THE USE OF COOLING-FACTOR CURVES FOR COORDINATING FUSES AND RECLOSERS

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Abstract—This paper describes how to precisely coordinate distribution feeder automatic-circuit reclosers using cooling-factor data that account for the heating and cooling of source-side or load-side fuses throughout the recloser's operating sequence. This method yields results that are more accurate than other coordination methods commonly used. Different coordination methods are discussed in this paper and the results are compared.

Keywords—Cooling factors, cooling factor curves, recloser-fuse coordination, fuse-recloser coordination

Contents

Introduction

The application of reclosers on distribution systems will require they be coordinated with both source-side and load-side fuses. In both cases, the fault current through the fuse will be interrupted by the recloser and then restored as the recloser progresses through its operating sequence.

Initially, the temperature of the fusible element is determined by the pre-fault load current and by the ambient temperature. When a fault occurs, the temperature of the fusible element increases toward its melting value. If the recloser opens before the fusible element reaches its melting value, the fuse will cool during the reclosing-time interval (contacts open). This current cycling will continue until the fault is cleared prior to the next reclosing operation (i.e., temporary fault), the fuse melts and clears the fault, or the recloser operates to lockout. **Figure 1** illustrates the heating and cooling of the fuse.

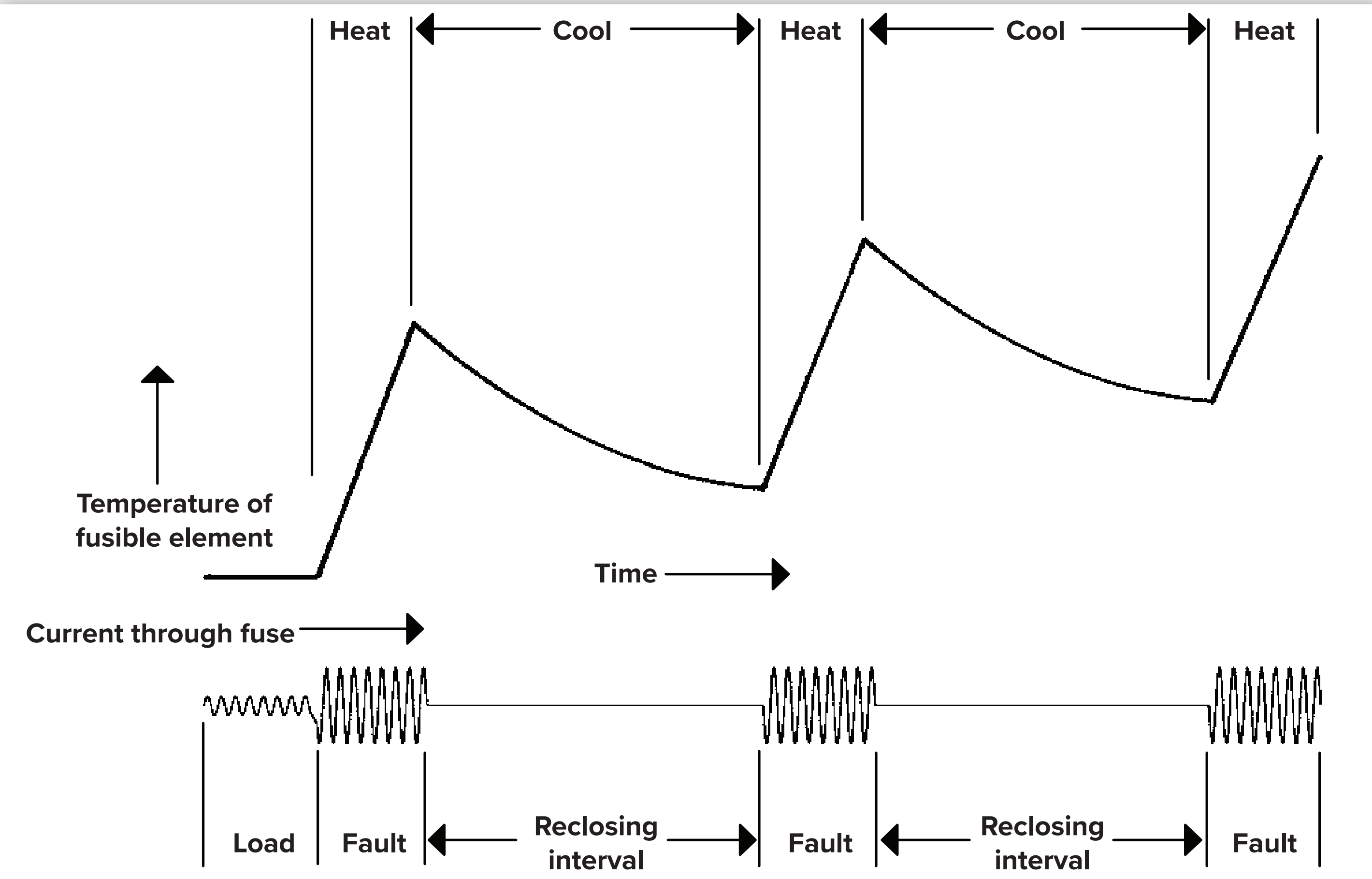

FIGURE 1. Heating and cooling of a fuse in series with a recloser during the recloser's operating sequence.

Clearly, when coordinating reclosers and fuses, the repeated heating and cooling of the fuse must be considered. To this end, adjustment factors are applied, not to the TCC curves of the fuse, but to the TCC curves of the recloser, to generate "equivalent" recloser curves as seen by the fuse.

Two different techniques are often used to create equivalent recloser curves, each providing differing levels of accuracy.

One method, called the Conservative Method, ignores fuse cooling entirely and considers only the heating of the fuse. Results of this method are, as the name suggests, conservative. The Cooling Factor Method precisely adjusts the recloser curves by reflecting both the heating *and* the specific cooling characteristics of the fuse as a function of the duration of each reclosing-time interval. Both methods are described in this paper, and the results are compared.

A third method, called the K-Factor Method, uses predetermined scaling factors for certain common recloser sequences and fuse speeds. It yields results somewhere between the Conservative Method and the Cooling Factor Method. It is not covered in this paper.

The coordination methods discussed in this paper are also applicable when coordinating fuses with circuit breakers equipped with reclosing relays.

As shown by **Figure 2**, cooling factors for fuses can vary substantially. For example, after a reclosing-time interval of 2 seconds has elapsed, the "slow" speed fuse link (20T) has lost 13% of its heat input as compared to a "very fast" speed fuse link (40N), which has lost 92% of its heat input. A "medium" speed fuse link (40 Std.) has lost 54% of its heat input after 2 seconds.

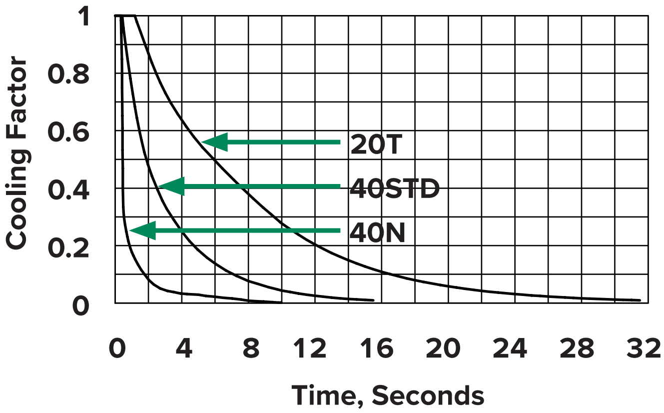

FIGURE 2. Typical cooling factors versus time for several fuse links manufactured by the authors' company.

Source-Side Fuse/ Load-Side Recloser

When a fuse is located on the source side of a recloser, the fuse must not melt before the recloser operates to lockout. The *maximum* current value up to which the fuse and a recloser will coordinate is determined by the lower of either:

- The maximum interrupting rating of the recloser or the fuse
- The intersection of the minimum melting curve of the fuse and maximum equivalent operating curve of the recloser (i.e., the lockout curve)

Conservative Method

The most conservative approach would be to ignore the cooling of the fuse during the reclosing-time interval and simply sum the heating effect of each Reclose operation. That is, you would create an equivalent recloser lockout curve by adding the proper number of fast and delayed operations.

This method will ensure coordination, but it may force the selection of a larger source-side fuse than is necessary. A larger fuse, in turn, will provide a reduced level of equipment protection (e.g., for a substation power transformer), and it may experience coordination problems with protective devices located even further upstream of the fuse.

Maximum equivalent curves for the recloser are obtained by use of the following equation:

$$T_l = \frac{\sum_{j=1}^{n} T_{Rj}}{1 - P} \tag{1}$$

Where:

T_l = The point on the maximum equivalent lockout curve of the recloser at selected current (I)

P = The reduction in melting time of the fuse caused by preloading, expressed as a decimal part of its total melting time

T_{Rj} = The maximum clearing time at current (I) for the j[th] operation (contacts closed) of the recloser

n = The number of operations (contacts closed) of the recloser

Cooling-Factor Method

To obtain precise coordination between a source-side fuse and a load-side recloser, it is necessary to compensate for heat stored in the fuse when the recloser contacts are closed and heat lost when the contacts are open. At a selected current value, the heat stored in the fuse (preheating), during the time the recloser contacts are closed, is directly proportional to the recloser's clearing time.

Therefore an adjustment can be made to the recloser's fast (A) and slow (B, C, etc.) curves by the application of a factor "C" to the clearing times. These cooling factors (C), for a specific reclosing-time interval, or cooling time, reflect the heat remaining in the fuse after preheating and cooling in percent of preheating. See **Figure 3** and **Figure 4 on page 5**.

Maximum equivalent lockout curves for the recloser, for various operating sequences, are obtained by use of the following equations:

One operation of the recloser

$$T_l = \frac{T_{R1}}{(1-P)} \tag{2}$$

Two operations of the recloser

$$T_l = \frac{T_{R1}C_1 + T_{R2}}{(1-PC_1)} \tag{3}$$

Three operations of the recloser

$$T_l = \frac{T_{R1}C_1C_2 + T_{R2}C_2 + T_{R3}}{(1-PC_1C_2)} \tag{4}$$

When the reclosing times are the same, this simplifies to:

$$T_l = \frac{T_{R1}C^2 + T_{R2}C + T_{R3}}{(1-PC^2)} \tag{4a}$$

Four operations of the recloser

$$T_l = \frac{T_{R1}C_1C_2C_3 + T_{R2}C_2C_3 + T_{R3}C_3 + T_{R4}}{(1-PC_1C_2C_3)} \tag{5}$$

When the reclosing times are the same, this simplifies to:

$$T_l = \frac{T_{R1}C^3 + T_{R2}C^2 + T_{R3}C + T_{R4}}{(1-PC^3)} \tag{5a}$$

Where:

T_l = The point on the maximum equivalent lockout curve of the recloser, at selected current (*I*)

P = The reduction in melting time of the fuse caused by preloading, expressed as a decimal part of its total melting time

T_{Rj} = The maximum clearing time at current (*I*) for the j^{th} operation (contacts closed) of the recloser

C_k = The cooling factors from **Figure 3** or **Figure 4 on page 5** for the k^{th} reclosing-time interval (contacts open) of the recloser

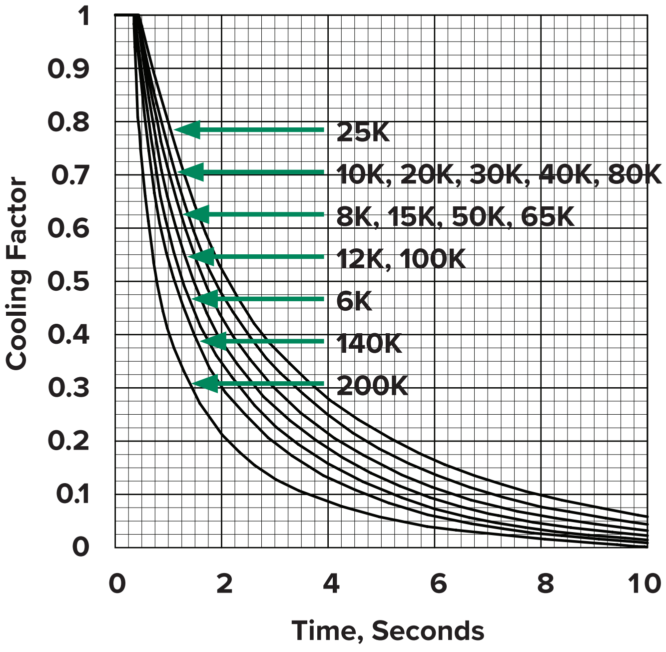

FIGURE 3. Cooling factor vs. time for K-speed fuse links manufactured by the authors' company.

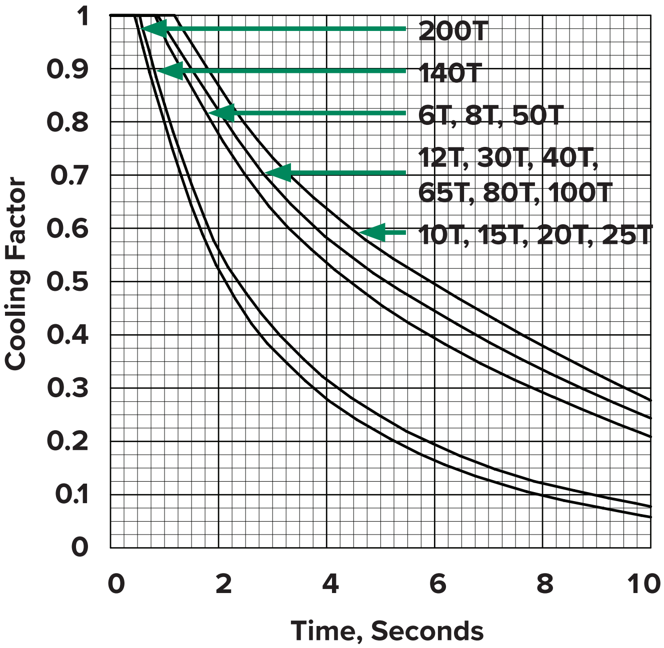

FIGURE 4. Cooling factor vs. time for T-speed fuse links manufactured by the authors' company.

Example

Determine whether a Type 4H oil-circuit recloser, with a 25A trip coil, will coordinate with a source-side 65K fuse link. The recloser is set for two fast (A) and two slow (B) operations (i.e., 2A/2B), with a fixed 1.5-second reclosing-time interval between each operation.

As noted before, the fuse must not melt before the recloser operates to lockout. The available fault current is 600 amperes. It is assumed the fuse is preloaded to 70% of its ampere rating.

Conservative Method

Because the fuse must allow the recloser to operate to lockout without melting, the recloser's maximum equivalent lockout curve is calculated by adding up the individual operating times of the two fast (A) curves and two slow (B) curves at the specified fault-current level. Note recloser fast (A) curves, as published, are expressed as maximum clearing times. Published slow (B) curves are expressed as average clearing times and must be adjusted by a 10% positive tolerance. See **Figure 5**.

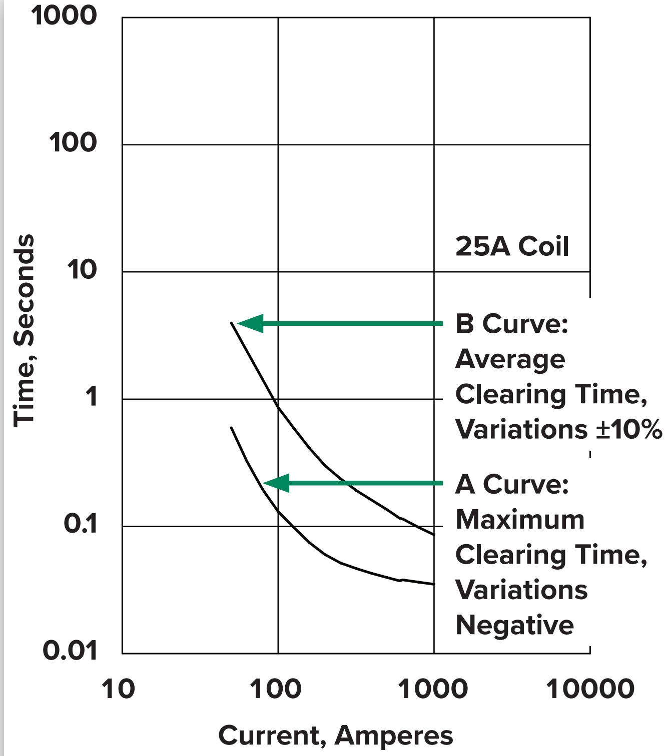

FIGURE 5. "A" (fast) and "B" (slow) TCC curves for a Type 4H recloser with a 25-ampere trip coil.

The recloser's maximum equivalent lockout curve can then be calculated by using **Equation 1 on page 3**:

$$T_l = \frac{2T_A + 2(1.1T_B)}{1-P}$$

Where T_A and T_B are points from the published recloser A and B curves respectively at the selected current *I*. At 600 amperes: T_A = 0.0373 seconds, and T_B = 0.116 seconds (both from **Figure 5**). For 70% preload: P = 0.10 (see **Figure 6 on page 6**).

$$T_l = \frac{2 \cdot 0.0373 + 2(1.1 \cdot 0.116)}{1-0.10} = 0.366\text{s}$$

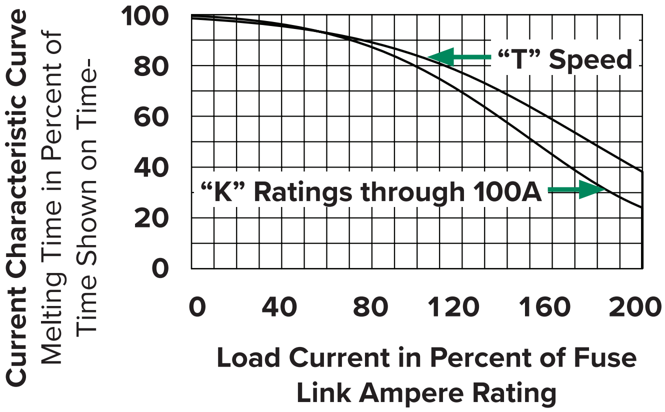

FIGURE 6. Fuse link preloading adjustment factors.

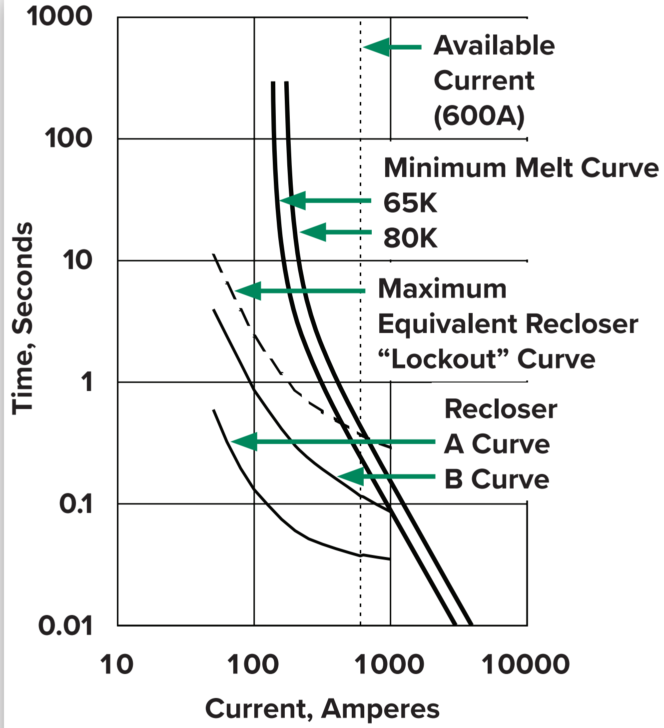

FIGURE 7. Source-side fuse/load-side recloser coordination using the Conservative Method.

Clearly, the fuse link must take longer than 0.366s to melt at 600 amperes to achieve coordination. A 65K fuse link melts in 0.257 seconds, so full coordination is **not** achieved. An 80K fuse link, which takes 0.439 seconds to melt at 600 amperes, would be required for coordination. See **Figure 7**.

Cooling-Factor Method

As in the previous example, the fuse must allow the recloser to operate to lock out, and the reclosing-time interval is fixed at 1.5 seconds. The maximum equivalent lockout curve of the recloser is calculated using **Equation 5a on page 4**:

$$T_l = \frac{T_A C^3 + T_A C^2 + 1.1 T_B C + 1.1 T_B}{(1 - PC^3)}$$

Where T_A and T_B are points from the published recloser A and B curves respectively at the selected current *I*. At 600 amperes: T_A = 0.0373 seconds and T_B = 0.116 seconds (both from **Figure 5 on page 5**). For 70% preload: P = 0.10 (see **Figure 6**). For a 1.5-second reclosing-time interval: C = 0.55 for a 65K fuse link (from **Figure 3 on page 4**).

$$T_l = \frac{0.0373 \cdot 0.55^3 + 0.0373 \cdot 0.55^2 + 1.1 \cdot 0.116 \cdot 0.55 + 1.1 \cdot 0.116}{(1 - 0.10 \cdot 0.55^3)} = 0.219\text{s}$$

A 65K fuse link melts in 0.257 seconds, so full coordination is achieved. See **Figure 8**.

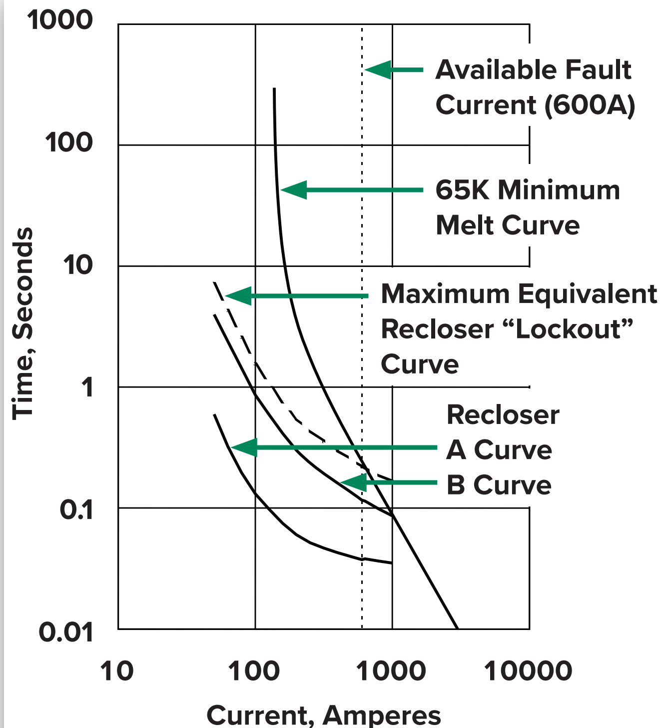

FIGURE 8. Source-side fuse/load-side recloser coordination using the Cooling Factor Method.

Comments

The above example illustrates including the cooling of the fuse link during the reclosing-time intervals allows for the selection of a smaller source-side fuse.

Source-Side Recloser/ Load-Side Fuse

When a fuse is located on the load-side of a recloser, the fuse should **not** melt while the recloser operates through its fast operations, but it **must** operate during the delayed operations to avoid recloser lockout. This is commonly referred to as a "fuse saving" scheme.

The maximum current value up to which a fuse and recloser will coordinate is determined by the lower of either:

1. The maximum interrupting rating of the recloser or the fuse
2. The intersection of the minimum-melting curve of the fuse with the maximum equivalent curve for just the fast operations of the recloser (**Note:** This is not the lockout curve.)

The equations given in the "Source-Side Fuse/Load-Side Recloser" section are used to calculate the maximum coordination current, but for the source-side recloser/load-side fuse and case, only the fast operations of the recloser are considered.

The *minimum* current value down to which the fuse and the recloser will coordinate is determined by the intersection of the total-clearing curve of the fuse and the minimum equivalent lockout curve of the recloser. Note that the final operation includes only relay time when the reclosing device is a relay-actuated circuit breaker.

Conservative Method

To determine the maximum coordination current, use **Equation 1 on page 3**, including only the recloser fast operations in the calculation. For the minimum coordination current, consider the intersection of the total-clearing curve of the fuse with the minimum equivalent lockout curve for the recloser, obtained by use of the following equation:

$$T_l = T_R \tag{6}$$

Where:

T_l = The point on the minimum equivalent lockout curve of the recloser, at selected current (I)

T_R = The minimum clearing time at current (I) for the delayed operation (contacts closed) of the recloser

Cooling-Factor Method

To determine the maximum coordination current, use **Equations 2 through 5a on page 4**, including only the recloser fast operations in the calculation. For the minimum coordination current, consider the intersection of the total-clearing curve of the fuse with the minimum equivalent lockout curve for the recloser, obtained by use of the following equations:

One operation of the recloser

$$T_l = \frac{T_{R1}}{(1 - P)} \tag{7}$$

Two operations of the recloser

$$T_l = \frac{T_{R1}C_1 + T_{R2}}{(1 - PC_1)} \tag{8}$$

Three operations of the recloser

$$T_l = \frac{T_{R1}C_1C_2 + T_{R2}C_2 + T_{R3}}{(1 - PC_1C_2)} \tag{9}$$

When reclosing times are the same, this simplifies to:

$$T_l = \frac{T_{R1}C^2 + T_{R2}C + T_{R3}}{(1 - PC^2)} \tag{9a}$$

Four operations of the recloser

$$T_l = \frac{T_{R1}C_1C_2C_3 + T_{R2}C_2C_3 + T_{R3}C_3 + T_{R4}}{(1 - PC_1C_2C_3)} \quad (10)$$

When reclosing times are the same, this simplifies to:

$$T_l = \frac{T_{R1}C^3 + T_{R2}C^2 + T_{R3}C + T_{R4}}{(1 - PC^3)} \quad (10a)$$

Where:

T_l = The point on the minimum equivalent lockout curve of the recloser, at selected current (I)

P = The reduction in the melting time of fuse caused by preloading, expressed as a decimal part of its total melting time

T_{Rj} = The minimum clearing time at current (I) for j[th] operation (contacts closed) of the recloser

C_k = The cooling factors from **Figure 3 on page 4** or **Figure 4 on page 5** for the k[th] reclosing-time interval (contacts open) of the recloser

Example

Determine the coordination range for a Type R Recloser with a 100A trip coil with a load-side 65T fuse link. The recloser is set for two fast (A) and two slow (C) operations (i.e., 2A/2C), with a fixed 2-second reclosing-time interval between each operation.

The fuse must not melt during the recloser fast operations, but the fuse must melt and clear the fault before the recloser operates to lockout. It is assumed the fuse is preloaded to 70% of its ampere rating.

Conservative Method

Because the fuse must withstand the two recloser fast operations without melting, the maximum equivalent recloser fast curve is calculated by summing the two fast (A) curves. As noted previously, published A curves are expressed as maximum clearing times.

The maximum equivalent recloser curve for the two fast operations can be calculated by using **Equation 1 on page 3**:

$$T_f = \frac{2T_A}{1 - P}$$

Where T_A is the point from the published recloser fast (A) curve for the selected current I. For 70% preload: P = 0.09 (from **Figure 6 on page 6**).

$$T_f = \frac{2T_A}{1 - 0.09}$$

This equation is applied at several current levels. The intersection of the maximum equivalent recloser curve for the two fast operations with the minimum-melting curve of the fuse is the maximum coordination current. As shown in **Figure 9**, the maximum coordination current is 1700A.

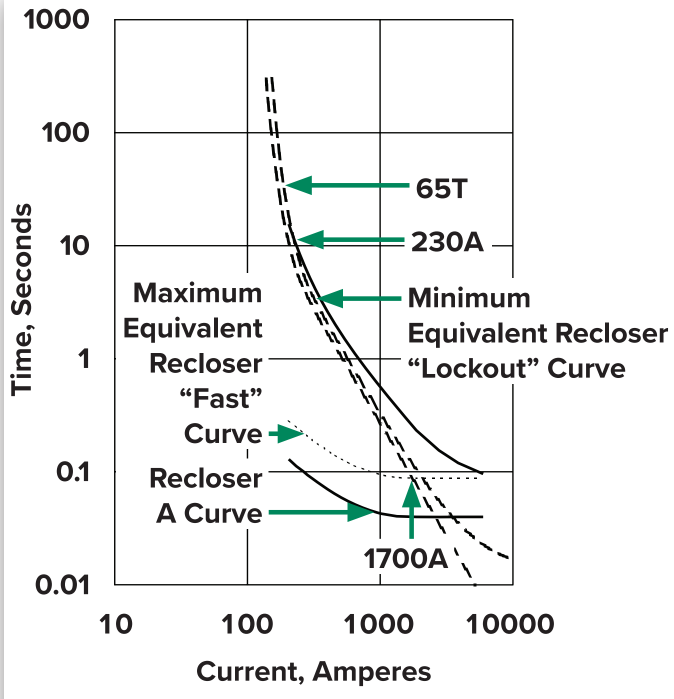

FIGURE 9. Source-side recloser/load-side fuse coordination using the Conservative Method.

The fuse must operate to clear the fault after the recloser's fast operations but before the recloser operates to all the way lockout. The minimum equivalent recloser lockout curve can be calculated by using **Equation 6 on page 7**:

$$T_l = 0.9T_C$$

Where T_C is the point from the published recloser C curve at the selected current *I*. The 0.9 factor represents the negative tolerance from the published average curve.

The intersection of the minimum equivalent recloser lockout curve with the total clearing curve of the fuse is the minimum coordination current. From **Figure 9 on page 8**, the minimum coordination current is 230A.

Cooling-Factor Method

As before, the fuse should withstand the two recloser fast operations without melting, with the reclosing-time interval fixed at 2 seconds. The maximum equivalent recloser fast curve is calculated using **Equation 3 on page 4**:

$$T_f = \frac{T_A C + T_A}{(1 - PC)}$$

Where T_A is the point from the published recloser A curve at the selected current *I*. For 70% preload: *P* = 0.09 (from **Figure 6 on page 6**). For a 2.0-second reclosing-time interval: *C* = 0.82 for a 65T fuse link (from **Figure 4 on page 5**).

$$T_f = \frac{T_A \cdot 0.82 + T_A}{(1 - 0.09 \cdot 0.82)}$$

This equation is applied at several current levels. The intersection of the maximum equivalent recloser fast curve with the minimum-melting curve of the fuse is the maximum coordination current. As shown in **Figure 10**, the maximum coordination current is 2015A.

The fuse must clear after the recloser fast operations but before the recloser operates to lockout. The minimum equivalent recloser lockout curve can then be calculated by using **Equation 10a on page 8**:

$$T_l = \frac{0.8T_A C^3 + 0.8T_A C^2 + 0.9T_C C + 0.9T_C}{(1 - PC^3)}$$

Where T_A and T_C are the points from the published recloser A and C curves respectively at the selected current *I*. For 70% preload: *P* = 0.09 (From **Figure 6 on page 6**). For a 2.0-second reclosing-time interval: *C* = 0.82 for a 65 T fuse link (see **Figure 4 on page 5**).

$$T_l = \frac{0.8 \cdot T_A \cdot 0.82^3 + 0.8 \cdot T_A \cdot 0.82^2 + 0.9 \cdot T_C \cdot 0.82 + 0.9 \cdot T_C}{(1 - 0.09 \cdot 0.82^3)}$$

The intersection of the minimum equivalent recloser lockout curve with the total-clearing curve of the fuse is the minimum coordination current. From **Figure 10**, the fuse and the recloser coordinate for all currents less than 2015A because the minimum recloser lockout curve and the fuse total-clearing curve do **not** intersect.

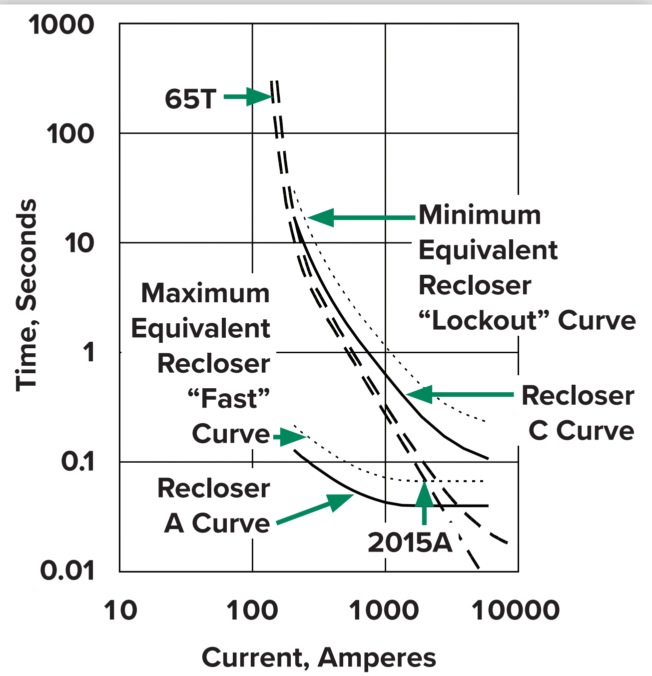

FIGURE 10. Source-side recloser/load-side fuse coordination using the Cooling Factor Method.

Comments

In this example, each method resulted in a different coordination range. See **Table 1**. The Conservative Method resulted in a substantially smaller coordination range than the Cooling Factor Method. In this example, if the available fault current is 2000A, the only method indicating complete coordination exists between the source-side recloser and the load-side fuse link is the Cooling Factor Method.

Method	Coordination Range	
	Minimum Current (A)	Maximum Current (A)
Conservative	230	1700
Cooling Factor	—	2015

TABLE 1. Load-Side Fuse/Source-Side Recloser Coordination Example

Conclusions

When coordinating reclosers and fuses, the repeated heating and cooling of the fuse should be considered. This paper has shown the proper use of specific cooling factors, to account for the thermal response of the fuse during multiple reclosing operations, results in more precise coordination of reclosers and fuses and the selection of smaller fuse ampere ratings for better equipment protection.

Bibliography

Time-current characteristic curves, preload- and ambient-temperature adjustment curves, and cooling-factor curves for fuses and fuse links manufactured by the authors' company are available for downloading from the company's website, sandc.com. Time-current characteristic curves for reclosers can be obtained from the recloser manufacturer.

Also available on the author's company's website is a protective device coordination program, Coordinaide™—The S&C Protection & Coordination Assistant, that can be used to evaluate specific source-side fuse/load-side recloser and source-side recloser/load-side fuse coordination problems.

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