Littelfuse Varistor Design Examples

Application Note | January 1998 | AN9772

This note is meant to be a guide for the user in selecting a varistor by describing common application examples, and illustrating the solution process to determine the appropriate varistor. Also described are varistor fusing and series/parallel connection rules.

Applications

Power Supply Protection Against Line Transient Damage

PROBLEM

It is desired to prevent failure of the power supply shown in Figure 1B to be used on residential 117V_{AC} lines. A representative transient generator is to be used for testing, as shown in Figure 1A.

If the transient is applied to the existing circuit, the rectifier will receive high negative voltages, transmitted through the filter capacitor. The LC network is there to prevent RFI from being transmitted into the power line (as in a TV set), but also serves to reduce the transient voltage. An analysis shows that the transient will be reduced approximately by half, resulting in about 2.5kV instead of 5kV at the rectifier.

This is still too high for any practical rectifier, so some suppression must be added. It is desirable to use the built-in impedance of the coil to drop the remaining voltage, so the suppressor would best be applied as shown. A selection process for a Littelfuse Varistor is as follows:

SOLUTION

Steady-State Voltage

The 117V_{AC}, 110% high line condition is 129V. The closest voltage rating available is 130V.

Energy and Current

The 100µH inductor will appear to be about 30Ω to the transient. The 30Ω is derived from the inductive reactance at the transient generator source frequency of $10^5\pi$ rad. Taking a first estimate of peak varistor current, 2500V/80Ω = 31A. (This first estimate is high, since it assumes varistor clamping voltage is zero.) With a tentative selection of a 130V Littelfuse Varistor, we find that a current of 31A yields a voltage of from 325V to 380V, depending on the model size, as shown in Figure 2A and Figure 2B.

Revising the estimate, I ≈ (2500V - 325V)/80Ω = 27.2A. For model V130LA20A, 27.2A coincides closely with a 320V clamping level. There is no need to further refine the estimate of peak current if model 20A remains the final selection.

To arrive at an energy figure, assume a sawtooth current waveform of 27A peak, dropping to zero in two time constants, or 20µs.

Energy is then roughly equal to (27A x 320V x 20µs)/2, the area under the power waveform. The result is 0.086J, well within the capability of the varistor (70J). Peak current is also within the 6500A rating.

Model Selection

The actual varistor selection is a trade-off between the clamping voltage desired and the number of transient current pulses expected in the life of the equipment. A 70J rated varistor will clamp at 315V and be capable of handling over 10^6 such pulses. An 11J unit will clamp to approximately 385V and be capable of handling over 10^5 such pulses. Furthermore, the clamping voltage determines the cost of the rectifier by determining the voltage rating required. A smaller, lower cost varistor may result in a more expensive higher voltage rectifier diode.

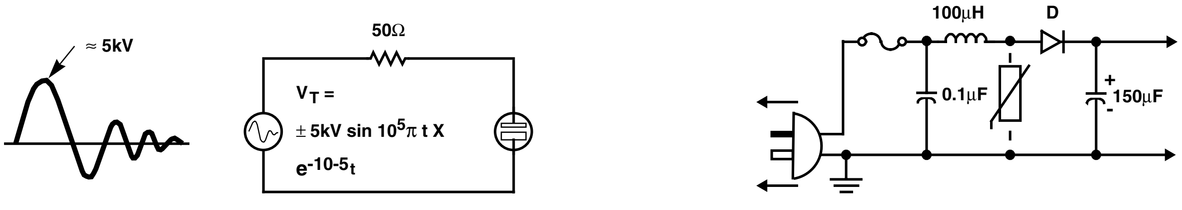


FIGURE 1A. TRANSIENT GENERATOR

FIGURE 1B. TYPICAL POWER SUPPLY CIRCUIT

FIGURE 1. POWER SUPPLY PROTECTION

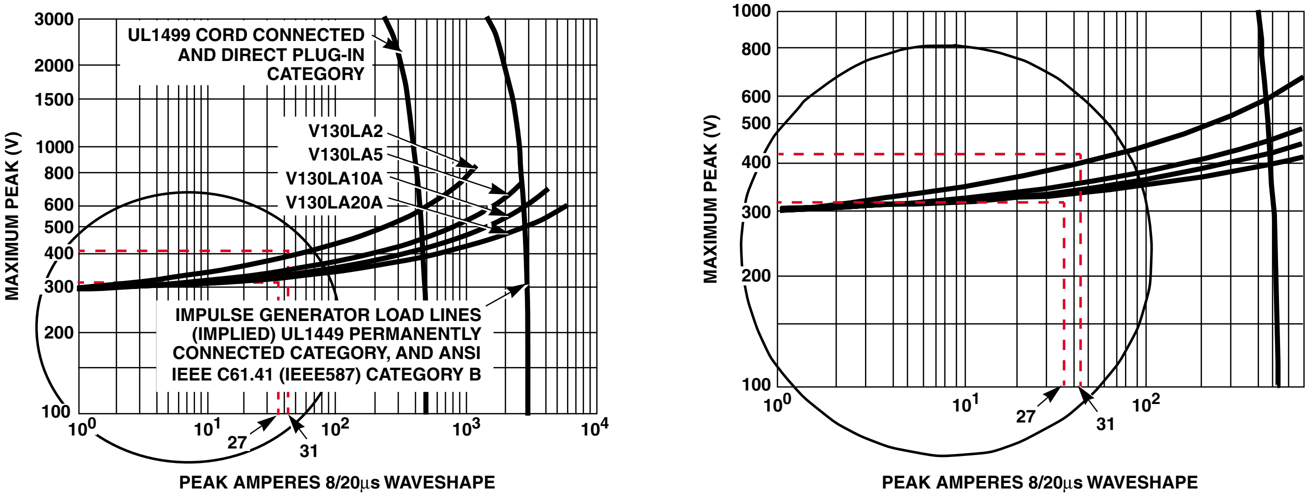


FIGURE 2A.

FIGURE 2B.

FIGURE 2. V130LA VARISTOR V-I CHARACTERISTICS

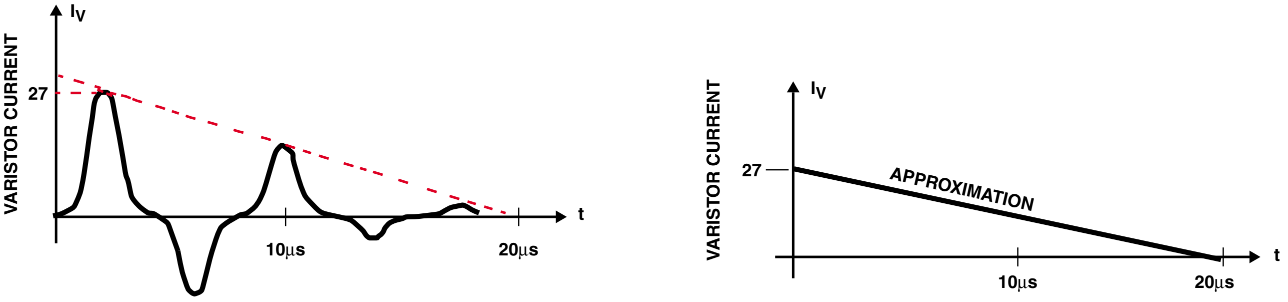


FIGURE 3A.

FIGURE 3B.

FIGURE 3. ENERGY APPROXIMATION

SCR Motor Control

PROBLEM

The circuit shown in Figure 4 experiences failures of the rectifiers and SCR when the transformer primary is switched off. The manufacturer has tried 600V components with little improvement.

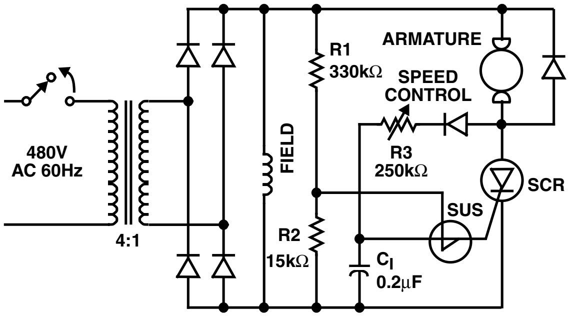


FIGURE 4. SCR MOTOR CONTROL

SOLUTION

Add a varistor to the transformer secondary to clamp the transformer inductive transient voltage spike. Select the lowest voltage Littelfuse Varistor that is equal to or greater than the maximum high line secondary AC voltage. The V130LA types fulfills this requirement.

Determine the peak suppressed transient voltage produced by the transient energy source. This is based on the peak transient current to the suppressor, assuming the worst-case condition of zero load current. Zero load current is normally a valid assumption. Since the dynamic transient impedance of the Littelfuse Varistor is generally quite low, the parallel higher impedance load path can be neglected.

Since transient current is the result of stored energy in the core of the transformer, the transformer equivalent circuit shown in Figure 5 will be helpful for analysis. The stored inductive energy is:

$$E_{L_M} = \frac{1}{2} L_M \hat{I}_M^2$$

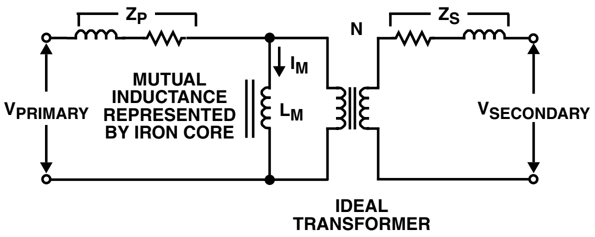


FIGURE 5. SIMPLIFIED EQUIVALENT CIRCUIT OF A TRANSFORMER

The designer needs to know the total energy stored and the peak current transformed in the secondary circuit due to the mutual inductance, L_M. At no load, the magnetizing current, (I_{NL}), is essentially reactive and is equal to I_M. This assumes that the primary copper resistance, leakage reactance and equivalent core resistive loss components are small compared to L_M. This is a valid assumption for all but the smallest control transformers. Since I_{NL} is assumed purely reactive, then:

$$X_{L_M} = \frac{V_{pri}}{I_{NL}}$$

and

$$i_M = I_{NL}$$

I_{NL} can be determined from nameplate data. Where nameplate is not available, Figure 6 and Figure 7 can guide the designer.

Assuming a 3.5% value of magnetizing current from Figure 7 for a 20kVA transformer with 480V_{AC} primary, and 120V_{AC} secondary:

$$i_M = (0.035)\frac{20\text{kVA}}{480\text{V}}$$

$$= 1.46\text{A}$$

$$\hat{i}_M = \sqrt{2} i_M$$

$$X_{L_M} = 480\text{V}/1.46\text{A}$$

$$= 329\Omega$$

$$L_M = X_{L_M}/\omega$$

$$= 0.872\text{H}$$

$$E_{L_M} = \frac{0.872(2.06^2)}{2}$$

$$= 1.85\text{J}$$

With this information one can select the needed semiconductor voltage ratings and required varistor energy rating.

Peak varistor current is equal to transformed secondary magnetizing current, i.e., $\hat{i}_M$(N), or 8.24A. From Figure 2, the peak suppressed transient voltage is 310V with the V130LA10A selection, 295V with the V130LA20B. This allows the use of 300V rated semiconductors. Safety margins exist in the above approach as a result of the following assumptions:

1. All of the energy available in the mutual inductance is transferred to the varistor. Because of core hysteresis and secondary winding capacitance, only a fraction less than two-thirds is available.
2. The exciting current is not purely reactive. There is a 10% to 20% safety margin in the peak current assumption.

After determining voltage and peak current, energy and power dissipation requirements must be checked. For the given example, the single pulse energy is well below the V130LA20B varistor rating of 70J at 85^{o}C maximum ambient temperature. Average power dissipation requirements over idling power are not needed because of the non-repetitive nature of the expected transient. Should the transient be repetitive, then the average power is calculated from the product of the repetition rate times the energy of the transient. If this value exceeds the V130LA20B capability of 1.0W, power varistors of the HA, DA, or DB Series may be required.

Should the ambient temperature exceed 85^{o}C or the surface temperature exceed 85^{o}C, the single pulse energy ratings and the average power ratings must be derated by the appropriate derating factors supplied on the data sheet.

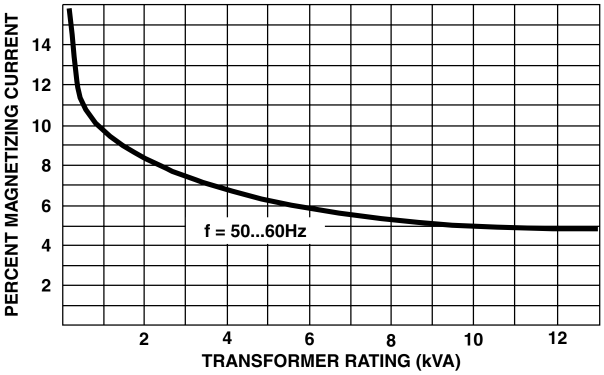


FIGURE 6. MAGNETIZING CURRENT OF TRANSFORMERS WITH LOW SILICON STEEL CORE

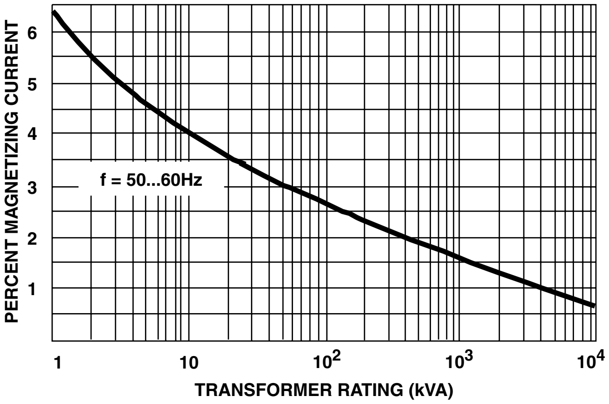


FIGURE 7. MAGNETIZING CURRENT OF TRANSFORMERS WITH HIGH SILICON STEEL CORE OR SQUARE LOOP CORE

Contact Arcing Due to Inductive Load

PROBLEM

To extend the life of the relay contacts shown in Figure 8 and reduce radiated noise, it is desired to eliminate the contact arcing.

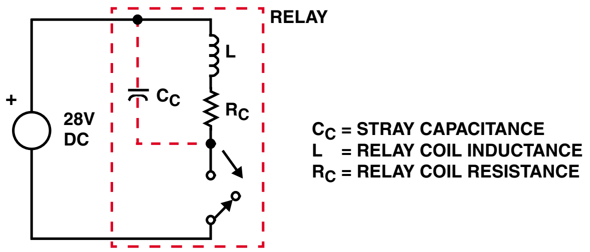


FIGURE 8. RELAY CIRCUIT

When relays or mechanical switches are used to control inductive loads, it is necessary to use the contacts at only about 50% of their resistive load current rating to reduce the wear caused by arcing of the contacts. The energy in the arcing is proportional to the inductance and to the square of the current.

Each time the current in the inductive load is interrupted by the mechanical contacts, the voltage across the contacts builds up as -L di/dt. When the contacts arc, the voltage across the arc decreases and the current in the coil can increase somewhat. The extinguishing of the arc causes an additional voltage transient which can again cause the contacts to arc. It is not unusual for the restriking to occur several times with the total energy in the arc several times that which was originally stored in the inductive load. It is this repetitive arcing that is so destructive to the contacts.

In the example, R_C is 30Ω and the relay contacts are conducting nearly 1A. The contacts will draw an arc upon opening with more than approximately 0.4A or 12V. The arc continues until current falls below 0.4A.

SOLUTION

To prevent initiation of the arc, it is necessary to reduce the current and voltage of the contacts below the arc threshold levels at the time of opening, and then keep them below breakdown threshold of the contacts as they open. Two obvious techniques come to mind to accomplish this: 1) use of a large capacitor across the contacts, and 2) a voltage clamp (such as a varistor). The clamp technique can be effective only when the minimum arc voltage exceeds the supply voltage.

In this example a clamping device operating above the supply voltage will not prevent arcing. This is shown in Figure 9.

The capacitor technique requires the capacitance to be sufficiently large to conduct the inductor current with a voltage rate-of-rise tracking the breakdown voltage rate-of-rise of the contacts as they mechanically move apart. This is shown in Figure 10A.

The limitations in using the capacitor approach are size and cost. This is particularly true for those cases involving large amounts of inductive stored energy. Furthermore, the use of a large capacitor alone creates large discharge currents upon contact reclosure during contact bouncing. As a result, the contact material may melt at the point of contact with subsequent welding. To avoid this inrush current, it is customary to add a series resistor to limit the capacitive discharge current. However, this additional component reduces the network effectiveness and adds additional cost to the solution.

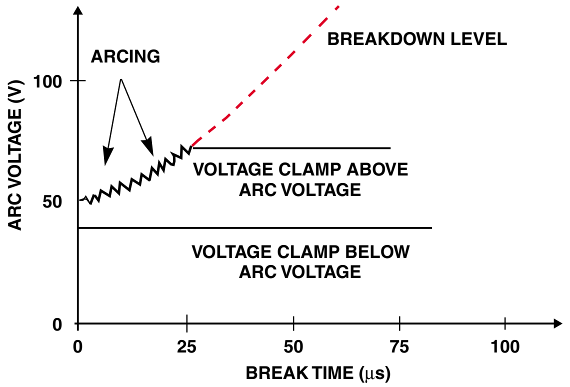


FIGURE 9. VOLTAGE CLAMP USED AS ARC SUPPRESSOR

A third technique, while not as obvious as the previous two, is to use a combination approach. This technique shown in Figure 10B parallels a voltage clamp component with an R-C network. This allows the R-C network to prevent the low voltage initial arcing and the clamp to prevent the arcing that would occur later in time as the capacitor voltage builds up. This approach is often more cost effective and reliable then using a large capacitor.

Also, with AC power relays the impedance of a single large R-C suppressor might be so low that it would allow too much current to flow when the contacts are open. The combination technique of a small R-C network in conjunction with a varistor is of advantage here, too.

In this example a 0.22µF capacitor and 10Ω resistor will suppress arcing completely, but by reducing the capacitance to 0.047µF, arcing will start at 70V.

Thus, to use a varistor as a clamp in conjunction with the R-C network, it must suppress the voltage to below 70V at 1A and be capable of operating at a steady-state maximum DC voltage of 28V + 10%, or 30.8V (assumes a ±10% regulated 28V DC supply).

The three candidates that come closest to meeting the above requirement are the MA series V39MA2B model and the ZA series V39ZA1 and V39ZA05 models, all of which have maximum steady-state DC voltage ratings of 31V. The V39MA2B and V39ZA05 V-I characteristics at 1A shows a maximum voltage of 73V, while the V39ZA1 characteristic at 1A shows a maximum voltage of 67V. Thus, the latter varistor is selected. Use of a 0.068µF capacitor in place of the 0.047µF previously chosen would allow use of the V39MA2B or V39ZA05.

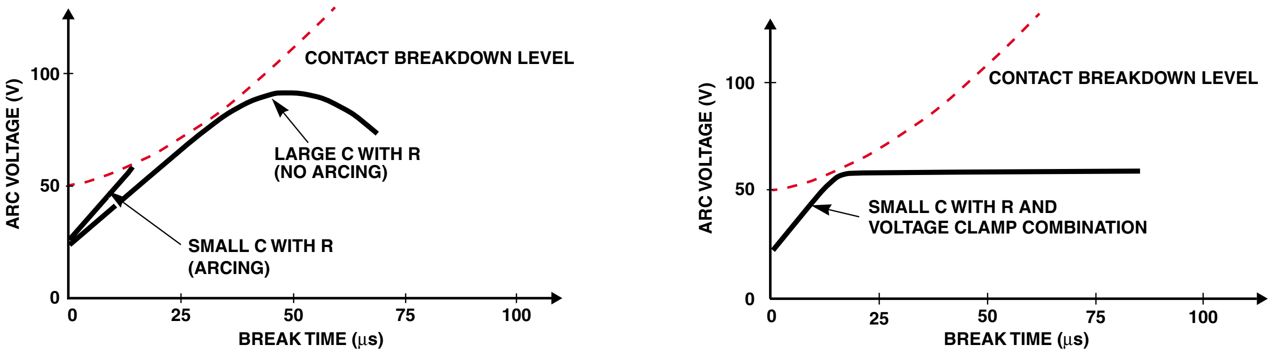


FIGURE 10A. R-C ARC SUPPRESSION

FIGURE 10B. R-C AND CLAMP ARC SUPPRESSION

FIGURE 10. RELAY ARC VOLTAGE SUPPRESSION TECHNIQUES

Placing only a Littelfuse Varistor rated for $31V_{DC}$ across the contacts results in arcing up to the 66V level. By combining the two, the capacitor size and voltage rating are reduced and suppression complete.

Besides checking the varistor voltage and arcing elimination, the designer should review energy and peak current requirements. Varistor energy is determined from a measurement of the coil inductance and the calculation $E = 1/2\ Li^2$. Peak current, of course, is under 1A. Power dissipation is negligible unless the coil is switched often (several times per minute).

In those cases where multiple arcs occur, the varistor energy will be a multiple of the above $1/2\ Li^2$ value. The peak current is well within the rating of either the MA or ZA series of varistors, but the number of contact operations allowable for either varistor is a function of the impulse duration. This can be estimated by assuming a L/R_C time constant at the 1A or peak current value. Since the voltage across the varistor is 67V at 1A, the varistor static resistance is 67Ω. The coil R_C value is 28V/1A, or 28Ω. The coil inductance was found to be 20mH. Thus, the approximate time constant is:

$$\tau = L/R_C = \frac{20\text{mH}}{95} = 210\mu\text{s}$$

From the pulse rating curves of the V39ZA1 model, the number of allowable pulses exceeds 100 million.

Noise Suppression

PROBLEM

Switching of a small timer motor at 120V, 60Hz, was causing serious malfunctions of an electronic device operating from the same power line. Attempts were made to observe the transient noise on the line with an oscilloscope as the first step in curing the problem. Observed waveforms were “hash,” i.e., not readily identifiable.

Noise in an electromechanical system is a commonly experienced result of interrupting current by mechanical contacts. When the switch contacts open, a hot cathode arc may occur if the current is high enough. On the other hand, low current will permit switch opening without an arc, but with ringing of circuit resonances. As a consequence, voltages can exceed the contact gap breakdown resulting in a replica of the old spark gap transmitter. It is the low current case that produces the most serious noise disturbances which can result in malfunctions or damage to electrical equipment. These pulses cause noise problems on adjacent lines, trigger SCRs and triacs, and damage semiconductors. In addition, they can disrupt microprocessor operation causing memory to be lost and vital instructions to be missed.

SOLUTION

A test circuit (Figure 11) was set up with lumped elements replacing the measured circuit values. The motor impedance was simulated by R_1, L_1, and C_1, and the AC line impedance by L_2 and C_2. A DC source allowed repeatable observations over the full range of current that could flow through the switch in the normal AC operation. A diode detector was used to observe the RF voltage developed across a 2” length of wire (50nH of inductance).

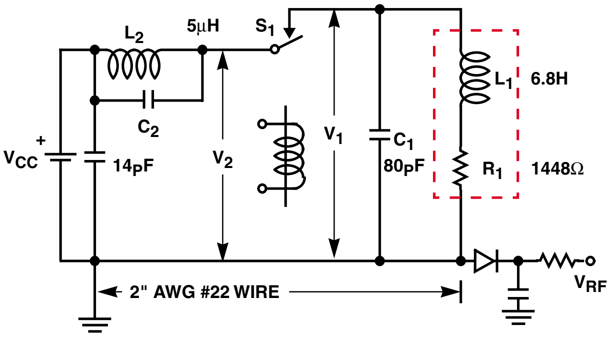
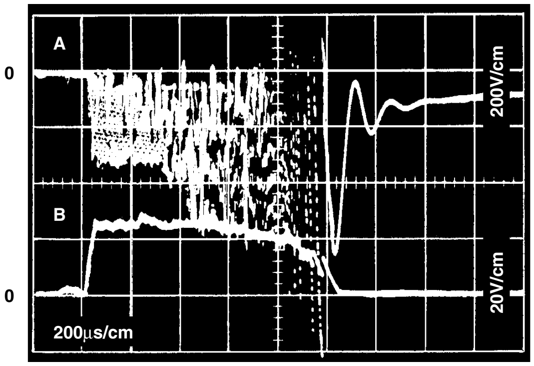


FIGURE 11. TEST CIRCUIT

The supply is set at 25mA to represent the peak motor current in normal $120V_{AC}$ operation. As switch S_1 was opened, the waveform in Figure 12 was recorded. Note the “showering arc” effect. The highest breakdown voltage recorded here is 1020V, and the highest RF detector output (shown in the lower trace) is 32V.

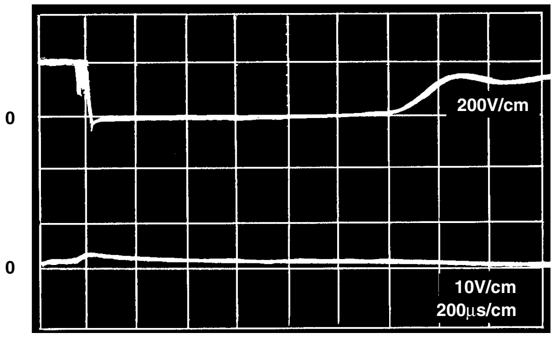


UPPER V_1: 200V/cm LOWER V_{RF}: 20V/cm

t: 0.2ms/cm

FIGURE 12. UNPROTECTED CONTACTS

Obviously, some corrective action should be taken and the most effective one is that which prevents the repeated breakdown of the gap. Figure 13 shows the waveform of V_1 (upper trace) and V_{RF} (lower trace) for the same test conditions with a Littelfuse Varistor, type V130LA10A, connected directly across the switch terminals. The varistor completely eliminates the relaxation oscillations by holding the voltage below the gap breakdown voltage (about 300V) while dissipating the stored energy in the system.



UPPER V_1: 200V/cm LOWER V_{RF}: 20V/cm

t: 0.2ms/cm

FIGURE 13. VARISTOR PROTECTED CONTACTS

Protection of Transistors Switching Inductive Loads

PROBLEM

The transistor in Figure 14 is to operate a solenoid. It may operate as frequently as once per second. The circuit (without any suppression) consistently damages the transistor.

The inductor drives the collector voltage up when the transistor base is grounded (turning "off"). The inductor forces current to flow until the energy stored in its field is dissipated. This energy is dissipated in the reverse bias condition of the transistor and is sufficient to cause breakdown (indicated by a sudden collapse of collector voltage during the pulse).

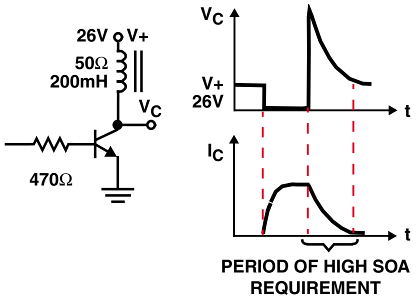


FIGURE 14A. BASIC SOLENOID CIRCUIT

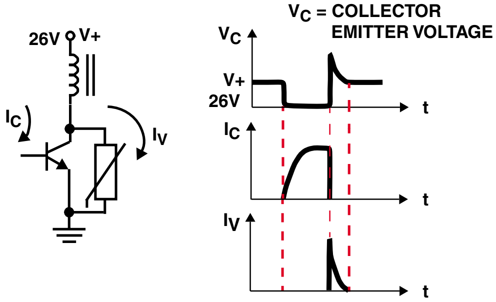


FIGURE 14B. SOLENOID CIRCUIT WITH VARISTOR PROTECTION

FIGURE 14. TRANSISTOR SWITCHING OF AN INDUCTIVE LOAD

SOLUTION

This condition can be eliminated either by shunting the transistor with a suppressor or by turning it on with a varistor connected collector-to-base. The first method will considerably reduce the demands upon the safe operating area (SOA) of the transistor. If the voltage is kept below its breakdown level, all energy will be dissipated in the suppressor. The latter method will cause the transistor to once again dissipate the stored energy, but in the forward-bias state in which the transistor can safely dissipate limited amounts of energy. The choice is determined by economics and reliability. A suppressor connected collector-emitter (C-E) will be more expensive than one connected C-B, since it is required to absorb more energy, but will allow the use of a transistor with reduced SOA.

If a collector-emitter varistor is used in the above example, it is required to withstand $28.6V_{DC}$ worst-case (26 + 10% regulation). The stored energy is $1/2\ Li^2$ or $1/2\ (0.20)\ (0.572)^2$ = 0.0327J. The energy contributed by the power supply is roughly equal to this (coil voltage ≈ supply voltage, since varistor clipping voltage ≈ 2 x supply voltage). Ignoring coil resistance losses for a conservative estimate, varistor energy dissipation is 0.065J per pulse. The peak current will be 0.572A, the same as the coil current when the transistor is switched off.

If the transistor operates once per second, the average power dissipation in the varistor will be 0.065W. This is less than the 0.20W rating of a small $31V_{DC}$ varistor (V39ZA1). From the data sheet it can be seen that if the device temperature exceeds 85°C, derating is required. The nonrecurrent joule rating is 1.5J, well in excess of the recurrent value. To determine the repetitive joule capability, the current pulse rating curves for the ZA series must be consulted. Two are shown in Figure 15.

To use Figure 27, the impulse duration (to the 50% point) is estimated from the circuit time constants and is found to be 1240µs. From Figure 27A, for this example, the 7mm V39ZA1 would not be limited to a cumulative number of pulses.

In cases where the peak current is greater and intersects with the recommended pulse life curves, the designer must determine the maximum number of operations expected over the life of the circuit and confirm that the pulse life curves are not exceeded. Figure 15B shows the curves for the larger, 14mm V39ZA6 device and, illustrates the resultant higher capability in terms of number of transients for a given peak pulse current and duration.

Also, it may be necessary to extrapolate the pulse rating curves. This has been done in Figure 16 where the data from Figure 15B is transposed. At low currents the extrapolation is a straight line.

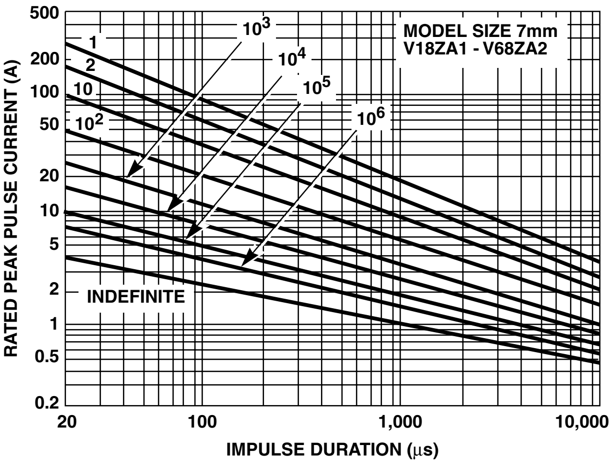


FIGURE 15A. ZA SERIES V18ZA1 TO V68ZA2 (MODEL SIZE 7mm)

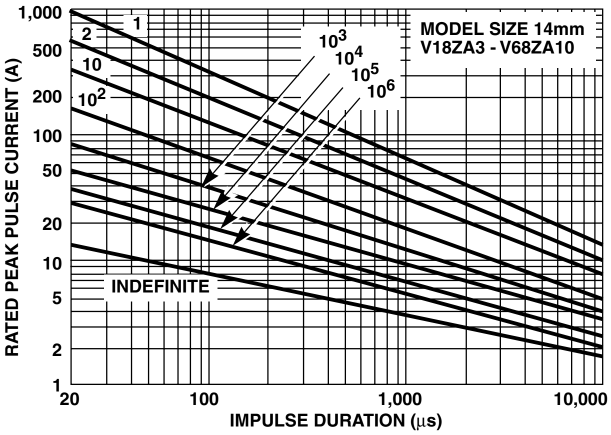


FIGURE 15B. ZA SERIES V18ZA3 TO V68ZA10 (MODEL SIZE 14mm)

Finally, the V-I characteristics curves must be consulted to determine the varistor maximum clamping voltage in order to select the minimum transistor breakdown voltage. In this example, at 0.572A the V39ZA6 (if chosen) provides a maximum of 61V requiring that the transistor have about a 65V or 70V capability.

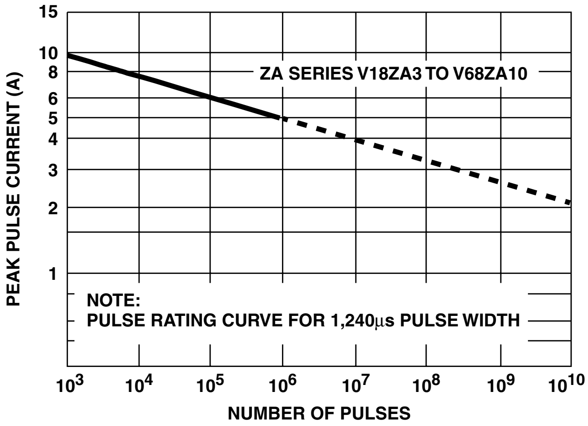
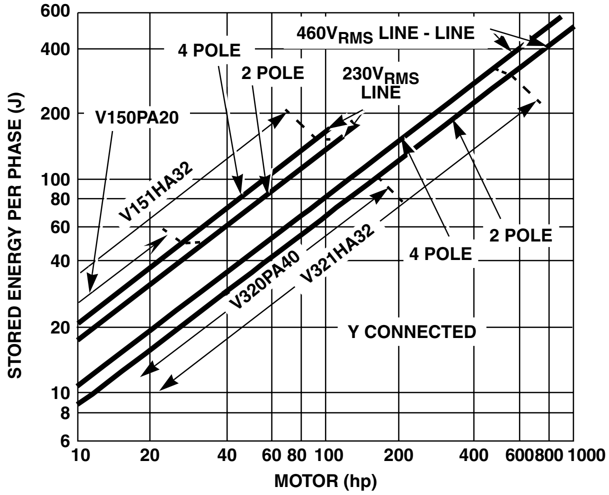


FIGURE 16. EXTRAPOLATED PULSE RATING CURVES

Motor Protection

Frequently, the cause of motor failures can be traced to insulation breakdown of the motor windings. The source of the transients causing the breakdown may be from either internal magnetic stored energy or from external sources. This section deals with the self-generated motor transients due to motor starting and circuit breaker operation. Externally generated transients and their control are covered in AN9768.

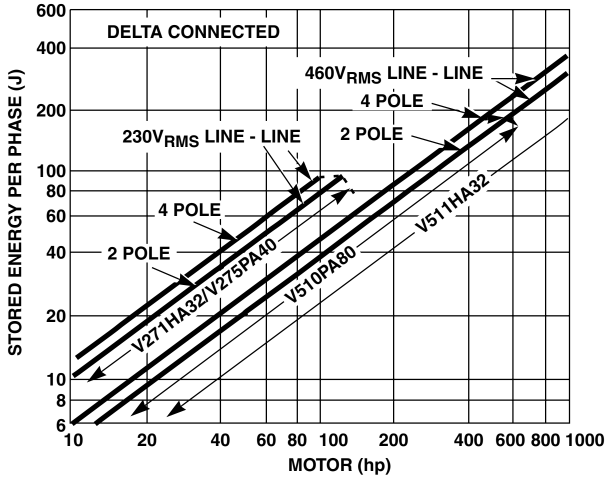
In the case of DC motors the equivalent circuit consists of a single branch. The magnetic stored energy can be easily calculated in the armature or field circuits using the nameplate motor constants. With AC induction motors the equivalent magnetic motor circuit is more complex and the circuit constants are not always given on the motor nameplate. To provide a guide for motor protection, Figures 17, 18, 19 were drawn from typical induction motor data. While the actual stored energy will vary according to motor frame size and construction techniques, these curves provide guidance when specific motor data is lacking. The data is conservative as it assumes maximum motor torque, a condition that is not the typical running condition. Stored energy decreases considerably as the motor loading is reduced. Experience with the suppression of magnetic energy stored in transformers indicates that Littelfuse Varistors may be used at their maximum energy ratings, even when multiple operations are required. This is because of the conservatism in the application requirements, as indicated above, and in the varistor ratings. Thus, no attempt is made to derate the varistor for multiple operation because of the random nature of the transient energy experienced.



NOTES:

1. Y connected 60Hz.
2. Energy at Max torque slip speed.
3. See Figure 20 for varistor circuit placement.

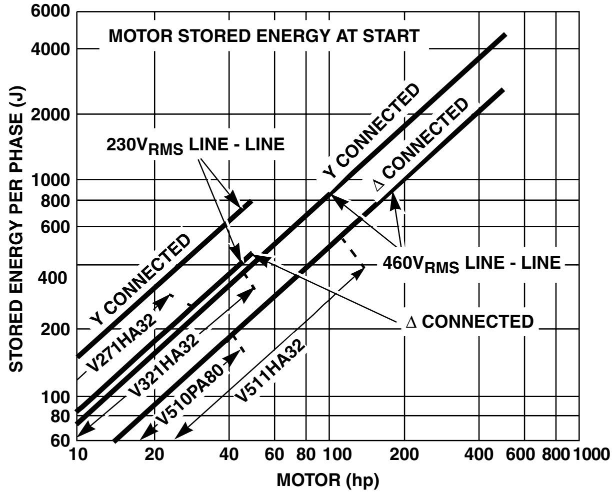
FIGURE 17. STORED ENERGY CURVES FOR TYPICAL WYE-CONNECTED INDUCTION MOTOR



NOTES:

4. Delta connected at 60Hz.
5. Energy at maximum torque slip speed.
6. See Figure 20 for varistor circuit placement.

FIGURE 18. STORED ENERGY CURVES FOR TYPICAL DELTA-CONNECTION INDUCTION MOTOR



NOTES:

7. 60Hz, see Figure 20 for varistor circuit placement.
8. Energy at start, i.e., SLIP = 1.
9. Induction motor.
10. 2, and 4 pole motors.

FIGURE 19. STORED ENERGY CURVES FOR A TYPICAL MOTOR WITH STALLED ROTOR

As an aid in selecting the proper operating voltage for Littelfuse Varistors, Table 1 gives guidelines for wye-connected and delta-connected motor circuits at different line-to-line applied voltages. Figure 20 provides guidance in proper placement of the varistor.

Interruption of motor starting currents presents special problems to the user as shown in Figure 19. Since the stored magnetic energy values are approximately 10 times the running values, protection is difficult at the higher horsepower levels. Often the motor is started by use of a reduced voltage which will substantially reduce the stored energy. A reduction in starting current of a factor of two results in a fourfold reduction in stored energy. If a reduced voltage starter is not used, then a decision must be made between protection for the run condition only, and the condition of locked rotor motor current. For most applications, the starting condition can be ignored in favor of selecting the varistor for the worst-case run condition.

TABLE 1. PREFERRED VARISTOR VOLTAGE RATINGS FOR DELTA- AND WYE-CONNECTED MOTORS

RMS Line Voltage (Line-Line)	⟹	230	380	460	550	600
Delta Connected	Applied V. Varistor Ratings	230 250/275	380 420/480	460 510/575	550 575/660	600 660
Y Connected	Applied V. Varistor Ratings	133 150	220 250/275	266 320	318 420	346 420

PROBLEM

To protect a two-pole, 75hp, 3ϕ, $460V_{RMS}$ line-to-line wye-connected motor from interruption of running transients.

Specific Motor Data Is Not Available

SOLUTION

Consult Figure 17 along with Table 1. Standard varistors having the required voltage ratings are the $320V_{RMS}$ rated models. This allows a 20% high-line voltage condition on the nominal 460V line-to-line voltage, or 266V line-neutral voltage. Figure 17 shows a two-pole 75hp, wye-connected induction motor, at the running condition, has 52J of stored magnetic energy per phase. Either a V320PA40 series or a V321HA32 series varistor will meet this requirement. The HA series Littelfuse Varistor provides a greater margin of safety, although the PA series Littelfuse Varistor fully meets the application requirements. Three varistors are required, connected directly across the motor terminals as shown in Figure 20.

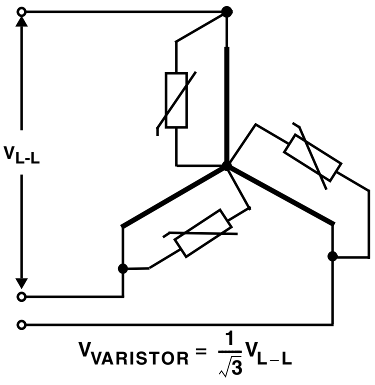


FIGURE 20A. WYE CONNECTED

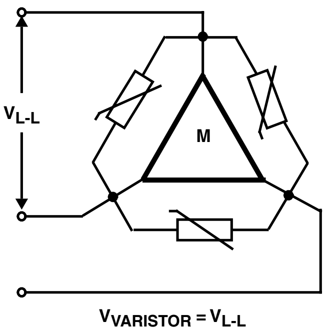


FIGURE 20B. DELTA CONNECTED

FIGURE 20. VARISTOR - 3ϕ INDUCTION MOTOR CIRCUIT PLACEMENT

Power Supply Crowbar

Occasionally it is possible for a power supply to generate excessively high voltage. An accidental removal of load can cause damage to the rest of the circuit. A simple safeguard is to crowbar or short circuit the supply with an SCR. To provide the triggering to the SCR, a high-voltage detector is needed. High voltage avalanche diodes are effective but expensive. An axial leaded Littelfuse Varistor provides an effective, inexpensive substitute.

PROBLEM

In the circuit of Figure 21, the voltage, without protection, can exceed twice the normal 240V peaks, damaging components downstream. A simple arrangement to crowbar the supply is shown.

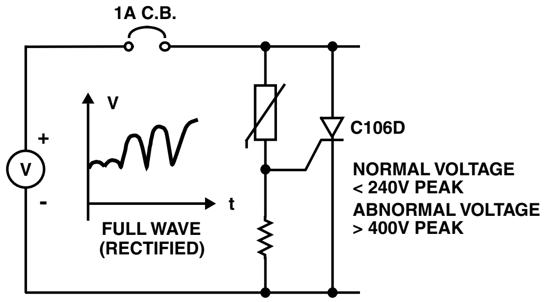


FIGURE 21. CROWBAR CIRCUIT

The supply shown can provide $2A_{RMS}$ of short-circuit current and has a 1A circuit breaker. A C106D SCR having a $4A_{RMS}$ capability is chosen. Triggering will require at least 0.4V gate-to-cathode, and no more than 0.8V at 200μA at $25^{o}C$ ambient.

SOLUTION

Check the MA series Littelfuse Varistor specifications for a device capable of supporting 240V peak. The V270MA4B can handle $\sqrt{2}$ ($171V_{RMS}$) = 242V. According to its specification of 270V ±10%, the V270MA4B will conduct $1mA_{DC}$ at no less than 243V. The gate-cathode resistor can be chosen to provide 0.4V (the minimum trigger voltage) at 1mA, and the SCR will not trigger below 243V. Therefore, R_{GK} should be less than 400Ω. The highest value 5% tolerance resistor falling below 400Ω is a 360Ω resistor, which is selected. Thus, R_{GK} is 378Ω maximum and 342Ω minimum. Minimum SCR trigger voltage of 0.4V requires a varistor of 0.4V/378Ω, or 1.06mA for a minimum varistor voltage of ≈245V. The maximum voltage to trigger the circuit is dependent upon the maximum current the varistor is required to pass to trigger the SCR. For the C106 at $25^{o}C$, this is determined by calculating the maximum current required to provide 0.8V across a parallel resistor comprised of the 360Ω R_{GK} selected and the equivalent gate-cathode SCR resistor of 0.8V/200μA, since the C106 requires a maximum of 200μA trigger current. The SCR gate input resistance is 4kΩ and the minimum equivalent gate-cathode resistance is the parallel combination of 4kΩ and $R_{GK(MIN)}$, or 360Ω -5%, 342Ω. The parallel combination is 315Ω. Thus, $I_{VARISTOR}$ for maximum voltage-to-trigger the C106 is 0.8V/315Ω, or 2.54mA. According to the specification sheet for the V270MA4B, the varistor will not exceed 330V with this current. The circuit will, therefore, trigger at between 245 and 330V peak, and a 400V rated C106 can be used. The reader is cautioned that SCR gate characteristics are sensitive to junction temperatures, and a value of 25^{O}C for the SCR temperature was merely chosen as a convenient value for demonstrating design procedures.

The maximum energy per pulse with this waveform is determined as approximately 1/2 x K x I_{PK} x V_{PK} x τ (duration of 1/2 wave pulse), or 0.52mJ for this example. Since the voltage does not drop to zero in this case, the SCR remains on, and the varistor sees only one pulse; thus, no steady-state power consideration exists.

General Protection of Solid State Circuitry, Against Transients On 117V_{AC} Lines

PROBLEM

Modern electronic equipment and home appliances contain solid state circuitry that is susceptible to malfunction or damage caused by transient voltage spikes. The equipment is used in residential, commercial, and industrial buildings. Some test standards have been adopted by various agencies (see application notes AN9769 and AN9773) and further definition of the environment is underway by the IEEE and other organizations.

The transients which may occur on residential and commercial AC lines are of many waveshapes and of varying severity in terms of peak voltage, current, or energy. For suppressor application purposes, these may be reduced to three categories.

First, the most frequent transient might be the one represented by a 30kHz or 100kHz ring wave. This test surge is defined by an oscillatory exponentially decaying voltage wave with a peak open circuit voltage of 6kV. This wave is considered representative of transients observed and reported by studies in Europe and North America. These transients can be caused by distant lightning strikes or distribution line switching. Due to the relatively high impedance and short duration of these transients, peak current and surge energy are lower than the second and third categories.

The second category is that of surges produced by nearby lightning strokes. The severity of a lightning stroke is characterized in terms of its peak current. The probability of a direct stroke of a given severity can be determined. However, since the lightning current divides in many paths, the peak current available at an AC outlet within a building is much less than the total current of the stroke. The standard impulse used to represent lightning and to test surge protective devices is an 8/20µs current waveshape as defined by ANSI Standard C68.2, and also described in ANSI/IEEE Standard C62.41-1991 and IEC 664-1 (1992).

A third category of surges are those produced by the discharge of energy stored in inductive elements such as motors and transformers. A test current of 10/1000µs waveshape is an accepted industry test impulse and can be considered representative of these surges.

Although no hard-and-fast rules can be drawn as to the category and severity of surges which will occur, a helpful guideline can be given to suggest varistors suitable in typical applications.

The guideline of Table 2 recognizes considerations such as equipment cost, equipment duty cycle, effect equipment downtime, and balances the economics of equipment damage risk against surge protection cost.

Failure Modes and Varistor Protection

Varistors are inherently rugged and are conservatively rated and exhibit a low failure rate. The designer may wish to plan for potential failure modes and the resultant effects should the varistor be subjected to surge currents or energy levels above its rating.

Failure Modes

Varistors initially fail in a short-circuit mode when subjected to surges beyond their peak current/energy ratings. They also short-circuit when operated at steady-state voltages well beyond their voltage ratings. This latter mode of stress may result in the eventual open-circuiting of the device due to melting of the lead solder joint.

When the device fails in the shorted mode the current through the varistor becomes limited mainly by the source impedance. Consequently, a large amount of energy can be introduced, causing mechanical rupture of the package accompanied by expulsion of package material in both solid and gaseous forms. Steps may be taken to minimize this potential hazard by the following techniques: 1) fusing the varistor to limit high fault currents, and, 2) protecting the surrounding circuitry by physical shielding, or by locating the varistor away from other components.

TABLE 2. LITTELFUSE VARISTOR SELECTION GUIDELINE FOR 117V_{AC} APPLICATIONS

APPLICATION TYPE	DUTY CYCLE	LOCATION	EXAMPLE	SUGGESTED MODEL
Light Consumer	Very Low	A	Mixer/Blender	V07E130 or V10E130
Consumer	Low	A	Portable TV/Electronics	V14E130
Consumer	Medium	A	Home Theater, PC	V14E130, V20E130
Light Industrial/Office	Medium	B	Copier, Server	V20E130, V20E140
Industrial	Medium	B	Motors, Solenoid, Relay	V20E140, V131HA32
Industrial	High	B	Large Computer Motor Control	V131DA40 or DB40
Industrial	High	B	Elevator Control Heavy Motors	V151DA40 or DB40

Fusing the Varistor

Varistor fusing should be coordinated to select a fuse that limits current below the level where varistor package damage could occur. The location of the fuse may be in the distribution line to the circuit or it may be in series with the varistor as shown in Figure 22. Generally, fuse rather than breaker protection is preferred. Breaker tripping may be too slow to prevent excessive fault energy in some applications.

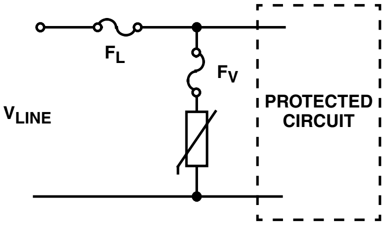


FIGURE 22. FUSE PLACEMENT FOR VARISTOR PROTECTION

In high power industrial circuits the line currents are generally so high as to rule out the use of a line fuse for varistor protection. The fuse may not clear under a varistor fault condition and would allow varistor failure. In low power (5-20A) applications it may be feasible to use the line fuse, F_L, only.

Use of a line fuse, F_L, rather than F_V, does not present the problem of having the fuse arc voltage being applied across the circuit. Conversely, with F_V alone, the fuse arc voltage adds to the varistor voltage, increasing the V_C, the transient clamp voltage. Since some fuses can have peak arc voltages in excess of twice peak working voltage, fuse clearing can have a significant effect on protection levels.

Another factor in the choice of location is the consequence of system interruption. Fuse location F_L will cause a shutdown of the circuit while location F_V will not. While the circuit can continue to operate when F_V clears, protection no longer is present. For this reason it is desirable to be able to monitor the condition of F_V.

Fusing Example (Light Industrial Application)

A process control minicomputer is to be protected from transients on a 115V nominal line. The minicomputer draws 7.5A from the line, which is guaranteed to be regulated to ±10% of nominal line voltage. A V130LA20A varistor is chosen on the basis that the worst-case surge current would be a 10/1000µs pulse of 100A peak amplitude. The rationale for this surge requirement is that the incoming plant distribution system is protected with lightning arrestors having a maximum arrestor voltage of 5kV. Assuming a typical 50Ω characteristic line impedance, the worst-case transient current through the varistor is 100A. The 1ms impulse duration is taken as a worst-case composite wave estimate. While lightning stroke discharges are typically less than 100µs, they can recur in rapid fire order during a 1s duration. From the pulse rating curves of the LA series size 20mm models, it is seen that the V130LA20 single pulse withstand capability at 1ms impulse duration is slightly in excess of 100A.

This is adequate for application in areas where lightning activity is medium to light. For heavy lightning activity areas, either a DA or DB series varistor might be desirable to allow a capability of withstanding over 70 transients. In making the choice between the LA series and higher energy series, the designer must decide on the likelihood of a worst-case lightning stroke and resultant fuse replacement should the varistor fail.

Assuming a low lightning activity area, the V130LA20A series is a reasonable choice. To coordinate the fuse with the varistor, the single pulse surge rating curve is redrawn as I^2t vs impulse duration as shown in Figure 23. The I^2t of the composite 10/1000µs impulse is found from: [1].

$$I^2t = \frac{1}{3}\hat{I}^2(10\mu s) + 0.722\ \hat{I}^2(\tau_{(0.5)} - 10\mu s)$$

When:

$$\tau_{(0.5)} \geq 200\mu s \text{(time for impulse current to decay by 0.5)}$$

$$I^2t \approx 0.722\ \hat{I}^2\tau_{(0.5)}$$

Where: the first term represents the impulse I^2t contributed by the 10µs rise portion of the waveform and the second term is the I^2t contributed by the exponential decay portion.

Figure 23 shows a cross-hatched area which represents the locus of possible failure of the varistor. This area is equal to an I^2 value of from two to four times that derived from the data sheet peak current pulse life curves. The curve extending beyond the cross-hatched area and parallel to it is where package rupture will take place.

The criteria for fuse selection is given below:

A) Fuse melts; i.e., opens, only if worst-case transient is exceeded and/or varistor fails.

B) If varistor fails, fuse clearing limits I^2t applied to varistor values below that required for package rupture.

C) Fuse is rated at $130V_{RMS}$.

D) Fuse provides current limiting for solid-state devices.

Based on the above, a Carbone-Ferraz $12A_{RMS}$, $130V_{RMS}$, Class FA fuse is tentatively selected. The minimum melting I^2t and maximum clearing I^2t curves for the 12A fuse are shown superimposed on the varistor characteristics.

This fuse is guaranteed to melt at an I^2t of 40% above the estimated worst-case transient. Upon melting, clearing I^2t and clearing time will depend upon available fault current from the $130V_{RMS}$ line. Table 3 lists clearing times for the selected fuse versus available prospective circuit current.

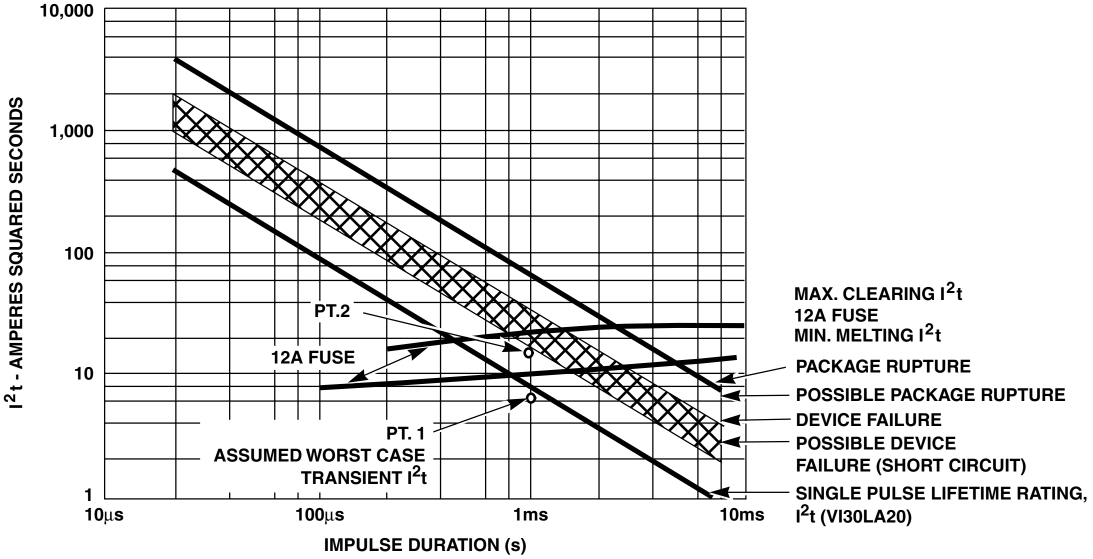


FIGURE 23. LITTELFUSE VARISTOR - FUSE COORDINATION CHART

TABLE 3. 12A FUSE - PROSPECTIVE CURRENT vs CLEARING TIME

PROSPECTIVE CURRENT (A_{RMS})	CLEARING TIME (ms)
60	8.0
120	5.6
240	3.5
1200	1.3
3600	0.57

As Figure 23 shows, a clearing time of less than 1.5ms is desirable. For fault currents in excess of 1.2kA, the fuse will clear at less than $24A^2s$ and 1.3ms. This will prevent varistor package rupturing. However, the distribution line may be “soft,” i.e., have a high source impedance at the 60Hz power frequency that limits the fault current to values below 1.2kA. Then, it is possible that the fuse would not protect the varistor package from rupturing, though it would serve to isolate the varistor in any case.

Upon further examination of this example, it is clear that the varistor will be protected from package rupturing even if the transient pulse current is 50% greater than that of the assumed value, resulting in an I^2t of $16A^2S$ (Point 2 on Figure 23).

Placement of the fuse for this example application could be in the line or in series with the varistor. If in series with the varistor, the line fuse should be a medium to slow speed, such as a “slow blow” type 15A fuse. That would assure a fault in the varistor would be isolated by the varistor fuse without interrupting the line fuse.

It is desirable to indicate the status of the varistor fuse if one is used in addition to the line fuse. The circuit shown in Figure 24 senses the presence of voltage across the varistor by use of a photocoupler. When the fuse interrupts the varistor circuit, the LED of the coupler becomes de-energized, and the coupler output signal can be used to annunciate an unprotected condition. Some fuse manufacturers provide indicating means upon fuse operation that may also be used to trip an alarm.

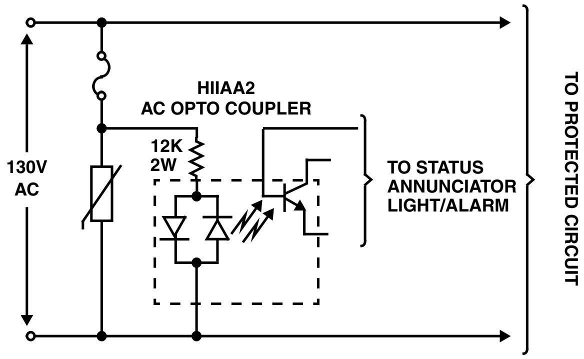


FIGURE 24. VARISTOR FUSE STATUS SENSING CIRCUIT

In selecting a fuse, the reader is advised to avoid data based on average values or data taken at operating conditions that are grossly different from the actual application. For example, DC data does not apply when the fuse will be used on an AC circuit. Also, test data taken in a resistive circuit with unity power factor does not hold for low power factor operation.

Series and Parallel Operation of Varistors

In most cases the designer can select a varistor that meets the desired voltage ratings from standard catalog models. Occasionally the standard catalog models do not fit the requirements either due to voltage ratings or energy/current ratings. When this happens, two options are available: varistors can be arranged in series or parallel to make up the desired ratings, or the factory can be asked to produce a “special” to meet the unique application requirement.

Series Operation of Varistors

Varistors are applied in series for one of two reasons: to provide voltage ratings in excess of those available, or to provide a voltage rating between the standard model voltages. As a side benefit, higher energy ratings can be achieved with series connected varistors over an equivalent single device. For instance, assume the application calls for a lead mounted varistor with an V_{RMS} rating of $375V_{AC}$ and having a I_{TM} peak current capability of 6000A. The I_{TM} requirement fixes the varistor size. Examining the LA series voltage ratings near $375V_{AC}$, only 320V and 420V units are available. The 320V is too low and the 420V unit (V420LA40B) results in too high a clamp voltage (V_C of 1060V at 100A). For a V130LA20B and a V250LA40B in series, the maximum rated voltage is now the sum of the voltages, or 380V. The clamping voltage, V_C, is now the sum of the individual varistor clamping voltages, or 945V at 100A. The peak current capability is still 6500A but the energy rating is now the sum of the individual energy ratings, or 200J.

In summary, varistors can be connected in series providing they have identical peak current ratings (I_{TM}), i.e., same disc diameter. The composite V-I characteristic, energy rating, and maximum clamp voltages are all determined by summing the respective characteristics and/or ratings of the individual varistors.

Parallel Operation of Varistors

Application requirements may necessitate higher peak currents and energy dissipation than the high energy series of varistors can supply individually. When this occurs, the logical alternative is to examine the possibility of paralleling varistors. Fortunately, all Littelfuse Varistors have a property at high current levels that makes paralleling feasible. This property is the varistor's series-resistance that is prominent during the “up-turn region” of the V-I characteristic. This up-turn is due to the inherent linear resistance component of the varistor characteristic (see Application Note AN9767). It acts as a series balancing, or ballasting, impedance to force a degree of sharing that is not possible at lower current levels. This is depicted in Figure 25. At a clamp voltage of 600V, the difference in current between a maximum specified sample unit and a hypothetical 20% lower bound sample would be more than 20 to 1. Thus, there is almost no current sharing and only a single varistor carries the current. Of course, at low current levels in the range of 10A -100A, this may well be acceptable.

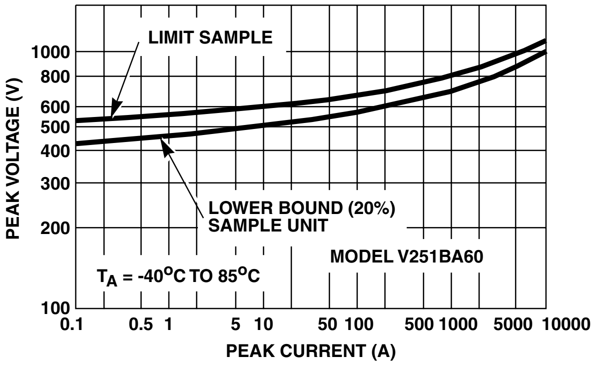


FIGURE 25. PARALLEL OPERATION OF VARISTORS BY GRAPHICAL TECHNIQUE

At high current levels exceeding 1000A, the up-turn region is reached and current sharing improves markedly. For instance, at a clamp voltage of 900V, the respective varistor currents (Figure 25) are 2500A and 6000A, respectively. While far from ideal sharing, this illustration shows the feasibility of paralleling to achieve higher currents and energy than achievable with a single model varistor.

Practically, varistors must be matched by means of high current pulse tests to make parallel operation feasible. Pulse testing should be in the range of over 1kA, using an 8/20µs, or similar pulse. Peak voltages must he read and recorded. High current characteristics could then be extrapolated in the range of 100A - 10,000A. This is done by using the measured data points to plot curves parallel to the data sheet curves. With this technique current sharing can be considerable improved from the near worst-case conditions of the hypothetical example given in Figure 25.

In summary, varistors can be paralleled, but good current sharing is only possible if the devices are matched over the total range of the voltage-current characteristic. In applications requiring paralleling, Littelfuse should be consulted.

Some guidelines for series and parallel operation of varistors are given in Table 4.

TABLE 4. CHECKLIST FOR SERIES AND PARALLEL OPERATION OF VARISTORS

	SERIES	PARALLEL
Objective	Higher voltage capability. Higher energy capability. Non-Standard voltage capability.	Higher Current Capability Higher Energy Capability
Selection Required	No	Yes
Models Applicable	All, must have same I_{TM} rating.	All models
Application Range	All voltages and currents.	All voltages - only high currents, i.e., >100A.
Precautions	I_{TM} ratings must be equal.	Must be identical voltage rated models. Must test and select units for similar V-I characteristics.
Effect on Ratings	Clamp voltages additive. Voltage ratings additive. Current ratings that of single device. Energy W_{TM}, ratings additive.	Current ratings function of current sharing as determined graphically. Energy ratings as above in proportion to current sharing. Clamp voltages determined by composite V-I characteristic of matched units. Voltage ratings that of single unit.

Reference

For Littelfuse documents available on the internet, see web site - http://www.littelfuse.com/

[1] Kaufman, R., *"The Magic of I^2t,"* IEEE Trans. IGA-2, No. 5, Sept.-Oct. 1966.