13. Charge Diverters: the Electronic Crowbar

With the exception of most line-type pulser, all of the modulator types discussed require some high-speed means (~μs) of providing an alternative path for fault current that results from an internal arc in the electron gun of our microwave tube.

13.1 What happens when an electron gun arcs?

A typical circuit arrangement and fault scenario is shown in Fig. 13-1. It involves a microwave tube with a gridded electron gun. The presence of the grid, which comprises small-diameter wires, coupled with the possibility—even if only rare—that an arc can terminate on it, brings into play both components of possible arc damage. The first component is the energy dissipated in the arc itself, which is the time integral of the arc voltage drop and the arc current. The voltage drop of an arc between copper electrodes in vacuum, shown in Fig. 13-2, is almost independent of arc current, up to at least 1000 A. And it is small, less than 20 V. Beyond 1000 A, some experiments have shown the rising characteristic illustrated in Fig. 13-2, where arc voltage drop increases to about 50 V at a current of 10,000 A. It increases rapidly beyond that as the arc becomes unstable. Other experiments have shown low arc voltage drop for currents well beyond the apparent upper limit of 10,000 A. In any case, 20-V arc drop for up to 1000-A arc current can usually be depended on. With the arc voltage constant, the other factor is the time integral of the current,

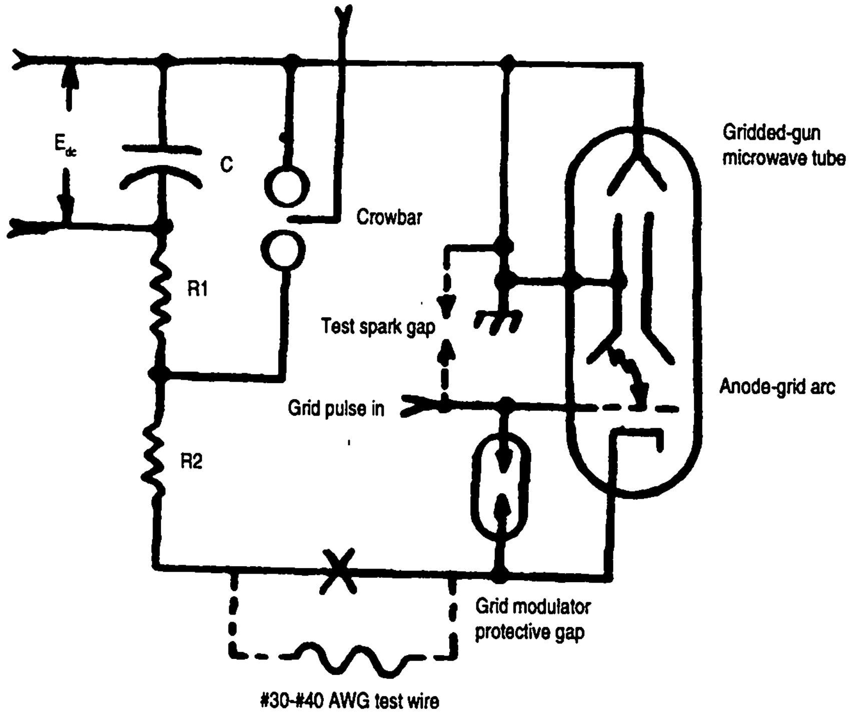


Figure 13-1. Typical fault scenario for gridded-electron gun.

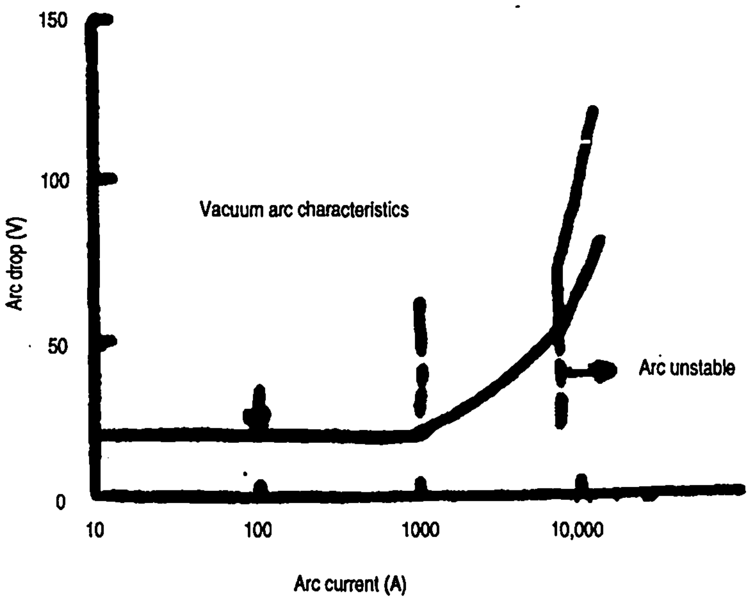


Figure 13-2. Properties of an arc in a vacuum between copper electrodes.

$$\int i \bullet dt,$$

which is nothing more than the total charge transport through the arc.

Referring back to Fig. 13-1, the circuit elements that determine what the fault current will be are the surge resistors *R1* and *R2*. Their total value must be V_{dc}/I_{FAULT}, where V_{dc} is the voltage across the storage capacitor C. If no charge-diverter path or crowbar is provided, then the charge transport through the arc will be the charge Q that is initially stored in C, where $Q = V_{dc} \times C$. The arc energy will be the product of the arc drop, 20 V, and charge Q. A commonly quoted permissible arc energy for microwave-tube electron guns is 50 J, although this value has been by no means been rigorously derived. Nevertheless, using this criterion we could stipulate that in cases where stored charge is less than 2.5 C, no crowbar is required, and when it exceeds 2.5 C, one is—providing that the fault current is limited to 1000 A or thereabouts. Note that no mention has been made so far of the energy stored in the capacitor bank C. This is because all but a tiny fraction of the stored energy will be dissipated in either *R1*, if the crowbar fires in a timely fashion, or in *R1* + *R2*, if it does not. (If there is no crowbar at all, *R1* and *R2* can become the same resistor.)

An electronic crowbar is often referred to as an energy diverter, which is certainly what we want it to do. However, it is no more capable of dissipating energy than the initial arc. The energy must be dissipated in the resistors. The crowbar switch becomes an alternative path for discharge current, diverting the charge from the initial arc. The current through the crowbar is limited by *R1*, which must be large enough that the diverted current does not exceed the capability of the crowbar arc. In some cases, *R1* can be made large with respect to *R2*, in which case crowbar and fault currents are nearly the same.

A crowbar charge diverter of low-enough impedance and rapid-enough firing time can limit the energy deposited in the initial gun arc to a tiny fraction of what it would have been. Often, however, this residual energy is actually too small to do any good in "processing" the voltage-hold-off capability of the faulting gun. Believe it or not, there are often good reasons for repetitive gun arcing—to control the growth of micro-projections, for instance. Micro-projections are metallic filaments that protrude from an otherwise-smooth copper surface. The tips of these projections have greatly enhanced electric-field intensities. An arc can burn these projections away. But if there is not enough energy in the arcs that the micro-projections can induce, then they will never be burned away. There is an optimum value of "let-through" energy for each individual case. Unfortunately, there is no analytical criteria for what that value might be. A high-speed electronic crowbar can always be delayed in its response, and some have been, with marked improvement in subsequent gun arc rate.

Other than the "50-joule" criterion, prior analytical determination of optimum crowbar performance has never been quite possible. But the experimental calibration of crowbar performance is. This procedure is often referred to as the "tinfoil" test, although 1-mil household aluminum foil is the experimental medium most often used. The test is performed using a calibrated ball gap. The aluminum foil is smoothed onto the surface of one of the balls. A capacitor is connected directly across the balls with no current-limiting resistance in series with it. The idea is for all of the stored energy to be delivered to the arc. The amount of energy required to raise a given volume of aluminum to the vaporization point is 10.5 J/mg. Figure 13-3 shows the correlation between calculated and measured hole sizes in the 1-mil foil resulting from different arc energy levels. What results from this test is "calibrated aluminum foil." The efficacy of an actual crowbar system can then be determined by replacing the actual microwave-tube electron gun with a ball gap that has aluminum foil smoothed onto one of the balls and is set to break down at the operating voltage of the actual gun. When this happens, the "let-through" energy can be inferred from the diameter of the resulting hole in the foil. Results of tests of this type have run the gamut from "what hole?" to "what foil?" depending upon the condition of the crowbar system at the time of the test. (Of course, the speed of the subsequent disconnect of the primary power from the high-voltage supply system must be considered also because there can be significant follow-through energy deposition.)

The second component of possible arc damage is the heat generated by ohmic loss in a finite conductor, such as a grid wire. If the arc terminates on it, the resulting "action" of the discharge current can be evaluated as

$$\int i^2 \bullet dt .$$

Any conductor will vaporize, no matter how large in diameter, if it is subjected to sufficient action, or "action-integral," as it is sometimes called. The duration of arc current is short enough that the heating is adiabatic, with no time for heat to be removed. The action required to fuse, or vaporize, copper conductors as a function of their cross-sectional areas is shown in Table 13-1. The units of action are either ampere^2-seconds, or joules/ohm. Let's take the circuit of Fig. 13-1 as an example. If there were no crowbar and the arc terminated on a grid wire, the action could be evaluated as

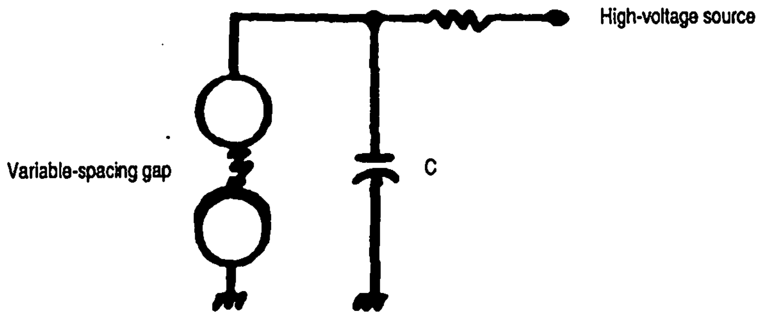
$$\frac{W_C}{R1+R2},$$

where W_C is the energy stored in the capacitor C. (This assumes that the total of $R1 + R2$ is much greater than the resistance of the grid-wire segment, which it should be.) If there is a crowbar and it acts so fast that the arc current has not diminished substantially before the crowbar takes it over, the action will be

$$\left(\frac{V_{dc}}{R1+R2}\right)^2 \times \Delta t,$$

where Δt is the firing delay time of the crowbar. Note that the protective spark gap shown shunting the output of the grid-pulse modulator may succeed in protecting the grid modulator from damage, but it can do nothing to save the grid itself. The only thing that can save the grid is enough surge resistance, enough crowbar response speed, or both. (Of course, the electron gun could be designed so that arcs to the grid itself are all but impossible.)

Grid wires are never made of copper. They are usually made of some metal



Energy (Joules)	Mass (mg)	Area (in.^{2})	Hole diameter (in.)
1	0.095	0.000066	0.0288
5	0.476	0.003	0.065
10	0.952	0.0066	0.091
20	1.90	0.013	0.129
25	2.38	0.016	0.144
30	2.86	0.0197	0.158
40	3.81	0.026	0.183
50	4.76	0.033	0.204
60	5.71	0.039	0.224
70	6.67	0.046	0.242
75	7.14	0.049	0.250
100	9.52	0.066	0.289

Figure 13-3. Calculation of aluminum-foil damage due to arc energy.

Table 13-1. Action required for fusing of copper wires of increasing size.

Wire size (AWG)	Area (circular mils)	Area (in.^{2})	Fusing action (J/ohm or A^2-s)
44	4.00	3.14×10^{-6}	0.33
42	6.25	4.9×10^{-6}	0.81
39	12.2	9.6×10^{-6}	3.1
36	25	1.96×10^{-5}	12.9
33	50.4	3.96×10^{-5}	52.5
30	100	7.85×10^{-5}	206.6
27	202	1.58×10^{-4}	843.1
24	404	3.17×10^{-4}	3372
21	812	6.38×10^{-4}	13623
18	1620	1.28×10^{-3}	54233
15	3260	2.56×10^{-3}	219579
12	6530	5.12×10^{-3}	881013
9	13090	0.010208	3540261
6	26240	0.02061	14226028
3	52620	0.04133	57208121
1/0	105600	0.08291	230400000
4/0	211600	0.1662	925100000

$$\textit{Fusing action} = \int i^2 dt = \frac{A^2}{33}\log\left(\frac{1083°\mathrm{C} - 40°\mathrm{C}}{234°\mathrm{C} + 40°\mathrm{C}}\right) = \left(\frac{\textit{Area in circular mils}}{6.957}\right)^2$$

that has even lower energy tolerance than copper. When the primary concern is the fusing of internal wirelike conductors, the standard test of crowbar efficacy is to replace the normal high-voltage lead with a length of small-diameter wire (in the AWG 30-to-44 category) and induce an external test arc the same way it was done for the tin-foil crowbar test. Some high-voltage systems have built-in crowbar-test circuits that use a high-voltage relay to short-circuit the output through a length of test wire, greatly facilitating periodic testing. If the wire does not fuse, the crowbar is presumed to be operating properly. When the test wire goes, however, it all goes, and nothing remains between the test-wire terminals. (In a marginal situation, the test wire can actually grow in length over repeated test shots. The wire is being heated to near its melting point while, at the same time, the magnetic force on the wire caused by the fault current is compressing it, making it smaller in diameter. The volume of metal stays the same, however, so the wire must grow in length. Eventually it will vaporize because its diameter is decreasing with each test shot.)

13.2 Types of crowbar switches

The crowbar function can be idealized as the simple, aperiodic, and usually unidirectional discharge of a capacitor bank. The current-limiting surge resistance in series with the discharge path is usually many times the value required for critical damping, $R = 2\sqrt{(L/C)}$. So any half-control switch with adequate voltage hold-off, peak-current handling capability, and charge-transport lifetime

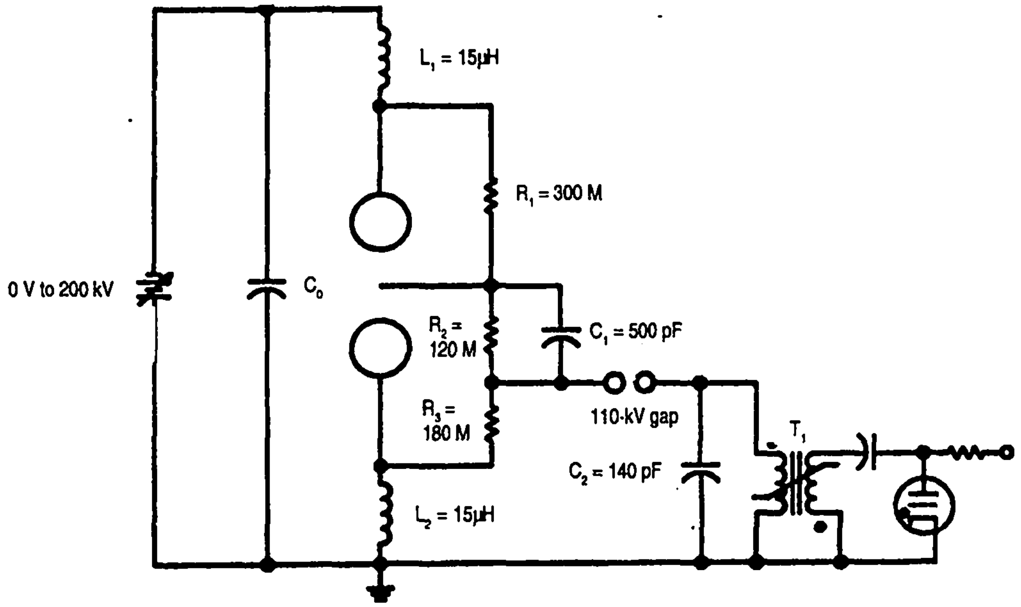


Figure 13-4. The "infinite-voltage-range" crowbar switch.

can be a candidate. Many successful electronic crowbars have been implemented with hydrogen thyratrons, ignitrons, and triggered air and vacuum spark gaps. However, few, if any, have used solid-state devices, including the most obvious such candidate, the SCR. Because the firing of a crowbar is intermittent with a period between firings that is orders of magnitude greater than the interpulse interval of even the lowest repetition rate periodic systems, it is tempting to make use of the simplest of all discharge switches, the triggered air gap.

A popular form of triggered air gap is schematically shown in Fig. 13-4. It is a simple ball gap with a needlelike mid-plane electrode. The space between the balls is adjustable in order to vary the self-firing voltage. The static voltage on the trigger electrode is maintained at 1/2 of the voltage between the balls by means of a balanced resistive voltage divider. Coupled to the trigger electrode through a pulse-sharpening ball gap is a short trigger pulse that has an open-circuit peak voltage of between 100 and 200 kV, which is obtained from the secondary winding of a step-up pulse transformer. Under normal conditions, the trigger electrode is electrically invisible, lying along the 50% equipotential line between the balls and having the same voltage itself. When the trigger voltage is applied, especially if its polarity is opposite to the system dc voltage, the electrical symmetry of the gap will be instantaneously destroyed, and breakdown between the trigger electrode and the ball connected to the system dc will immediately follow. The channel between the trigger electrode and the other ball will be overvoltaged by at least a factor of two. The effect will be magnified by the field enhancement at the tip of the trigger electrode. Nevertheless, in a simple, conventional mid-plane-triggered gap, the ratio between maximum self-firing voltage, which must obviously be safely above the maximum system operating voltage, and the minimum system voltage for which there will be reliable breakdown between both balls of the gap is rarely more than 3:1. This means that for operating voltages less than 1/3 of the maximum there will be no reliable crowbar protection. This situation is often intolerable.

But note that the gap arrangement shown in Fig. 13-4 is not just a simple mid-plane triggered gap. There are 15-µH inductors in series with both of the main balls of the gap, and a coupling capacitor, *C1*, in series with the trigger electrode. The purpose of these elements is to transform the simple triggered gap into the "infinite-voltage-range" crowbar switch. The inductors appear as high-impulse impedances to the triggering waveform. When one or the other gap initially breaks down due to the injection of the triggering pulse, the trigger voltage is developed across the inductor in series with the ball terminating the trigger arc. Instead of the trigger electrode being effectively short-circuited to whatever dc voltage is applied to the ball it initially arcs to, the arc pulls the ball up to the trigger voltage, which is momentarily supported by the series inductor, thus allowing the remaining channel to break down as well. Even if the system voltage is such that it initially subtracts from the trigger-pulse amplitude so that the second channel does not break down, the underdamped resonant circuit formed by *C1* and one or the other of the inductors will cause the trigger-pulse polarity to rapidly reverse, correcting the situation and assuring complete arc-channel breakdown—even with no system voltage applied at all. If it will break down completely with zero system voltage, then its operating ratio is truly infinite, even if the maximum self-breakdown voltage is not.

The version shown is double-ended; it will work with either polarity of system voltage. In most cases, however, the system voltage polarity is fixed and not likely to ever reverse. In this case, a simpler single-ended version can be used that has an inductor in series with the high-voltage connection only and whose trigger-voltage polarity is opposite to the system voltage. To assure operation down to zero system voltage, however, the mid-plane trigger electrode must be mechanically biased slightly toward the ball having the inductor in series with it to make sure that the initial trigger arc is to that ball and not the other one. As system voltage is increased, however, the tendency to break down to the proper ball increases as well.

The presence of inductance in series with the main arc channel does have a price, however. The rate-of-rise of current in the crowbar path will be V/L, where V is the system voltage and L is the 15-µH inductance. In practical situations, where a little let-through energy is usually a good thing, this is almost never a problem, especially if there is intentional, or even inadvertent, inductance in series with the initial fault-current path. The inductance will limit the rate-of-rise of initial fault current as well.

The performance of a practical application of a single-ended version of this circuit is shown in Fig. 13-5. This crowbar was designed for a dc storage system associated with a high-power dual-klystron RF source. The system's capacitor bank totaled 11.2 µF. Its maximum voltage rating was 130 kV, although it normally operated at less than 90 kV. The 17.5-ohm surge-limiting resistor was placed in series with the crowbar path, and an additional 21 ohms was placed between the crowbar junction and the klystron cathode bus. Therefore, a total of almost 40 ohms was placed in the klystron gun-arc path. The resistors were of wound construction and therefore had self-inductance, shown as *L1* and *L3*. The crowbar was tested by simulating an arc path through the crowbar test relay,

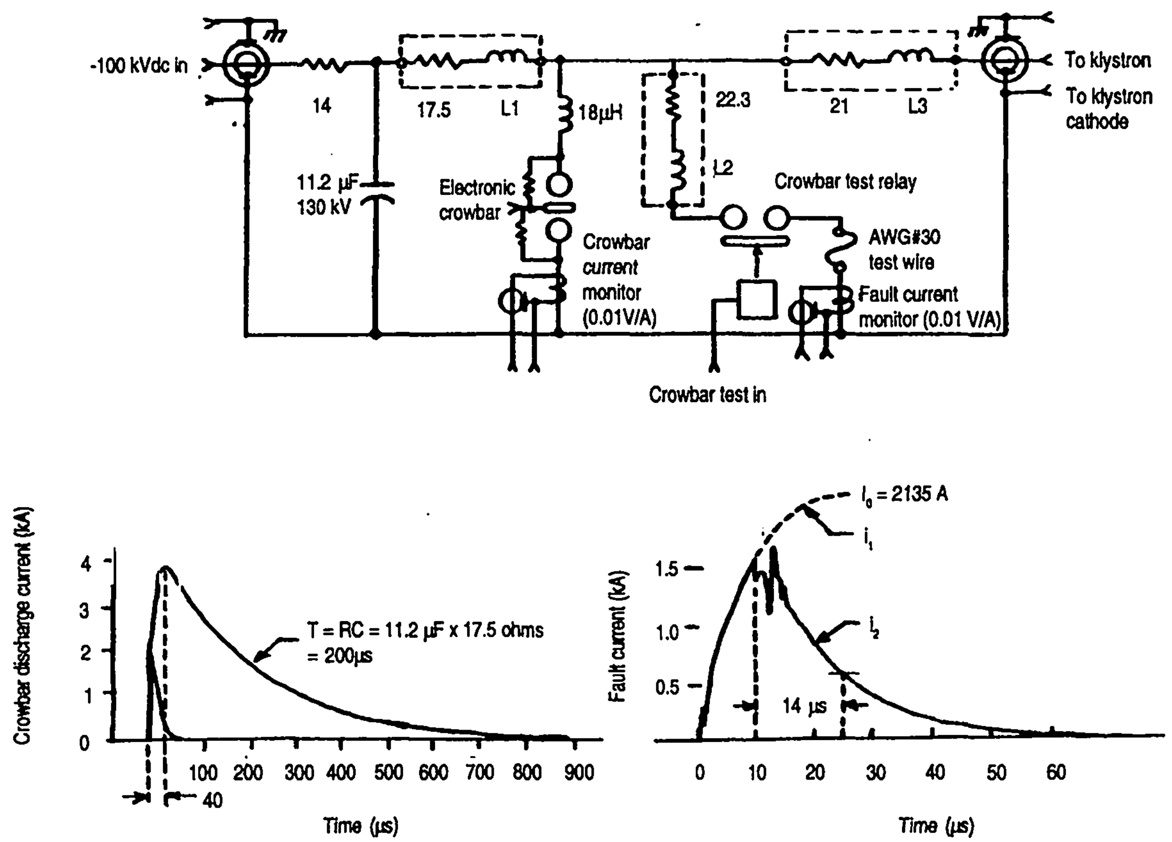


Figure 13-5. Experimental performance of "infinite-voltage-range" crowbar switch.

which had 22 ohms resistance and a length of AWG-30 wire in series with it. Both fault current and crowbar current were monitored by current-viewing transformers.

The waveforms resulting from a test firing are also shown in Fig. 13-5. Fault current in a zero-inductance path would reach a peak of 2135 A at a system voltage of 85 kV, as shown in the following calculation:

$$\frac{V}{R} = \frac{85kV}{17.5\Omega + 22.3\Omega} = 2135A \ .$$

The actual current waveform is a double-exponential, with a rise time governed by the *L/R* time-constant and the fall time by the RC time-constant. The crowbar firing delay is 10 μs, which is neither exceptionally fast nor slow. By the time the gap ionizes, however, fault current, *i*, has built up to 1500 A, and from that point on it diminishes as discharge current is taken over by the crowbar path. The current through the crowbar continues to build to a peak of 3900 A and then decays with an time-constant of $T = RC = 11.2$ μF x 17.5 ohms, or 200 μs.

Evaluating the fault-current pulse we see that its action, or i^2t time integral, is 26 A^2-s (or J/ohm), where the integral is made up of the rising current slope , i_1, and the falling current slope, i_2. The fusing action for AWG-30 copper wire is 290 A^2-s. No problem there. The total charge transfer is 0.03 C, so the arc energy, assuming 20-V arc drop, is 0.6 J. In all likelihood this is an over-protective crowbar, one that is not nearly as effective as it could be in the processing of cranky or arc-prone electron guns.

13.3 The nature of surge-limiting resistors

Resistors used in the role of surge-current limiting must be capable of absorbing large amounts of single-shot energy. Those resistors limiting the current through the crowbar must be capable of safely dissipating all of the system stored energy. Those resistors limiting the initial arc current are located between the crowbar junction and the electron gun high-voltage terminal. Although they are removed from the high-dissipation path by the firing of the crowbar, they too must be rated for their fair share of stored energy in case the crowbar does not fire (and often you will not know if it should have fired or not).

These same resistors, especially when used in high-duty-factor applications, must be capable of dissipating large amounts of continuous average power as well, due to the flow of normal load current through them. In a pulsed system this is usually the dissipation rating most likely to be miscalculated. (Remember, it is RMS current not the average current that determines resistor dissipation.) The resistor properties that give it a high-energy rating are not the same as those that give it a high-average-power rating.

What determines the energy absorption capability of a resistor is the mass of the active resistive element and its specific heat, which is about 0.4 J/g-°C for most metals. Remember that we're talking about *active* resistive mass. The mass of the ceramic core of a tape or wire-wound resistor does not count. Only the mass of the tape or the wire itself is important. This is why conventional wirewound resistors, even with high-average-power ratings, are often poor choices in high-energy applications. There are, however, special high-mass surge windings that can greatly improve their energy handling. Figure 13-6 shows the "ribwound" style of resistor having such a high-mass surge winding. It can often be an excellent compromise where high energy and high continuous-average power must be handled simultaneously. This trade-off is valid because average-power dissipation is determined entirely by the surface area and the maximum operating temperature of the resistive material. The greater the temperature difference between resistive element and ambient environment, the more power a given surface area of resistor can dissipate.

A resistor that is already operating at its average-power-dissipation rating, which is related to a specified temperature rise above ambient (often as high as 375°C), is not in the best condition to take a transient rise in temperature caused by the energy discharge from a capacitor bank. The sum of the temperature rise due to continuous-power dissipation and the transient rise due to specific energy dissipation should ideally not exceed the resistor's maximum specified steady-state rise. The amount of energy that the resistor can absorb for a given temperature rise is given as $W = \Delta T \times \text{mass} \times \text{specific heat}$. One must also remember that average power is nothing more than the time rate of energy. If the capacitor bank is discharged frequently enough, the resistors will never recover to their steady-state temperatures. (Discharging a 1-MJ capacitor bank approximately once every 1.5 minutes is the equivalent of 10-kW average-power dissipation.) As an example of a specific resistor's capability, a ribwound resistor using a 2-kW frame

(3-1/4-in. diameter by 20 in. long) with a 1.45# (700 g) surge winding will absorb 100 kJ with about a 360°C temperature rise. It is obvious that this resistor cannot be used to simultaneously dissipate 2 kW of continuous average power from the flow of normal pulse current at high duty factor and then absorb a 100-kJ shot of energy without being seriously overheated.

The globar style of resistor, also shown in Fig. 13-6, is designed especially for high-energy application. Its entire mass is active resistive material. Its surface-area-to-mass ratio, however, is lower than that of the wound type of resistor, and the thermal conductivity of its material is not as great, so that the temperature gradient in the radial direction cannot be ignored. As an approximate rule of thumb, a globar-style resistor with the same physical dimensions as a ribwound resistor that has a surge winding might have twice the energy-handling capability but only 1/5 the average-power capability. For example, such a resistor that is 1-1/2 in. in diameter and 24 in. long may be rated at 164-kJ energy capability but only 300-W average power dissipation, along with 165-kV voltage hold-off.

Another specially designed type of resistor is the accordion style, also shown in Fig. 13-6. Most of its mass, which is also active resistive material, is shaped like ribbon candy. It can be built in almost any practical length for high voltage hold-off. A resistor rated for 500-kJ energy dissipation, 250-W average power, and 120-kV voltage hold-off has a cross section of 4 in. by 12 in. and is 18 in. long.

"Ribwound" style withg surge-rated winding

"Globar" style high-energy resistor

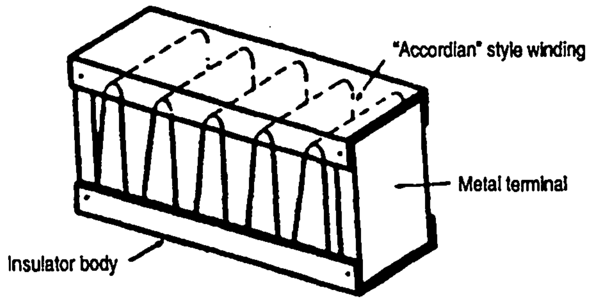


Figure 13-6. Different styles of high-energy, high-power resistors.