APPLICATION
NOTES

Littelfuse
Varistor Design Examples

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 varisor. The note also describes 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 117VAC lines. A representative transient generator is to be used for testing as shown in Figure 1a.
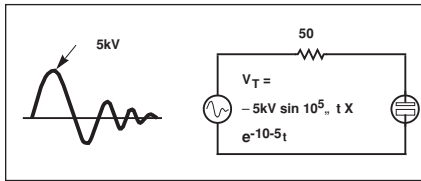

Figure 1a. Transient Generator

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.
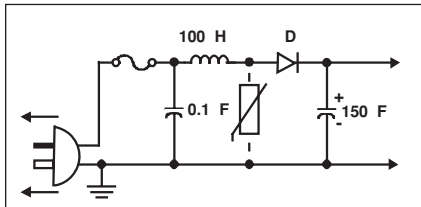

Figure 1b. Typical Power Supply Circuit

This is still to 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

Stead-State Voltage
The 117VAC, 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 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 Harris 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 (27Ax320Vx20μs)/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
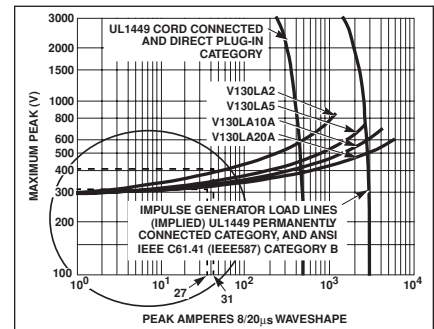

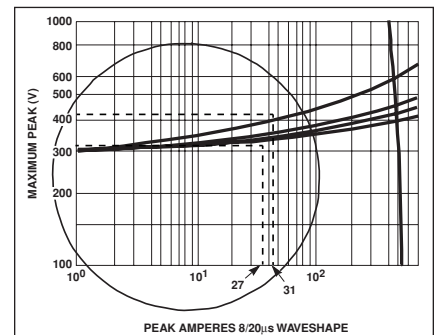*Figure 2a. V130LA Varistor V-I Characteristics*

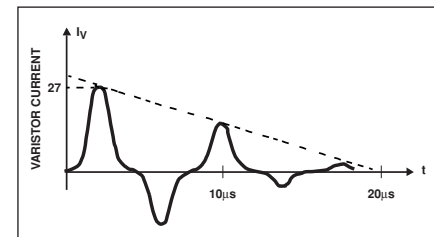*Figure 2b. V130LA Varistor V-I Characteristics*

Figure 3. Energy Approximation

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.

Littelfuse®
Circuit Protection Specialists

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.
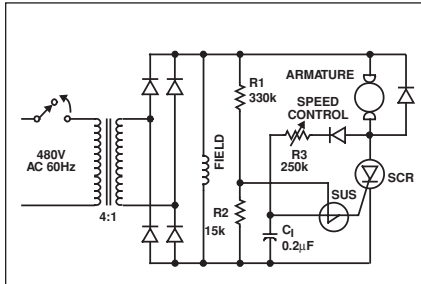

Figure 4. SCR Motor Control

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:

$$E_{L_M} = \frac{1}{2} L_M i_M^2$$

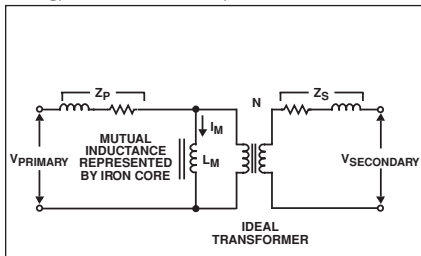The designer needs to know the total energy stored and the peak current trans-

Figure 5. Simplified Equivalent Circuit of A Transformer

formed 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:

$$i_M = (0.035)\frac{20kVA}{480V}$$
$$= 1.46A$$
$$i_M = \sqrt{2}i_M$$
$$X_{L_M} = 480V/1.46A$$
$$= 329‰$$

$$L_M = X_{L_M}/w$$
$$= 0.872H$$
$$E_{L_M} = \frac{0.872(2.06^2)}{2}$$
$$= 1.85J$$

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˚C maximum ambient temperature. Average power dissipation requirements over idling power are not needed because of the non-repetitive nature of the expected transient.
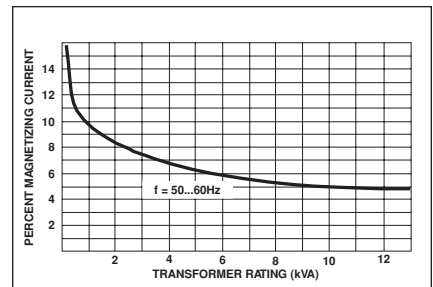

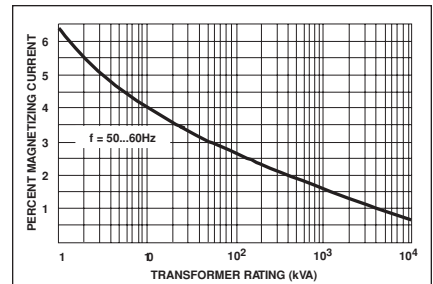*Figure 6. Magnetizing current of transformers with low silicon steel core*

Figure 7. Magnetizing current of transformers with high silicon steel core or square loop core

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˚C or the surface temperature exceed 85˚C, the single pulse energy ratings and the average power ratings must be derated by the appropriate derating factors supplied on the data sheet.

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.
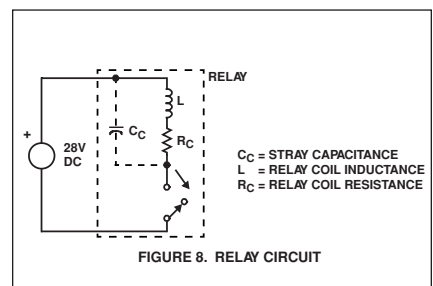

Figure 8. Relay Circuit

When relays or mechanical switches are used to control inductive loads, it is neces-

sary 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 30 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
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.
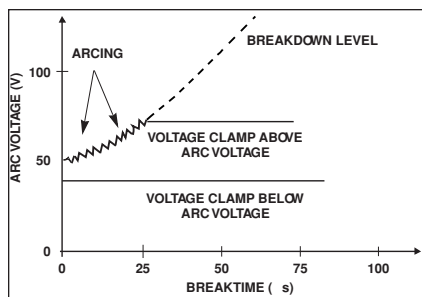

Figure 9. Voltage clamp used as arc suppressor

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.
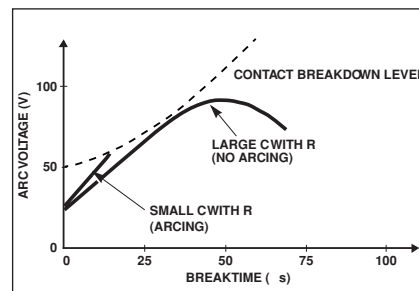

Figure 10a. R-C arc suppression

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.

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.
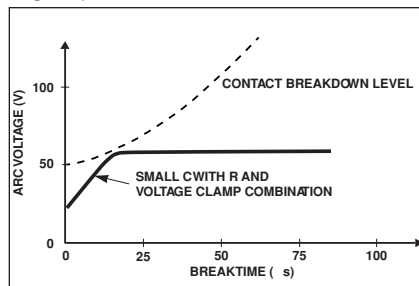

Figure 10b. R-C and clamp arc suppression

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.

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 67. The coil R_C value is 28V/1A,

or 28. The coil inductance was found to be 20mH.
Thus, the approximate time constant is:

From the pulse rating curves of the V39ZA1

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

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
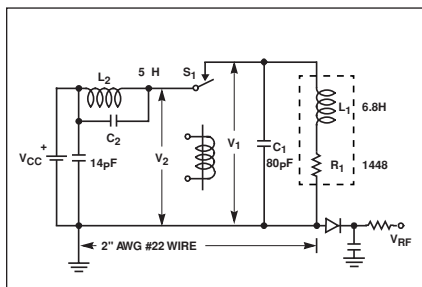

Figure 11. Test Circuit

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).

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.
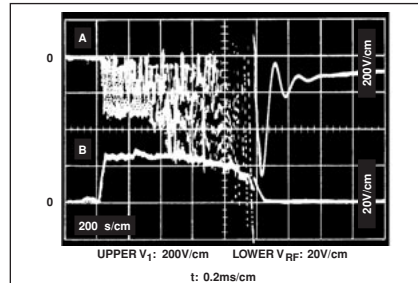

Figure 12. Unprotected Contacts

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.
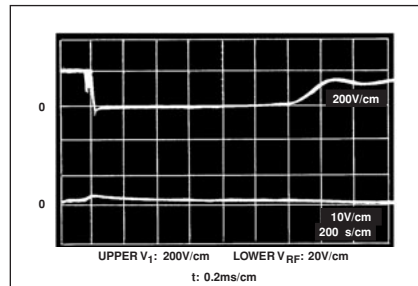

Figure 13. Varistor protected contacts

PROTECTION OF TRAN-SISTORS 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.
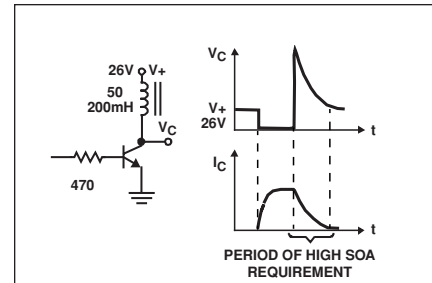The inductor drives the collector voltage up
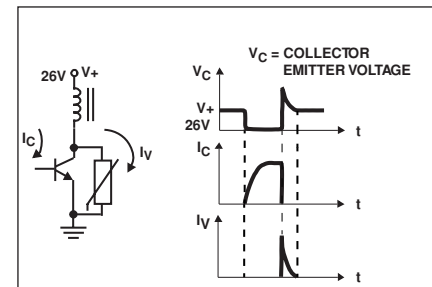
Figure 14a. Basic solenoid circuit

Figure 14b. Solenoid circuit with varistor protection

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).

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 Li² 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 × 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 non-recurrent 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
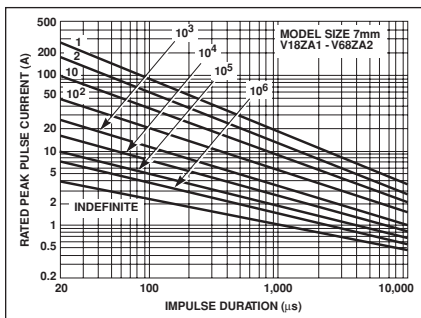

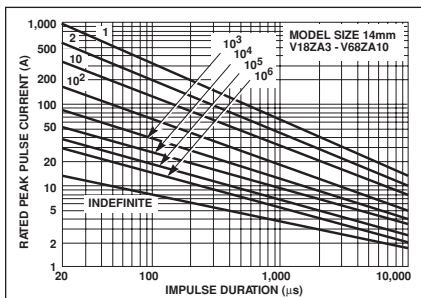
Figure 15a. ZA Series V18ZA1-V68ZA2 (7mm)

Figure 15b. ZA Series V18ZA3 to V68ZA10 (14mm)

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.

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.
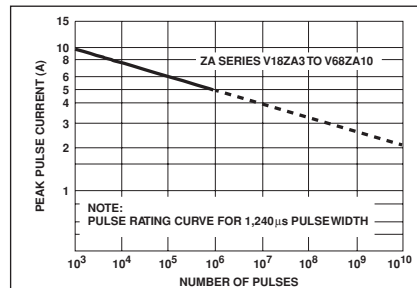

Figure 16. Extrapolated pulse rating curves

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.

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.
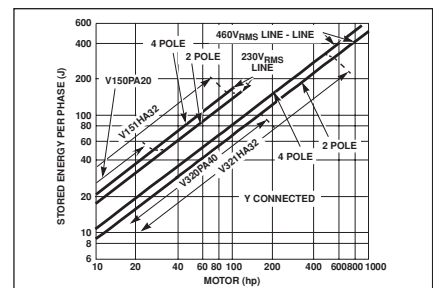
Figure 17. Stored energy curves for typical wye-connected induction motor

NOTES:
1. Y connected 60Hz.
2. Energy at Max torque slip speed.
3. See Figure 20 for varistor circuit placement.
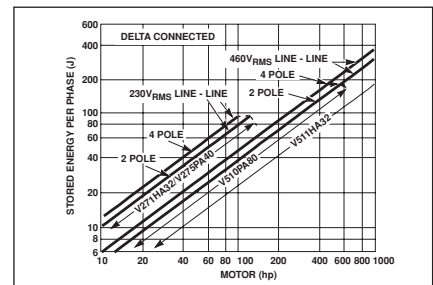
Figure 18. Stored energy curves for typical delta-connection induction motor

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

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.

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

Table 1.. Littelfuse varistor selection guideline for 117VAC applications
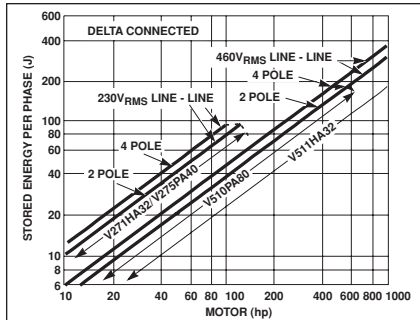

Figure 19. Stored energy curves for a typical motor with stalled rotor

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.

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.

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.
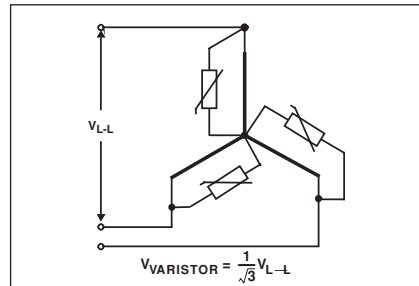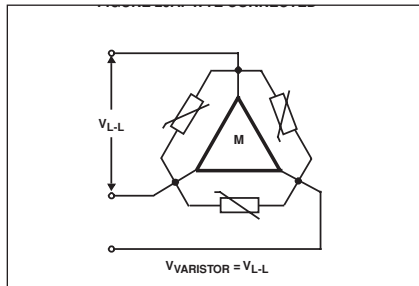

Figure 20a. Wye connected

Figure 20b. Delta connected

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.
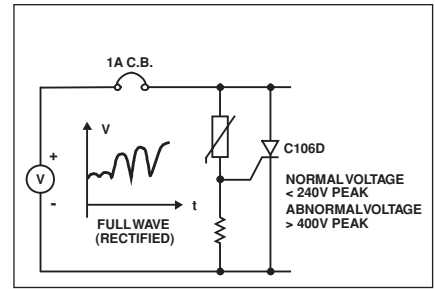

Figure 21. Crowbar circuit

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 200A at 25°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 400. The highest value 5% tolerance resistor falling below 400 is a 360 resistor, which is selected. Thus, R_{GK} is 378 maximum and 342 minimum. Minimum SCR trigger voltage of 0.4V requires a varistor of 0.4V/378, 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°C, this is determined by calculating the maximum current required to provide 0.8V across a parallel resistor comprised of the 360 R_{GK} selected and the equivalent gate-cathode SCR resistor of 0.8V/200A, since the C106 requires a maximum of 200A trigger current. The SCR gate input resistance is 4k and the minimum equivalent gate-cathode resistance is the parallel combination of 4k and R_{GK}(MIN) , or 360Ω -5%, 342. The parallel combination is 315Ω. Thus, I $_{VARISTOR}$ for maximum voltage-to-trigger the C106 is 0.8V/315, 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°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 $1/2 \times K \times I_{PK} \times V_{PK} \times t$ (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 117VAC 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 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 60664-1.

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 10/1000s 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.

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 375VAC 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 375VAC , 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

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

Table 2. Littelfuse varistor selection guideline for 117V$_{AC}$ applications

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. It acts as a series balancing, orballasting, impedance to force a degree of sharing that is not possible at lower current levels. This is depicted in Figure 20. 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.

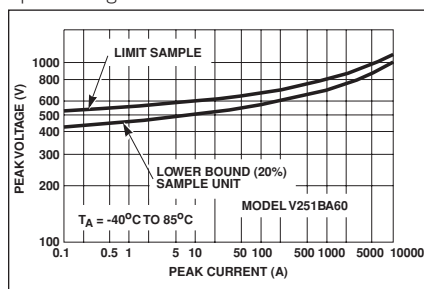At high current levels exceeding 1000A, the up-turn region is reached and current shar-

Figure 22. Parallel operation of varistors by graphical technique

	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.

Table 3. Checklist for series and parallel operation of varistors

ing improves markedly. For instance, at a clamp voltage of 900V, the respective varistor currents (Figure 20) 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 22.

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 3.

Reference

For more information concerning Littelfuse Industrial application solutions visit the Littelfuse web site-http://www.littelfuse.com [1] Kaufman, R., "The Magic of I²t," IEEE Trans. IGA-2, No. 5, Sept.-Oct. 1966.

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