REDUCING ARC ENERGIES WITH CURRENT LIMITING FUSES

By Mike Lang
Principal Field Engineer

I. WHY USE CURRENT LIMITING FUSES

Current limiting fuses can reduce both the magnitude and duration of a fault current. A UL Listed, current limiting fuse must clear a short circuit current in less than one half cycle in its current limiting range. In this condition the fuse will melt in the first quarter cycle and prevent the fault current from reaching the first peak of the asymmetrical waveform, significantly limiting the total electrical energy delivered to the fault. This energy limitation enables class J, RK1, T, and L fuses to reduce incident heat energy from an arc flash to very low levels.

Current limitation is one of the most important features of today's fuses. By isolating a faulted circuit before the fault current has sufficient time to reach its maximum value, a current limiting fuse can:

- Limit the total energy delivered to arcing faults.
- Limit thermal and mechanical stresses created in the system by the fault currents.
- Reduce the magnitude and duration of the system voltage drop caused by fault currents.
- Minimize downtime, since current limiting fuses can be precisely and easily coordinated even under short circuit conditions.

If the arc fault current is large enough for a current limiting fuse to be in its current limiting range, the fuse will dramatically reduce the electrical energy delivered to the arc. The photos below illustrate how the proper application of current limiting fuses can mitigate the hazards of arc faults.

The discussion in the following section illustrates the reduction of incident heat energy and the associated Flash Hazard Boundary with the use of Fuse Incident Energy Charts. The notes at the end of the section contain comments on the specifics on the development of the performance data and cautions about the other hazards of arc faults.

II. Using Fuse Incident Energy Charts

The following steps show how to calculate incident energy and the flash protection boundary with AmpTrap2000® fuses as part of a flash hazard analysis.

Determine the available fault current at the line side terminals of the equipment being analyzed. This is 38,596 amps at point A in Figure 1.

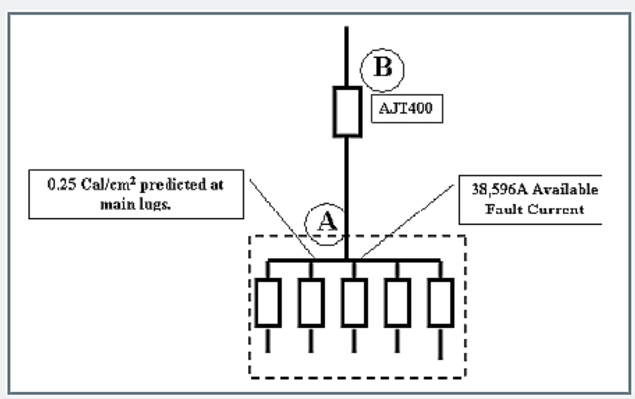

Figure 1: One-line diagram

Identify the type and ampere rating of the Amp-Trap 2000 fuse providing the overcurrent protection for the panel. In Figure 1, this is the AJT400 at Point B.

Using Chart 1, determine the incident energy exposure possible at an 18 inch working distance. Following the arrows up from 38,596 amps on the x-axis, to the AJT400 plot and reading to the left, the predicted incident energy would be 0.25 cal/cm^2 at an 18 inch working distance.

Using Chart 2, determine the Flash Protection Boundary (FPB) for the incident energy calculated in step 3. Enter the X-axis at 0.25 cal/cm^2, follow the arrow up and read across to the y-axis. The distance at which a worker would expect the onset of a 2nd degree burn (1.2 cal/cm^2) due to an arc flash event would be approximately 6 inches.

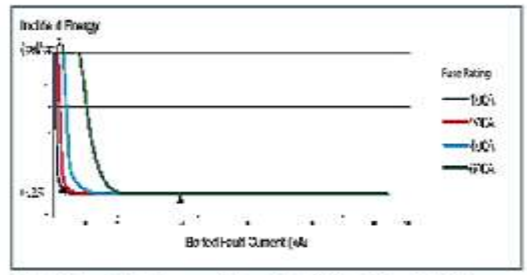

Chart 1: Incident Energy Chart for A6D, AJT and A6T at working distances of 18 inches

Identify the actual working distance of the job to be performed. If your expected working distance is less than the FPB, you will need to select the PPE appropriate for the incident energy expected at that working distance. Use Chart 3 to adjust the energy calculated at 18 inches to the actual working distance. If your calculation in Step 3 yielded 10 cal/cm^2 at 18 inches and the actual distance is 24 inches reduce the incident energy calculation as follows. Start at 24 inches on the x-axis. Go up until you reach the curve labeled 10 cal/cm^2. Reading to the left, the incident energy would be expected to be slightly lower, 6.5 cal/cm^2, at the greater distance.

6. Select PPE for at least Hazard /Risk Category 2 per the guidelines provided in Chapter 1 of NFPA 70E.

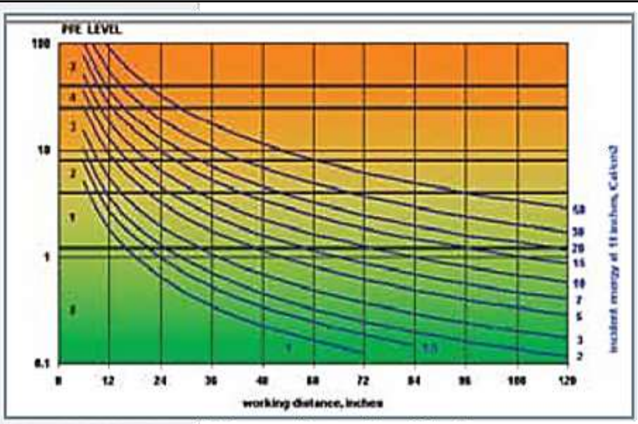

Chart 3: Working Distance Correction Chart

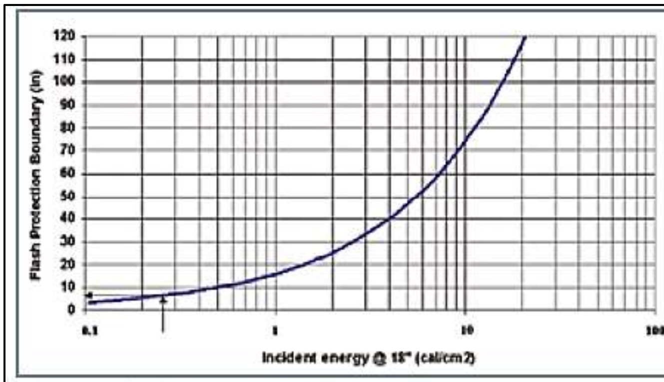

Chart 2: Flash Protection Boundary

NOTES

This information is an aid in determining the proper PPE to safe-guard an individual from burns that can be sustained from an arc flash incident. This information does not take into account the effects of pressure, shrapnel, metal spray, copper vapor, or plasma jets resulting from an arc fault.

The information is based on actual test results of Mersen fuses which were tested in accordance with methods outlined by the P-IEEE 1584 Committee.

The incident energy levels achieved are equal to or lower than those calculated using the fuse equations contained in IEEE 1584.

PPE selected from the incident energy shown in this calculator will be adequate for 98% of arc flash incidents. In up to 2% of the incidents, incurable burns may result. This is based on PPE with standard ATPVs of 1.2, 4, 8, 25 and 40. For PPE with other values, use the next lower ATPV rating. PPE must be utilized any time work is performed on or near energized electrical equipment or on equipment which could become energized. PPE must be utilized during lockout/tag-out procedure until the voltage testing has been completed confirming that the equipment has been de-energized.

The data is based on 1-1/4 inch electrode spacing, 600V 3 phase ungrounded system, with the electrodes located 4 inches from the rear of a 20 inch cubic box, open on one side. Incident energy is measured at a working distance of 18 inches.

Amp-Trap fuse data is based on results of tests that were conducted at various fault levels for Mersen A6D, AJT, and A4BQ fuses. Actual results could be different for the following reasons: (1) system voltage, (2) short circuit power factor, (3) distance from arc (4) enclosure size (5) arc gap, (6) electrode orientation, (7) conductor size during arc fault initiation.

Fuses below 100 amps were not tested, since the incident energy measured with the 100 amp rating is well below 1.2 cal/cm^2 from 1.5kA up.

Minimum reported incident energy is 0.25 cal/cm^2 which is the accuracy limit of the test equipment. The values of incident energy from fuse tests which are reported based on bolted fault currents do take into account the difference between bolted fault currents and arcing fault currents.

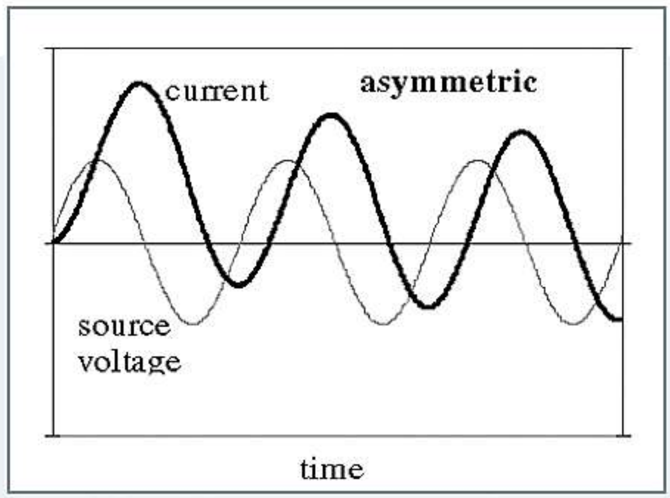

Figure 2: Typical short circuit current waveform

UNDERSTANDING CURRENT LIMITATION

III. SHORT CIRCUIT CURRENTS

Short circuit currents usually have a decaying asymmetrical wave shape in the first several cycles of the fault, as illustrated in Figure 2. In a purely reactive circuit the first peak is the highest and can be any value between 1.414 to 2.828 times the rms value of the fault current. Since all circuits include some resistance, a 2.3 multiplier has traditionally been chosen as a practical limit for bolted fault tests. Arcing faults will typically have lower offsets due to the resistive nature of the added arc impedance. For additional information see "More on Short Circuits" on page 5.

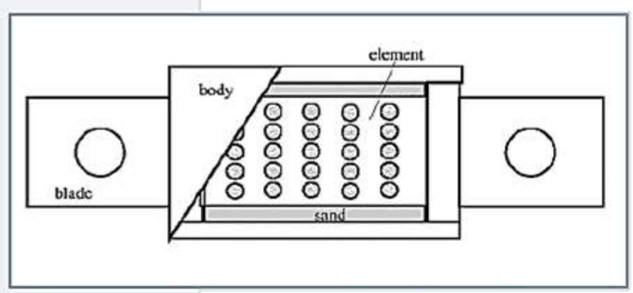

Figure 3: Cut away view of short circuit element

IV. CURRENT LIMITING OPERATION

The short circuit element of a fuse is made of strips of copper or silver with regions of reduced cross sectional area called notches. There may be several strips in parallel, depending on the ampere rating of the fuse. The short circuit elements are enclosed in an insulating tube filled with pure quartz sand. At each end are terminals such as blades or ferrules to permit installation into fuse-folders or connection to bus bars. Please see Figure 3 for an illustration.

During normal load operation, the fuse elements carry the currents without melting. Current limiting operation begins at the initiation of a short circuit. As the short circuit current starts to rise, the elements melt very quickly at the notches and a number of small electric arcs are produced in the notch zones. The increasing impedance of the arcs causes the fault current to be rapidly reduced to zero and the arcs are extinguished.

Figure 4 illustrates the operation of a fuse interrupting a short circuit fault current in an ac circuit. During the pre-arcing (melting) period the current closely follows the available current wave and the voltage drop across the fuse is quite low. When the fuse element melts and internal arcing begins, the voltage across the fuse increases rapidly and the current is forced to zero well before the natural zero crossing of the available current wave.

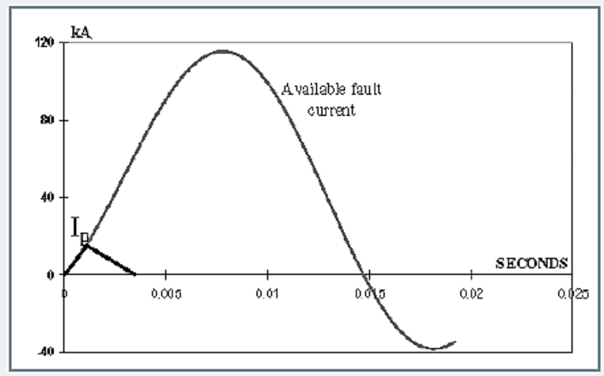

Figure 4: Current Limited Waveform

V. LET-THRU CURRENT

Let-thru current refers to the current passed by a fuse while the fuse is interrupting a fault that is within its current-limiting range. The degree of current limitation provided by a fuse is measured two ways: peak let-thru current (I_p) and I^2t. Maximum allowable I_p and I^2t values are specified in UL standards for all UL Listed current-limiting fuses.

I_p

The highest instantaneous current value reached is referred to as peak let-thru current, and is expressed as a peak instantaneous value (I_p). See Figure 4. I_p is useful in predicting peak electromagnetic forces created throughout the faulted circuit. The peak forces will be proportional to the square of the instantaneous value of current of the first halfcycle peak or $I_p^{\,2}$ for current-limiting fuses. As a practical example, an AJT200 Class J fuse, when subjected to an available current of 230kApeak (100kA rms available with a 2.3 offset multiplier), can limit the peak current to 19kA. This will reduce mechanical stresses on the circuit by a factor of $(19/230)^2$ or to only 0.68% of the level without fuse protection.

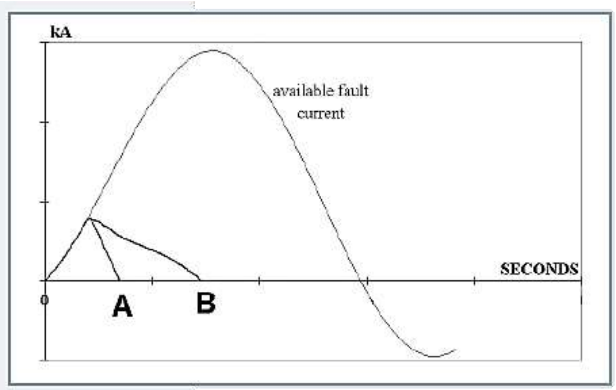

Figure 5: Clearing time effects on I^2t

I^2t

When it comes to predicting the energy delivered to a fault, I^2t is more useful. As Figure 5 depicts, two fuses can have the same I_p, but different total clearing times. Fuse clearing I^2t takes into account both I_p and total clearing time. Fuse clearing I^2t values are derived from data captured during testing of fuses in their current limiting region. It is calculated as follows:

$$I^2t = \int_0^t I^2\,dt$$

The "t" in the equation is the total clearing time for the fuse. The I^2t passed by a fuse depends on the fuse characteristics and applied voltage. For example, as application voltage decreases, I^2t will decrease. Unless stated otherwise, published I^2t values are based on AC testing. (For additional information, see "More on Current Limitation" on page 5.)

VI. MORE ON SHORT CIRCUITS

The rms value of the steady-state current which would flow in the circuit if there were no fuse protection is called the available short circuit current. In an AC circuit, the transient short-circuit current is given by:

$$i = \sqrt{2} * I \{\sin(\omega t + O - \emptyset) - \sin(O - \emptyset)e^{-\omega t/\tan\emptyset}\}$$

Where:

I- is the rms available fault short circuit current

ω -is the supply angular frequency (=2πf)

O -is the electrical angle at which the short circuit begins

Ø- is the power factor angle of the short circuit impedance

The first term in the above expression is the steady-state AC short circuit current, while the second term is an exponentially-decaying transient DC component.

If O = Ø the short circuit current will have an asymmetrical waveform with an exponentially decaying dc component (see Figure 6).

The maximum value of the first asymmetrical peak current is obtained if the circuit is closed at the voltage zero (0 = 0). It can reach 2.828 times the rms symmetrical current in a purely inductive circuit, or about 2.3 in a circuit with an X/R ratio of 6.6:1.

If 0 = Ø the short circuit current will not have an asymmetrical waveform. Likewise if it is a purely resistive circuit (X/R = 0) the waveform will be symmetrical as shown in Figure 7. It will reach 1.414 times the rms current. Most fault currents in AC systems will lie between the two extremes shown here.

VII. MORE ON CURRENT LIMITATION

I_p

The peak let-through current is a very important parameter for current limiting fuses. Fuse data is presented in the form of peak let-through characteristic curves. These curves are published for specified voltages, frequencies and power factor. Chart 4 shows peak let-through characteristic curves for a

A6D200R and A4BQ2000 current limiting fuses. For low available fault currents, the fuse takes several a.c. cycles to melt, and the highest value of current is equal to the peak current in the first half-cycle. This can be as low as $1.414*I_{rms}$ for a symmetric wave to about $2.3*I_{rms}$ for an asymmetric wave (See the discussion under More On Short Circuits). These limits are shown by the black lines. However above a certain level of available fault current, called threshold current, melting occurs within the first half-cycle, and current-limiting action occurs. At high available currents, the peak current is much lower than the peak available value. For the A6D200R shown, the peak current is limited to only 16kA with an available current of 40kA rms. (peak of 92kA on the faint gray line). For a given rms available fault current, the peak let-through can vary depending on 0, the electrical angle at which the fault begins.

I^2t

The I^2t passed by the fuse is called the Total Clearing I^2t and is given by:

$$\textbf{Total Clearing } I^2t = \textbf{melting } I^2t + \textbf{arcing } I^2t$$

The lower curve in Figure 8 shows how the melting I^2t of the fuse varies with the rms available current. For very high currents, the melting I^2t is constant. This is called the adiabatic region, because the rate of heating is so high that heat losses from the element notches to the surrounding medium are negligible. For lower available currents, the melting time is longer and heat losses from the notch zones means more I^2t energy is required to melt the notches.

When applying fuses for reducing arc energies, excellent results can be expected if the arcing fault current is large enough for the fuse to operate in its adiabatic region. See for example,

Chart 1 on page 2.

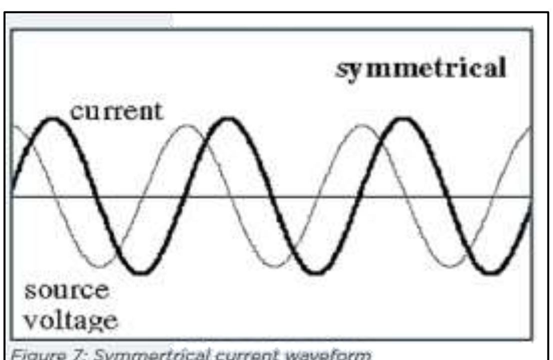

Figure 7: Symmertrical current waveform

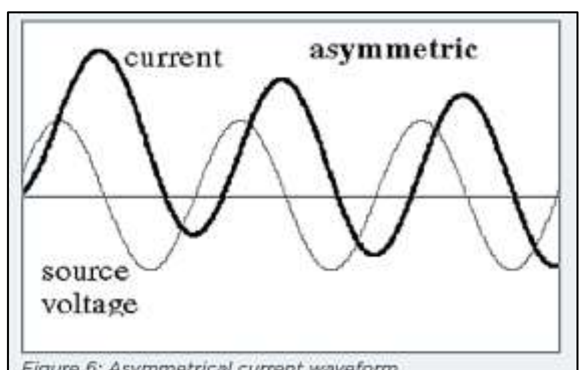

Figure 6: Asymmetrical current waveform