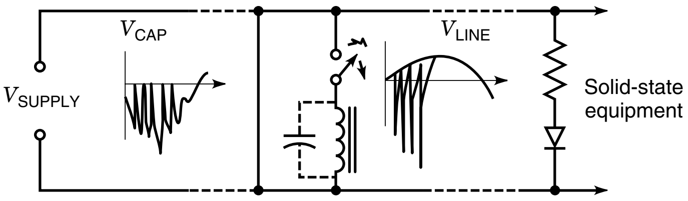


Figure 4. Voltage transients caused by switch arcing.

Random Transients

Overvoltage transients create the most confusion because it is difficult to define their amplitude, duration, and energy content. In general terms, the anticipated surge voltage level depends on the location of the equipment to be protected. When it is inside a building, the stress depends on the distance from the electrical service entrance to the equipment, the size and length of the connection wires, and the complexity of the branch circuits. IEEE Std. 587-1980 proposes three location categories for low-voltage ac power circuits that are representative of a majority of locations from the electrical service entrance to the most remote wall outlet. These categories are shown in Fig. 5 and described as follows:

1. *Category A: Outlets and Long Branch Circuits.* This is the lowest-stress category in which outlets and branch circuits are "long distance" from electrical service entrance. This category includes all outlets more than 10 m (30 ft) from category B with #14 to #10 AWG wires. It also includes all outlets more than 20 m (60 ft) from service entrance with #14 to #10 wires. In category A, the stress voltage may be of the order of 6 kV, but the stress current is relatively low, of the order of 200 A maximum.

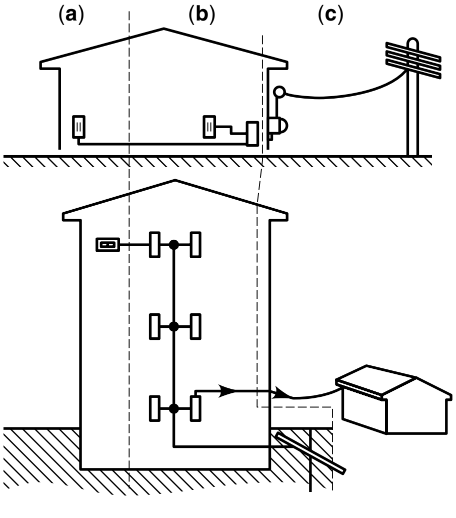


Figure 5. Location categories. (a) Outlets and Long Branch Circuits: All outlets at more than 10 m (30 ft) from Category B with wires #14 to #10; All outlets at more than 20 m (60 ft) from Category C with wires #14 to #10. (b) Major Feeders and Short Branch Circuits: Distribution panel devices; Bus and feeder systems in industrial plants; Heavy appliance outlets with "short" connections to the service entrance; Lighting systems in commercial. (c) Outside and Service Entrance: Service drop from pole to building entrance; Run between meter and distribution panel; Overhead line to detached buildings; Underground lines to well pumps.

2. *Category B: Major Feeders and Short Branch Circuits.* This category covers the highest-stress conditions likely to be subjected to an equipment power supply. It applies to distribution panel boards, bus and feeder systems in industrial plants, heavy appliance outlets with "short" connections to the service entrance, and lightning systems in commercial office buildings. Note that category B locations are closer to the service entrance, so stress voltage of the order of 6 kV and stress current level of up to 3000 A may be expected.
3. *Category C: Electrical Service Entrance and Outdoor Locations.* This location is defined as the power line between pole and electrical service entrance of a building. Very high stress conditions can occur. Since most of the sensitive electronic equipment will be in category A and B, within a partially protected environment inside the building, only protection to categories A and B is normally required.

Rate of Occurrences

The rate of occurrence of voltage transients varies over a wide range, depending on a particular power system, although low-level surges are more prevalent than high-level transients. Prediction of the rate of occurrence for a particular system is always difficult and frequently impossible. Data collected from various sources are the basis of the curves shown in Fig. 6.

1. *Low Exposure.* These are systems with little load-switching activity, which are located in geographical areas of light lightning activity.
2. *Medium Exposure.* Medium-exposure systems are in areas of frequent lightning activity and severe switching transients problems.
3. *High Exposure.* These are rare but real systems supplied by overhead lines and subject to reflections at line

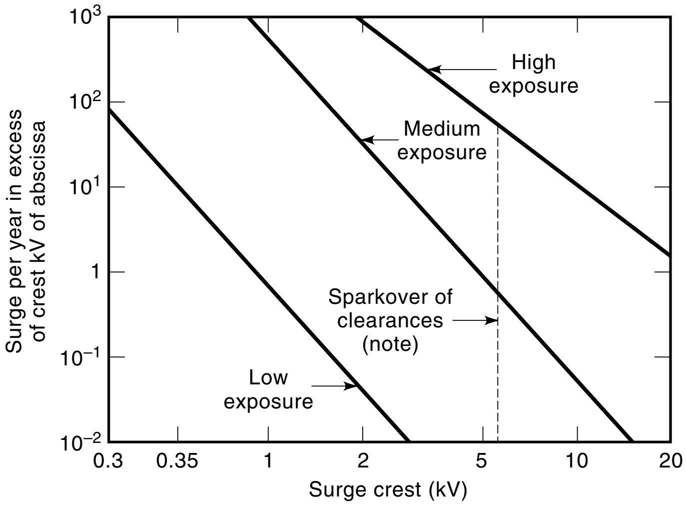


Figure 6. Rate of surge occurrence versus voltage level at unprotected locations. Note: In some locations, sparkover of clearances may limit the overvoltages.

Table 1. Surge Voltages and Current Deemed to Represent the Indoor Environment and Suggested for Consideration in Designing Protective Systems

Location Category	Comparable to IEC 664 Category	Impulse		Type of Specimen on Load Circuit	Energy (Joules) Deposited in a Suppressor[c] with Clamping Voltage of	
		Waveform	Medium-Exposure Amplitude		500 V (120 V System)	1000 V (240 V System)
A. Long branch circuits and outlets	II	0.5 ms–100 kHz	6 kV	High impedance[a]	—	—
			200 A	Low impedance[b]	0.8	1.6
B. Major feeders short branch circuits, and load center	III	1.2/50 μs	6 kV	High impedance[a]	—	—
		8/20 μs	3 kA	Low impedance[b]	40	80
		0.5 ms–100 kHz	6 kV	Low impedance[a]	—	—
			500 A	High impedance[b]	2	4

[a] For high-impedance test specimens or load circuits, the voltage shown represents the surge voltage. In making simulation tests, use that value for the open-circuit voltage of the test generator.

[b] For low-impedance test specimens or load circuits, the current shown represents the discharge current of the surge (not the short-circuit current of the power system). In making simulation tests, use that current for the short-circuit current of the test generator.

[c] Other suppressors which have different damping voltages would receive different energy levels.

ends, where the characteristics of the installation produce high sparkover levels of the clearances.

These data were taken from unprotected (no limiting voltage devices) circuits, meaning that the transient voltage is limited only by the sparkover distance of the wires in the distribution system.

Overvoltage Transient Waveforms

The definition of a transient waveform is critical for the design of overvoltage protection circuitry. An unrealistic voltage waveform with long duration of the voltage or very low source impedance requires a high-energy protection device, resulting a cost penalty to the end-user. IEEE Std. 587 defines two overvoltage current waveforms to represent the indoor environment recommended for use in designing protection devices. Table 1 describes the waveforms, open circuit voltage, source impedance, and energy stored in the protection circuitry.

1. *Category I.* The waveform shown in Fig. 7 is defined as "0.5 μs–100 kHz ring wave." This waveform is representative of category I indoor low-voltage (ac lines less than 600 V) system transients. This 100 kHz ring wave has a rise time of 0.5 μs (from 10% to 90% of its final amplitude), with oscillatory decay at 100 kHz, each peak being 60% of the previous one. The rapid rate of rise of the waveform can cause d*v*/d*t* problems in the semiconductors. The oscillating portion of the waveform produces voltage polarity reversal effects. Some semiconductors are sensitive to polarity changes or can be damaged when unintentionally turned on or off.

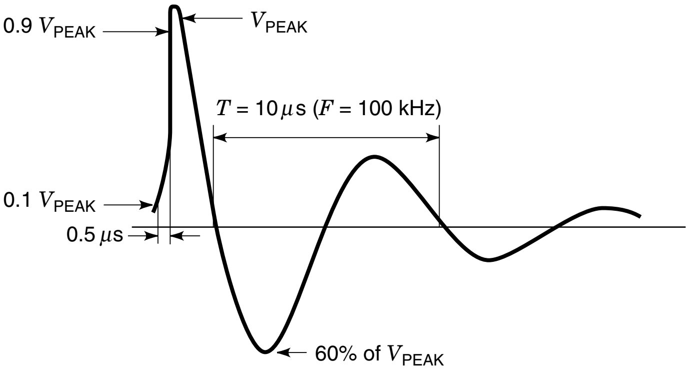


Figure 7. 0.5 μs to 100 kHz ring wave (open-circuit voltage).

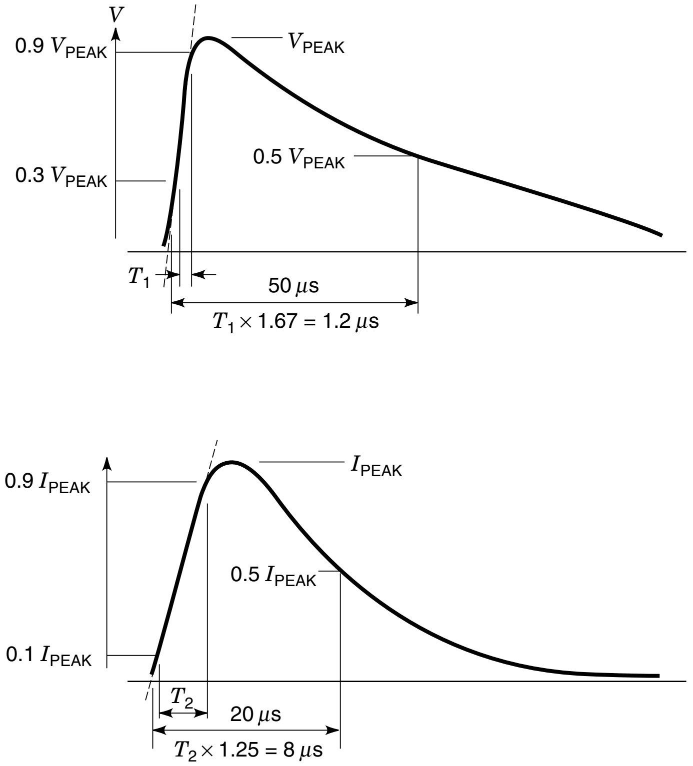


Figure 8. Unidirectional waveshapes.

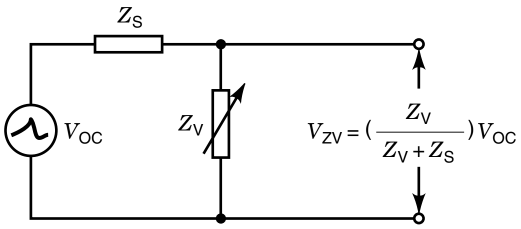


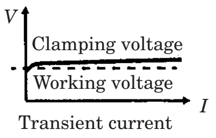
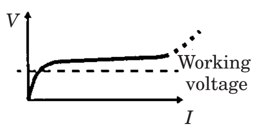
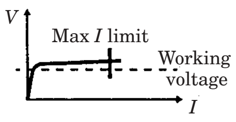
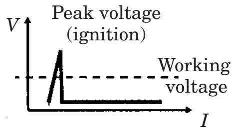
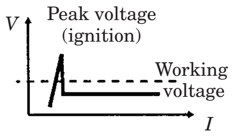
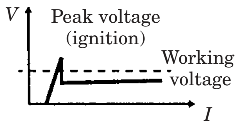
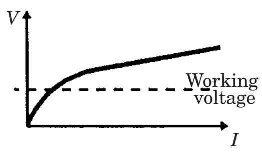
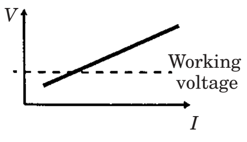
Figure 9. Voltage-clamping device.

2. *Category II.* In this category, close to the service entrance, much larger energy levels are encountered. Both oscillatory and unidirectional transients have been recorded in this outdoor environment. IEEE Std. 587 recommends two unidirectional waveforms and an oscillatory waveform for category II. These two waveforms are shown in Fig. 8. The various stress conditions are computed in Table 1.

OVERVOLTAGE PROTECTION DEVICES

There are two major categories of transient suppressors: (1) those that attenuate transients, thus preventing their propa-

Table 2. Characteristics and Features of Transient Voltage Suppressor Technology

V–I Characteristics	Device Type	Leakage	Follow on *I*	Clamping Voltage	Energy Capability	Capacitance	Response Time	Cost
	Ideal device	Zero to low	No	Low	High	Low or high	Fast	Low
	Zinc oxide varistor	Low	No	Moderate to low	High	Moderate to high	Fast	Low
	Zener	Low	No	Low	Low	Low	Fast	High
	Crowbar (Zener–SCR combination)	Low	Yes (latching holding *I*)	Low	Medium	Low	Fast	Moderate
	Spark gap	Zero	Yes	High ignition voltage Low clamp	High	Low	Slow	Low to high
	Triggered spark gap	Zero	Yes	Lower ignition voltage Low clamp	High	Low	Moderate	High
	Selenium	Very high	No	Moderate to high	Moderate to high	High	Fast	High
	Silicon carbide varistor	High	No	High	High	High	Fast	Relative low

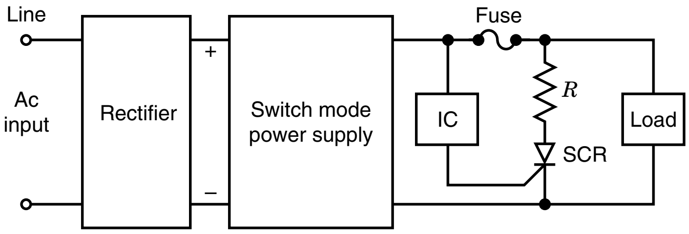


Figure 10. SCR crowbar overvoltage protection circuit for switching power supplier.

gation into the sensitive circuit; and (2) those that divert transients away from sensitive loads and so limit residual voltages. Attenuating a transient, that is, keeping it from propagating away from the source or keeping it from impinging on a sensitive load, is accomplished with series filters within a circuit. The filter, generally of low-pass type, attenuates the transients (high-frequency) and allows the signal or power flow (low-frequency) to continue undisturbed. Diverting a transient can be accomplished with a voltage-clamping device or with a "crowbar" type device.

Filters. The frequency of a transient is several orders of magnitude above the power frequency (50/60 Hz) of an ac circuit. Therefore, an obvious solution is to install a low-pass filter between the source of transients and the sensitive load. The simplest form of filter is a capacitor placed across the line. The impedance of the capacitor forms a voltage divider with the source impedance, resulting in attenuation of the transients at high frequencies. This simple approach may have undesirable effects, such as (1) unwanted resonance with inductive components located in the circuit resulting in high-peak voltages; (2) high capacitor in-rush current during switching, and (3) excessive reactive load on the power system voltage. These undesirable effects can be minimized by adding a series resistor (*RC* snubber circuit).

Voltage-Clamping Devices. A voltage-clamping device is a component having variable impedance depending on the current flowing through the device or on the voltage across its terminal. These devices exhibit nonlinear impedance characteristics. Under steady-state, the circuit is unaffected by the presence of the voltage-clamping device. The voltage-clamping action results from increased current drawn through the device as the voltage tends to rise. The apparent "clamping" of the voltage results from the increased voltage drop in the source impedance due to the increased current. It must be clearly understood that the device depends on the source impedance to produce clamping. One is seeing a voltage divider action at work, where the ratio of the division is nonlinear (Fig. 9). The voltage-clamping device cannot be effective with zero source impedance. Table 2 lists various types of voltage-clamping devices and their features and characteristics.

Crowbar Devices. Crowbar-type devices involve a switching action, either the breakdown of a gas between electrodes or turn-on of a thyristor. After switching on, the crow-bar device offer a very low impedance path which diverts the transient away from the parallel-connected load. These crowbar devices have two limitations. The first is their delay time, typically microseconds, which leaves the load unprotected during initial voltage rise. The second limitation is that a power current from the steady-state voltage source will follow the transient discharge current (called "follow current" or "power-follow").

OVERVOLTAGE PROTECTION FOR SWITCH-MODE POWER SUPPLIES

During fault conditions, most power supplies have the potential to deliver higher output voltages than those normally specified or required. If unprotected, the higher output voltage can cause internal and external equipment damage. To protect the equipment under these abnormal conditions, it is common practice to provide some means of overvoltage protection within the power supply. Overvoltage protection techniques for switch-mode power supplies fall broadly into three categories:

1. Simple SCR "crowbar" overvoltage protection
2. Overvoltage protection by voltage-clamping techniques
3. Overvoltage protection by voltage-limiting techniques

SCR "Crowbar" Overvoltage Protection

Figure 10 shows the principle of a SCR (silicon-controlled rectifier) "crowbar" overvoltage protection circuit connected to the output of a switch-mode power supply. If the output voltage increases under a fault condition, the SCR is turned on and a short-circuit is imposed at the output terminals via the

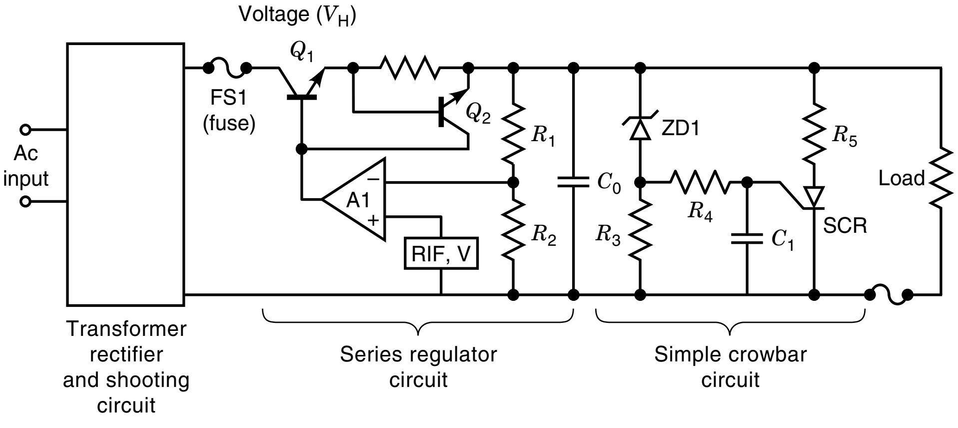


Figure 11. A simple SCR crowbar circuit for linear regulators.

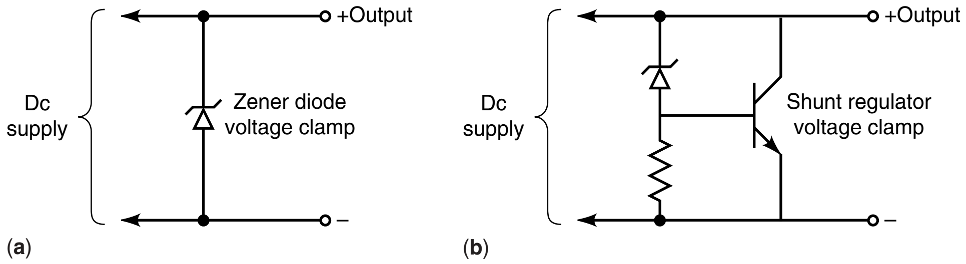


Figure 12. Shunt regulator type voltage clamp circuits.

resistor *R*, and the overvoltage condition is prevented. With linear regulator-type dc power supplies, SCR crowbar overvoltage protection is the normal protection method, and the simple circuit shown in Fig. 11 is often used. The linear regulator and crowbar operate as follows:

The dc output voltage, V_H, is regulated by a series transistor, Q1, to provide a lower but regulated output voltage, V_{out}. Amplifier A1 and resistors R1 and R2 provide the regulator voltage control, and transistor Q2 and current-limiting resistor R1 provide the current-limiting protection. The worst case overvoltage condition would be a short-circuit of the series-regulating device Q1 so that the higher unregulated voltage, V_H, is now presented to the output terminals. Under such fault conditions, both voltage control and current limiting actions are lost, and the crowbar SCR must be activated to short-circuit the output terminals.

In response to such a fault condition, the overvoltage protection circuitry in Fig. 11 responds as follows: As the voltage across the output terminals rises above the voltage-limiting threshold of the circuit, or zener diode ZD1 conducts the driving current via R4 into SCR gate C1. After a short delay defined by the values of C1, R4, and the applied voltage, C1 charges will reach gate firing voltage (0.6 V), and SCR will conduct to short-circuit the output terminals via low-value limiting resistor R5. However, a large current now flows from the unregulated dc input voltage through the shunt-connected SCR. To prevent overdissipation in the SCR, it is necessary to use a fuse, FS1, or circuit-breaker in the unregulated dc supply. If the series regulator device Q1 has failed, the fuse or circuit breaker now clears to disconnect the source from the output before the SCR is destroyed. This approach is popular for many noncritical applications. Although this circuit has the advantage of low cost and circuit simplicity, it has ill-defined operating voltage, which can cause large operating spreads. Design modifications can be incorporated to overcome these limitations.

Overvoltage Clamping Technique

In low-power applications, overvoltage protection may be provided by a simple clamp action. In many cases, a shunt-connected zener diode is sufficient to provide the required overvoltage protection [see Fig. 12(a)]. If higher current capability is required, a more powerful transistor shunt regulator may be used [Fig. 12(b)]. It should be noted that when a voltage clamp device is employed, it is highly dissipative, and the source resistance must limit the current to acceptable levels. Hence, shunt clamping action can be used only where the source resistance (under failure conditions) is large. In many cases, shunt protection of this type relies on the action of a

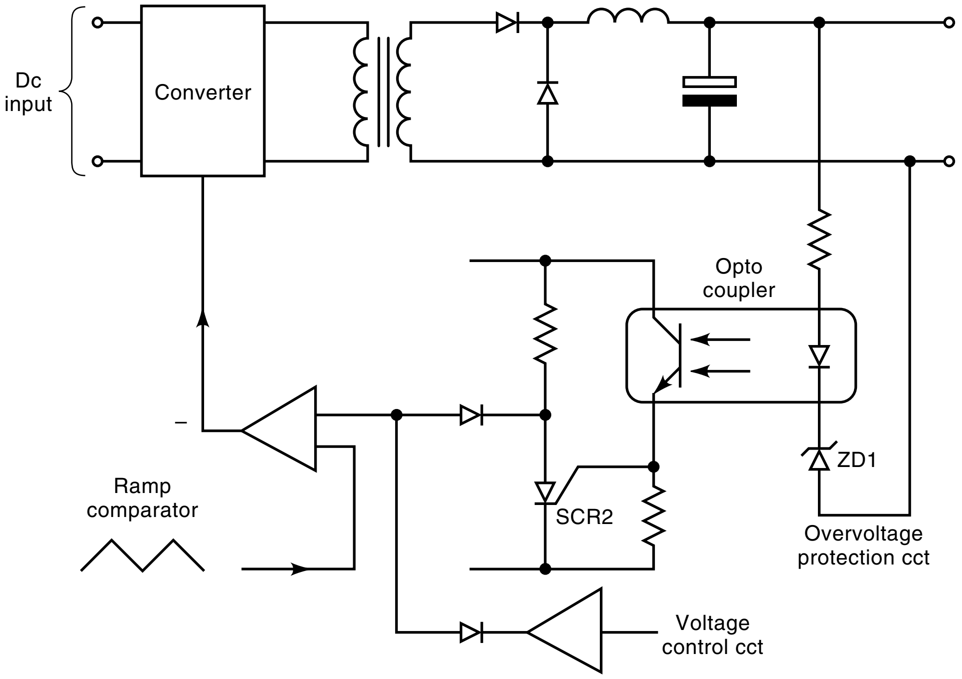


Figure 13. Typical overvoltage shutdown protection circuit for switch mode power supplier.

separate current or power-limiting circuit for its protective performance. An advantage of the clamp technique is that there is no delay in the voltage clamp action, and the circuit does not require resetting upon removal of the voltage condition.

Overvoltage Clamping with SCR Crowbar Backup

For low-power application, an SCR crowbar circuit can be used in parallel with a zener clamp diode. In that case, the advantage of the fast-acting voltage clamp can be combined with the more powerful SCR crowbar. With this design, the delay required to prevent spurious operation of the SCR will not compromise the protection of the load, as the zener clamp diode will provide protection during the SCR delay period.

Overvoltage Protection by Voltage-Limiting Technique

Figure 13 shows a typical example of a voltage-limiting circuit used in switch-mode power supplies. In this circuit, a separate optocoupler is energized in the event of an overvoltage condition. This triggers a small-signal SCR on the primary circuit to switch off the primary converter. The main criterion for such protection is that the protection loop is entirely independent of the main voltage control loop. This may be impossible to achieve if a single IC is employed for voltage control and shut-off. Additional design modifications may become necessary.

Voltage-limiting circuitry may either latch, requiring cycling of the supply input to reset, or be self-recovering, depending on application requirements. In multiple output applications, where independent secondary limits or regulators are provided, the voltage limit circuit may act upon the current limit circuit to provide the overvoltage protection. Once again, the criterion is that a single component failure should not result in an overvoltage condition. Many techniques are used solid are beyond the scope of this article.

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OXIDE RAMP DIODES. See SCHOTTKY OXIDE RAMP DIODES.