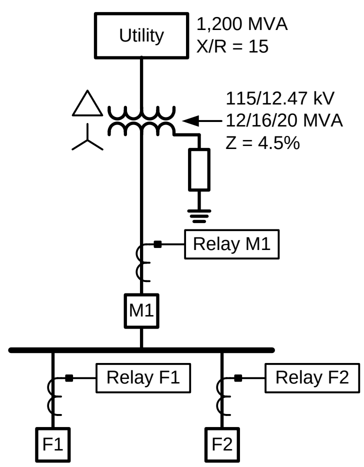
Exercise: Implementing Instantaneous Settings for a Maintenance Mode Scheme

Below is a one-line diagram of a substation with a main and two feeders. Because there is virtually no difference between the fault current for a fault on the bus side of a feeder and for a fault on the load side, there is no opportunity to set an instantaneous trip setting on the main breaker and maintain selectivity. Selectivity requires that the main breaker coordinate with the feeder breaker time-overcurrent elements. This results in all bus faults normally being cleared with a delayed element. When the feeders must coordinate with downline protective relays, the delay can be prolonged even more as time-overcurrent elements stack up. A bus fault would be expected to have the highest fault availability on this radial system, and significant exposure for personnel exists in this area. The situation can be improved with an instantaneous setting that is enabled as needed when personnel are in the hazard area. The added feature is easy to implement and can be done so with no added equipment costs. The tradeoff for this feature, however, is conceding proper coordination and possible overtripping for faults on a feeder when the maintenance mode is enabled. The same logic can be used on the main or feeder breakers.



In this exercise, you will use the example system shown above to determine the incident energy for arcing faults on the bus and for close-in faults on the feeders. This is the incident energy at Breakers F1 and F2 that a worker could be exposed to during an arc-flash event. For comparison, you will calculate the incident energy for both open-air and switchgear (box) configurations. You will also see how implementing an instantaneous setting during maintenance reduces the arc-flash incident energy by a factor of 8.3.

The calculations in this exercise are based on the IEEE 1584 empirical method. They meet the Occupational Safety and Health Administration (OSHA) calculation method recommendations for arcs in the open air or in an enclosure (switchgear) at 12.47 kV.

Refer to the relay settings below for the steps in this exercise.

Feeder Relays F1 and F2	**Main Relay M1**
CTR = 120	CTR = 200
51PIP = 5	51PIP = 5
51PIC = U3	51PIC = U3
51P1TD = 5	51PITD = 6

Step 1: Determine Bolted Three-Phase Fault Current at Bus

The first step in calculating the incident energy is determining the maximum available bolted three-phase fault current.

The available utility fault current for this example system is given as 1,200 MVA, and the X/R ratio is 15. Use the following formula to convert this information to the transformer impedance base:

$$Z_{source} = 100 \bullet \left(\frac{kV_u^{\ 2} \bullet MVA_t}{kV_t^{\ 2} \bullet MVA_u} \right) \angle \tan^{-1}\left(X/R\right) \tag{1}$$

where:

- Z_{source} = utility impedance in percent based on transformer base.
- kV_u = utility voltage base.
- kV_t = transformer voltage base.
- MVA_u = utility fault MVA.
- MVA_t = transformer MVA base.
- X/R = utility X/R ratio.

The resulting calculations for this example system are as follows:

$$Z_{source} = 100 \bullet \left[\frac{115^2 \bullet 12}{115^2 \bullet 1,200} \right] \tan^{-1} 15 \tag{2}$$

$$Z_{source} = 1.0 \underline{|86.2°} = 0.0663 + j0.9978 \tag{3}$$

Calculate the total impedance to the bus by adding the utility source impedance and transformer impedance together, as shown below:

$$Z_{total} = Z_{source} + Z_{XFMR} = 0.0663 + j0.9978 + j4.5 \tag{4}$$

$$Z_{total} = 0.0663 + j5.5 = 5.5 \underline{|89.3°} \text{ (in percent)} \tag{5}$$

Calculate the transformer base current, and then divide it by the total system impedance (Z_{total}) to get the bolted three-phase fault current, as follows:

$$I_{Base}(XFMR) = \frac{12,000,000}{\sqrt{3} \bullet 12,470} = 556 \text{ A} \tag{6}$$

$$I_{Fault} = \frac{556}{0.055} = 10.1 \text{ kA} \tag{7}$$

Step 2: Determine Arc-Fault Currents

The arc-fault current is typically lower than the bolted three-phase fault current due to the arc impedance. The following calculations are used to determine the arcing current:

$$\mathrm{LogI_a} = 0.00402 + 0.983 \bullet \mathrm{LogI_{bf}} \quad (8)$$

$$\mathrm{I_a} = 10^{\mathrm{LogI_a}} \quad (9)$$

where:

I_{bf} = maximum bus fault current in kA.

I_a = maximum arcing current in kA.

Use these equations with I_{bf} equal to 10.1 kA to calculate the arcing current (I_a) for this example system as follows:

$$\mathrm{LogI_a} = 0.00402 + 0.983 \bullet \mathrm{Log}10.1 = 0.9913 \quad (10)$$

$$\mathrm{I_a} = 10^{0.9913} = 9.80\ \mathrm{kA} \quad (11)$$

Step 3: Determine Main Relay M1 Operating Time for Bus or Close-In Feeder Faults

The IEEE U3 curve formula is as follows:

$$\mathrm{Tp} = \mathrm{TD} \bullet \left(0.0963 + \frac{3.88}{\mathrm{M}^2 - 1}\right) \quad (12)$$

where:

Tp = operating time in seconds.

TD = time-dial settings.

M = applied multiples of pickup current.

The U3 curve computations for the Relay M1 operating time are as follows:

$$\mathrm{M} = \frac{\text{Fault Current in Primary Amperes}}{\text{Relay Secondary in Per Unit} \bullet \text{CTR}} = \frac{9{,}800}{5 \bullet 200} = 9.8 \quad (13)$$

$$\mathrm{Tp}(\text{Relay M1}) = 6 \bullet \left(0.096 + \frac{3.88}{9.8^2 - 1}\right) = 0.821\ \text{seconds} \quad (14)$$

Add a breaker time of 0.083 seconds (5 cycles) to the relay operating time to get the total operating time as shown below:

$$\text{Relay M1} + \text{Breaker M1} = 0.821\ \text{seconds} + 0.083\ \text{seconds} = 0.904\ \text{seconds} \quad (15)$$

Step 4: Identify System Voltages and Working Distance

Based on IEEE 1584 Table 4, for arcs at 12.47 kV, the gap between conductors is 153 mm (0.5 ft) for switchgear or open-air configurations.

Based on IEEE 1584 Table 3, the working distance is 910 mm (3 ft).

Step 5: Determine Incident Energy

The empirically derived method presented in IEEE 1584 provides two equations to calculate the incident arc-flash energy. The first calculates the normalized incident energy. The second calculates the incident energy with specific parameters.

The normalized incident energy equation assumes a typical working distance of 610 mm (2 ft) and an arc duration of 0.2 seconds. The normalized incident energy equation for this example is as follows:

$$\mathrm{LogE_n} = \mathrm{K_1} + \mathrm{K_2} + 1.081 \bullet \mathrm{LogI_a} + 0.0011 \bullet \mathrm{G} \tag{16}$$

$$\mathrm{E_n} = 10^{\mathrm{LogE_n}} \tag{17}$$

where:

E_n = normalized incident energy in joules per square centimeter (J/cm^2).

K_1 = –0.555 for a switchgear configuration and –0.792 for an open-air configuration.

K_2 = 0.0 for a resistance-grounded system and –0.113 for a grounded system.

I_a = maximum arcing current in kA.

G = gap between conductors (153 mm [0.5 ft]).

Use this equation to calculate the normalized incident energy for open-air configurations in the example system as follows:

$$\mathrm{LogE_n} = -0.792 + -0.113 + 1.081 \bullet \mathrm{Log}9.80 + 0.0011 \bullet 153 \tag{18}$$

$$\mathrm{LogE_n} = 0.335 \tag{19}$$

$$\mathrm{E_n} = 10^{0.335} = 2.2\ \mathrm{J/cm^2} \tag{20}$$

Next, vary the parameters to calculate the incident energy for specific configurations for this example system. For 5 kV open-air configurations, use a working distance of 910 mm (3 ft), and then calculate the incident energy for the operating time of 0.904 seconds. IEEE 1584 provides the following equation for calculating incident energy with specific parameters:

$$\mathrm{E} = 4.184 \bullet \mathrm{C_f} \bullet \mathrm{E_n} \bullet \left(\frac{\mathrm{t}}{0.2}\right) \bullet \left(\frac{610^{\mathrm{x}}}{\mathrm{D^x}}\right) \tag{21}$$

where:

E = incident energy in J/cm^2.

E_n = normalized incident energy in J/cm^2.

C_f = 1.0 for voltages above 1.0 kV.

t = arcing time in seconds.

D = distance from the possible arc point (910 mm [3 ft]).

x = distance exponent (0.973 for 15 kV switchgear configurations and 2.000 for open-air configurations).

The resulting equation for this example system with an open-air configuration is as follows:

$$\mathrm{E} = 4.184 \bullet 1 \bullet 2.2 \bullet \left(\frac{0.904}{0.2}\right) \bullet \left(\frac{610^2}{910^2}\right) = 18.6\ \mathrm{J/cm^2} \tag{22}$$

Convert the arc energy into calories per square centimeter (cal/cm^2) using the following formula:

$$5.0\ \text{J/cm}^2 = 1.2\ \text{cal/cm}^2 \tag{23}$$

The result is as follows:

$$E = 18.6 \bullet \frac{1.2}{5} = 4.5\ \text{cal/cm}^2 \tag{24}$$

Now, calculate the incident energy if a switchgear configuration is used, and compare it with the open-air configuration results.

The calculations for incident energy normalized for switchgear are as follows:

$$\text{LogE}_n = -0.555 + -0.113 + 1.081 \bullet \text{Log}9.80 + 0.0011 \bullet 153 = 0.572 \tag{25}$$

$$E_n = 10^{0.572} = 3.73\ \text{J/cm}^2 \tag{26}$$

Vary the parameters to calculate the incident energy for the switchgear configuration example, as shown below:

$$E = 4.184 \bullet 1 \bullet 3.73 \bullet \left(\frac{0.904}{0.2}\right) \bullet \left(\frac{610^{0.973}}{910^{0.973}}\right) = 47.6\ \text{J/cm}^2 \tag{27}$$

$$E = 47.6 \bullet \frac{1.2}{5} = 11.4\ \text{cal/cm}^2 \tag{28}$$

Looking at these results, notice that for the same fault current and operating times, the incident energy is much larger for switchgear applications (11.4 cal/cm^2) than open-air applications (4.5 cal/cm^2). It is good practice to check the incident energy at a lower fault current level (80 to 85 percent) to see if the combination of lower fault current and longer trip times increases the incident energy. In this example, the incident energy is highest at the calculated fault current of 10.1 kA.

Step 6: Implement Instantaneous Settings for a Maintenance Mode in Relay M1

Arc-flash energy is proportional to V • I • t. Notice from the incident energy equation for specific parameters (repeated below) that reducing time (t) reduces the arc-flash energy by the same proportion.

$$E = 4.184 \bullet C_f \bullet E_n \bullet \left(\frac{t}{0.2}\right) \bullet \left(\frac{610^x}{D^x}\right) \tag{29}$$

Also notice from this equation that by reducing the arcing time (t), incident energy is reduced by that same proportion. To reduce the arcing time, you need to implement a faster tripping time in the relay.

Implementing faster tripping time in Relay M1 reduces the incident energy when work is done on Breakers F1 or F2.

The pickup time of the overcurrent element in a modern relay is not instantaneous. The pickup can be delayed by filtering inside the relay and by the time it takes for the output contact of the relay to close. This time is typically 0.025 seconds (1.5 cycles).

The relay operating time using the U3 curve was previously calculated to be 0.821 seconds with a breaker time of 0.083 seconds.

The instantaneous time is 0.025 seconds, for a total operating time of 0.025 seconds + 0.083 seconds = 0.108 seconds.

The energy reduction based on the new operating time of 0.108 seconds is as follows:

$$\frac{0.821+0.083}{0.025+0.083}=\frac{0.904}{0.108}=8.37 \tag{30}$$

The result is 8.37 times less energy when using maintenance mode than when not using it.

Now, using the incident energy equation for switchgear, the energy reduction result should also be 8.37. Calculate the new incident energy with a relay instantaneous time of 0.025 seconds, as shown below:

$$E_{new} = 4.184 \bullet 1 \bullet 3.73 \bullet \left(\frac{0.108}{0.2}\right) \bullet \left(\frac{610^{0.973}}{910^{0.973}}\right) = 5.73 \text{ J/cm}^2 \tag{31}$$

$$E_{new} = 5.73 \bullet \frac{1.2}{5} = 1.37 \text{ cal/cm}^2 \tag{32}$$

Compare this maintenance mode incident energy result with the previous calculation that used the U3 curve of 11.4 cal/cm^2:

$$\frac{11.4}{1.37}=8.32 \tag{33}$$

The result is 8.32 times less energy when using maintenance mode with an instantaneous setting, which is essentially the same as the previous 8.37 reduction in energy. This is a major reduction in incident energy. The method of using instantaneous settings for a maintenance mode is also inexpensive to implement, making it an economical solution to reduce arc-flash incident energy. Table 1 shows the incident energy change when using maintenance mode.

Table 1 Incident Energy for Example System

Relay M1 Settings With Breaker M1 Time	Open Air (cal/cm^2)	Switchgear (cal/cm^2)
0.9-second delay	4.5	11.4
0.108-second delay (maintenance mode)	0.54	1.37

Step 7: Consider Conditions When Selecting Instantaneous Current Pickup

Take care when implementing the maintenance mode scheme to understand how it works and the type of load and system that it will be applied on. If there are transient conditions (such as motor starting or inrush) that cause the current seen by the relay to go above the pickup setting, the scheme would need to be modified to accommodate those conditions to avoid nuisance operations that can be extremely disruptive and costly.

Step 8: Control Maintenance Mode—Turning It On and Off

Enabling and disabling the maintenance mode can be accomplished in several ways. For distribution feeders, the hot-line tag function (if set up for arc-flash detection) can be turned on and off from the front panel of the relay. For many arc-flash applications, the relay can be located in the hazard area where personnel have to adhere to more restrictive personal protective equipment (PPE) requirements when enabling or disabling the maintenance mode. Having local control only over the maintenance mode can result in a higher probability of human error, leading to failing to enable the mode when needed or leaving it in the mode when not needed. When supervisory control and data acquisition (SCADA) and/or communications are available to the relay via metallic, fiber, or wireless media, the maintenance mode can be remotely applied and monitored. Absent the communications, the digital I/O in the relay can be used to set up automatic enabling based on a door alarm or remote switch so that personnel do not have to be in the hazard area to change modes. An output contact from the relay can be used to give a clear indication of the mode from a distance via a lamp or beacon.