How to Coordinate Transformer Primary-Side Fuses with Feeder Reclosers Using Coordinaide^{TM} — The S&C Protection and Coordination Assistant — Part I: Conservative Method

This is the first in a series of articles explaining how to coordinate transformer primary-side fuses with a secondary-side automatic circuit recloser, such as in a utility substation. In this installment we'll use the "conservative" coordination method, which ignores the effects of fuse cooling during the reclosing time intervals (contacts open) of the recloser. Next month we'll repeat the exercise using the more precise "Cooling Factor" coordination method. Future articles will address source-side recloser/load-side fuse applications.

Source-Side Fuse/Load-Side Recloser Coordination

Automatic circuit reclosers sense overcurrents, interrupt them, and then automatically reclose to reenergize the feeder. Most faults on overhead distribution systems—perhaps as many as 75 to 80%—are temporary in nature, lasting only a few cycles to a few seconds. With their "trip and reclose" capability, reclosers eliminate prolonged outages on distribution systems due to such temporary faults. If a fault is permanent rather than temporary, however, the recloser will "lock out" after a preset number of reclosing attempts (usually three or four), thus isolating the faulted feeder from the system.

Automatic circuit reclosers have dual timing capabilities, which help maintain coordination with other protective devices and limit the areas affected by permanent faults. Typically the first—sometimes the first two—fault-clearing operations are performed per the "fast" timing characteristic, clearing *temporary* faults before load-side protective devices operate. Subsequent operations incorporate a predetermined time delay which allows protective devices nearer the fault to interrupt *permanent* faults, thereby limiting the extent of the service interruption. This arrangement is often referred to as a "fuse saving" scheme, since fuses only respond to permanent faults within their zones of protection.

For the application covered in this article, the transformer primary-side fuse is located upstream of the automatic circuit recloser. The goal is that the fuse *not* melt before the recloser operates to lockout in response to a permanent fault. The maximum fault current value up to which the fuse and the recloser will coordinate is generally the lower of:

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

In the conservative coordination method, cooling of the fuse during reclosing time intervals (contacts open) is ignored. You simply sum the heating effect, or heat input, of each recloser operation. That is, the lockout curve of the recloser is developed by summing the total clearing times for the proper number of fast and slow operations, at various current levels, per the following equation:.

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

Where:

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

P = Reduction in the melting time of the fuse due to preloading, expressed as a decimal part of its total melting time.

T_{Rj} = *Maximum* clearing time at current (*I*) for the jth operation (contacts closed) of the recloser.

n = Number of operations (contacts closed) of the recloser.

Since the fuse must allow the recloser to operate to lockout without melting, the recloser's *maximum* equivalent lockout curve should be developed. Recloser fast curves (A) are typically published to maximum test points. But slow curves (B, C, and D) are published to nominal test points and must be adjusted (maximized) by the amount of the positive tolerance, which is assumed to be 10%.

Example

Consider a rural electric power substation having a single transformer, protected by fuses, with three or fewer feeder reclosers. Ratings for the primary-side fuse, the transformer, and the load-side reclosers are as follows:

Transformer: The transformer has a base (OA) rating of 7500 kVA three-phase, 115 kV primary, 13.2 kV secondary. It has a forced-air (FA) rating of 9375 kVA (125%). The transformer impedance is 7.5%, and the maximum three-phase secondary fault current is 478 amperes (2000 MVA), as seen on the primary side of the transformer. The transformer is connected delta grounded-wye.

Fuse: The primary-side fuse is a 65E-ampere Standard Speed S&C SMD-2B Power Fuse rated 115 kV. The full-load current of the transformer, based on its force-air rating is 47 amperes. At this level of transformer loading, the fuse will be loaded to 72% of rating (47 amperes ÷ 65 amperes = 0.72). The preload adjustment factor, as determined from S&C Data Bulletin 210-195, is 0.88.

Feeder Recloser: The load-side recloser is a hydraulically-controlled Cooper Type W Recloser, rated 14.4 kV, 560 amperes continuous. The phase-trip pickup current is 280 amperes (140-ampere coil), and the operating sequence is one fast (A) and three slow (C) operations. The reclosing time interval between the fast operation and the first delayed operation is 0.5 second (instantaneous). Between the delayed operations, the reclosing time interval is 5 seconds.

Completing the Exercise Using Coordinaide

To complete the coordination exercise, launch **Coordinaide** by clicking the appropriate link on the page of S&C's website you're visiting . . . A **Coordinaide** link is featured on the home page. Additional links are found under the drop-down menu labeled "Support" and also on applicable product pages; e.g., S&C Type SMD Power Fuses. These tab-style links are on the left-hand side of the page, immediately below the "For More Information" label and above the "TCCs for [product]" tab.

After clicking on one of the links, you'll be directed to **Coordinaide's** opening page. It provides a brief description of the applications **Coordinaide** is designed to handle. When you launch the program, you'll be directed to a second page containing a brief "Conditions of Use" disclaimer, followed by a short note detailing minimum web browser requirements and a link to a "Users Guide." One final click launches the program and takes you to the "General Information" page. Please follow these directions to select the primary-side fuse, the transformer, and the load-side recloser.

Step 1 — Enter General Information

- Project Name: *Fuse-Recloser Coordination Exercise*
- Date: [provided by Coordinaide]
- By: *Optional*

Step 2 — Enter System Information and Select Devices

- Three-Phase Voltage, kV: *115*
- Available Fault Current, Amperes RMS Symmetrical: *10000*
- Device #1 — *Power Fuse*
- Device #2 — *Transformer (Damage Curve)*
- Device #3 — *Recloser*

Click "Continue" after entering system information and selecting the devices. You'll be directed to the first "device" page.

Step #3 — Select and Enter Device Parameters

Device #1 — Transformer-Primary Fuse (Select Parameters)

- Manufacturer: *S&C*
- Type: *SMD-2B*
- Speed: *Standard*
- Voltage Range, kV: *115-138*
- Ampere Rating: *65E*

Click "Continue" after selecting the parameters for Device #1. The time-current characteristic curve for Device #1 will be displayed.

Device #2 — Transformer (Select Parameters)

- Three-Phase Primary Voltage, kV: *115* [Provided by Coordinaide]
- Three-Phase Secondary Voltage, kV: *13.2*
- Three-Phase Rating, kVA: *7500*
- Impedance, %: *7.5*
- Fault Current, Amperes RMS Symmetrical: *10000* [Provided by Coordinaide]
- Display Magnetizing Inrush Points? ○ Yes ● No (default)
- Connection: *Delta Grounded-Wye*

Click "Continue" after selecting the parameters for Device #2. The time-current characteristic curve for Device #2 will be displayed.

Device #3 — Feeder Recloser (Select Parameters)

- Coordinates With: ● Source-Side Device ○ Load-Side Device **See Note 1**
- Coordination Method: ○ Cooling Factor ● Conservative (default) **See Note 2**
- Manufacturer: *Cooper (McGraw): Hydraulic*
- Type: *W*
- kV Range, kV: *14.4* [Provided by Coordinaide]
- Phase-Trip Operating Sequence: *1 Fast / 3 Slow*
- Fast Curve: *"A"*
- Slow Curve: *"C"*
- Coil Rating, Amperes: *140*
- Ground-Trip Operating Sequence: *Skip for this example*

Note 1: Since the recloser is on the load side of the primary-side fuse, select "Coordinates with Source-Side Device (default in this example)."
Note 2: Select "Conservative Method" to disregard the effects of cooling of the primary-side fuse during reclosing time intervals (contacts open) of the recloser. You are encouraged to repeat this example using the more precise cooling-factor method, and then compare the results.

Click "Continue" after selecting the parameters for Device #3. The time-current characteristic curve for Device #3 will be displayed.

Step #4 — Go to "Results" Page

Click on the tab at the top labeled "Results." You'll be directed to a log-log grid with TCC curves of the devices you've selected.
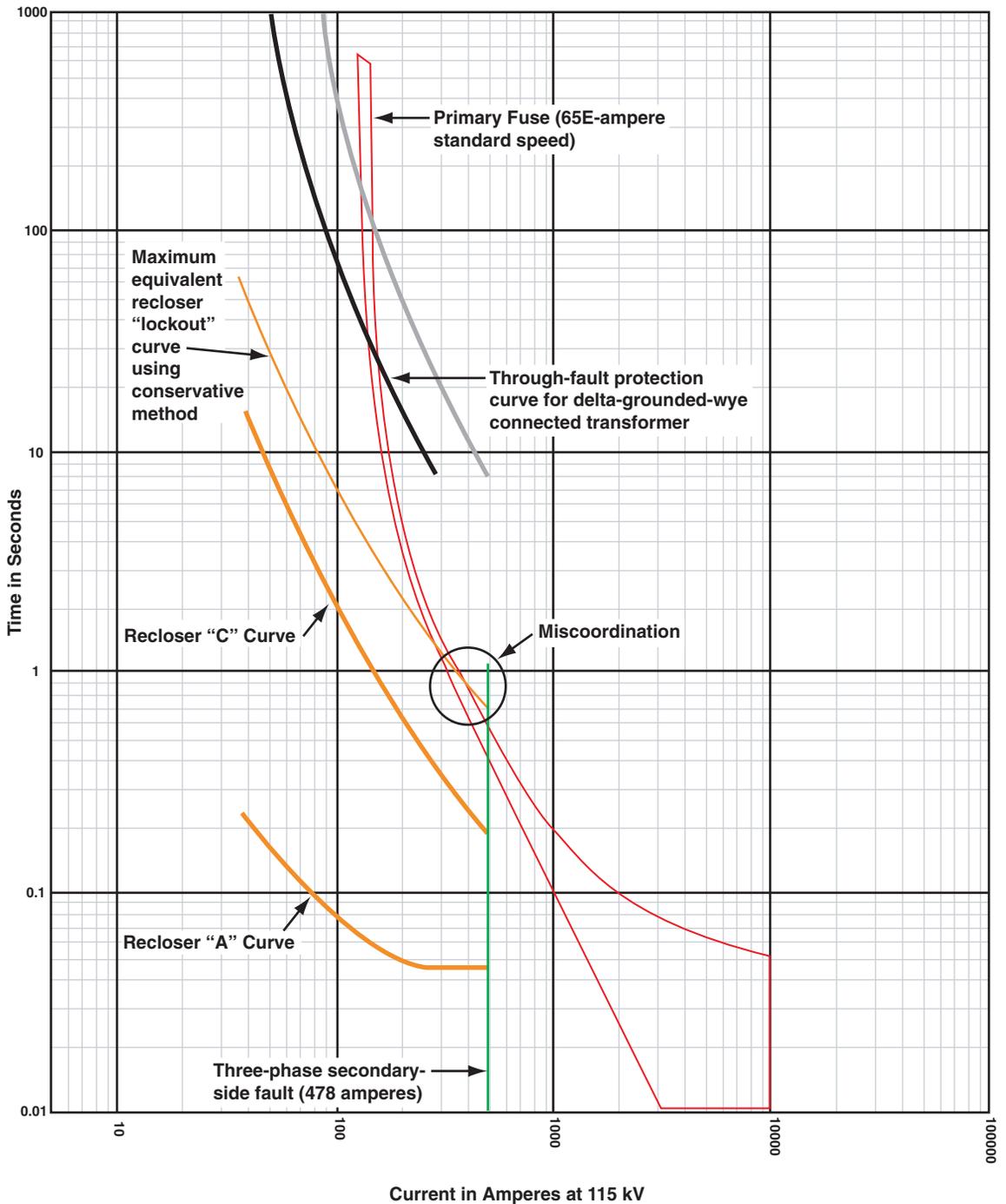
If desired, you can change the current scale of the grid from the default, 5 to 100,000 amperes, to 0.5 to 10,000 amperes. You can also eliminate the hash-fill applied to the TCC curves, to make the plot more readable. And you can zoom in on a particular section of the grid by entering the upper and lower current and time values in the appropriate cells. To see a full-size TCC plot or full-size summary information, click on "Printer Friendly Graph" or "Printer Friendly Summary," as applicable.

Now let's review the TCC plot of the coordination example under consideration.

Device #1, the 65E-ampere Standard Speed primary-side power fuse, is plotted in red. Device #2, the transformer damage curve, is plotted in black. And Device #3, the load-side recloser, is plotted in orange. The two thicker orange curves are the recloser fast curve (A) and slow curve (C), respectively, based on TCC data published by the recloser manufacturer. The thin orange curve is the maximum-equivalent lockout curve of the recloser, reflecting positive tolerances.

The 65E-ampere Standard Speed power fuse provided excellent protection for the transformer as evidenced by the fact the total-clearing curve of the fuse crosses the transformer damage curve at current levels less than the maximum values obtained for any type of fault. This fuse has a published peak-load capability of 107 amperes, which means that the transformer can be loaded to nearly 280% of nameplate—well in excess of the desired OA/FA rating (125% of nameplate). Unfortunately, the primary-side fuse *does not* coordinate with the maximum-equivalent lockout curve of the recloser, since the minimum-melting time of the fuse at 478 amperes (0.42 second) is less than the maximum-equivalent lockout curve of the recloser at this current level (0.69 second). Note that the secondary-side recloser curves have been shifted to the right, by 15% in terms of current, to account for the primary-side to secondary-side current imbalance that would exist were a phase-to-phase ungrounded secondary-side fault to occur.

When faced with this situation, the natural reaction is to select the next-larger-ampere-rated primary-side power fuse, a fuse with a slower time-current characteristic, or perhaps both . . . until coordination is achieved. While this solution may result in complete coordination between the fuse and the recloser, it does so at the expense of transformer protection — not the optimal result. Before selecting a larger fuse, or one with a slower time-current characteristic, repeat this exercise using the more precise cooling-factor method (the subject of next month's article). You may find that the primary-side fuse initially selected provides complete coordination after all!

Primary Fuse (65E-ampere standard speed)

Maximum equivalent recloser "lockout" curve using conservative method

Through-fault protection curve for delta-grounded-wye connected transformer

Recloser "C" Curve

Miscoordination

Recloser "A" Curve

Three-phase secondary-side fault (478 amperes)

Time in Seconds

Current in Amperes at 115 kV

How to Coordinate Transformer Primary-Side Fuses with Feeder Reclosers Using Coordinaide™ — The S&C Protection and Coordination Assistant — Part 2: Cooling-Factor Method

This is the second in a series of articles explaining how to coordinate transformer primary-side fuses with a secondary-side automatic circuit recloser, such as in a utility substation. In this installment we'll use the more precise "cooling-factor" coordination method, which takes into account the effects of fuse cooling during the reclosing time intervals (contacts open) of the recloser. In the last exercise (see article dated October 30, 2006) the less precise "conservative" coordination method was used. Future articles will address source-side recloser/load-side fuse applications.

Source-Side Fuse/Load-Side Recloser Coordination

Automatic circuit reclosers sense overcurrents, interrupt them, and then automatically reclose to reenergize the feeder. Most faults on overhead distribution systems—perhaps as many as 75 to 80%—are temporary in nature, lasting only a few cycles to a few seconds. With their "trip and reclose" capability, reclosers eliminate prolonged outages on distribution systems due to such temporary faults. If a fault is permanent rather than temporary, however, the recloser will "lock out" after a preset number of reclosing attempts (usually three or four), thus isolating the faulted feeder from the system.

Automatic circuit reclosers have dual timing capabilities, which help maintain coordination with other protective devices and limit the areas affected by permanent faults. Typically the first—sometimes the first two—fault-clearing operations are performed per the "fast" timing characteristic, clearing *temporary* faults before load-side protective devices operate. Subsequent operations incorporate a predetermined time delay which allows protective devices nearer the fault to interrupt *permanent* faults, thereby limiting the extent of the service interruption. This arrangement is often referred to as a "fuse saving" scheme, since fuses only respond to permanent faults within their zones of protection.

When coordinating a transformer primary-side fuse with an automatic circuit recloser, the fault current flowing through the primary-side fuse will be interrupted by the recloser and then restored as the recloser goes through its operating sequence. Initially the temperature of the fusible element in the primary fuse is determined by the pre-fault load current and by elevated (or reduced) ambient temperatures. When a fault is initiated, the temperature of the fusible element increases towards its melting point. If the recloser opens before the fuse reached its melting point, the fuse will cool during the reclosing time interval (contacts open). This current cycling will continue until: a) the fault is cleared by a fast operation of the recloser, followed by a successful reclose; b) a load-side fuse clears the fault during the recloser's delayed operation; or c) the recloser operates to lockout.

For the application covered in this article, the transformer primary-side fuse is located upstream of the automatic circuit recloser. Clearly you would want the recloser to operate to lockout, in response to a permanent fault, *before* the primary-side fuse operates.

The maximum fault current value up to which the transformer primary-side fuse and the recloser will coordinate is generally the lower of:

1. The maximum interrupting capacity of the recloser or primary-side fuse, or
2. The intersection of the minimum-melting curve of the primary fuse and the maximum-equivalent operating curve of the recloser (i.e., the "lockout" curve).

As just noted, when coordinating reclosers and fuses, the repeated heating and cooling of the transformer primary-side fuse must be considered. To achieve this end, adjustment factors("C"), also known as cooling factors, are applied to the total-clearing curves of the recloser — rather than to the primary-side fuse — to generate an "equivalent" recloser lockout curve as "seen" by the primary fuse. Cooling factors reflect the heat *remaining* in the fuse after preheating and cooling, in percent of preheating, for a specific reclosing time interval (cooling time). Cooling factors vary based on the ampere rating and speed characteristic of the fuse.

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

a. One operation of the recloser

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

b. Two operations of the recloser

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

c. Three operations of the recloser

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

d. Four operations of the recloser

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

Where:

T_l = Point on the maximum equivalent lockout curve of the recloser, at current (I).

P = Reduction in the melting time of the transformer primary-side fuse due to preloading, expressed as a decimal part of its total melting time.

T_{Rj} = *Maximum* clearing time at current (I) for the jth operation (contacts closed) of the recloser.

C_k = Cooling factors for the kth reclosing time interval (contacts open) of the recloser.

Since the transformer primary-side fuse must allow the recloser to operate to lockout without melting, the recloser's *maximum* equivalent lockout curve should be developed. Recloser fast curves (A) are typically published to maximum test points. But slow curves (B, C, and D) are published to nominal test points and must be adjusted (maximized) by the amount of the positive tolerance, which is assumed to be 10%.

Example

Consider a rural electric power substation having a single transformer, protected by primary-side fuses, with three or fewer feeder reclosers. Ratings for the primary fuse, the transformer, and the load-side reclosers are as follows:

Transformer: The transformer has a base (OA) rating of 7500 kVA three-phase, 115 kV primary, 13.2 kV secondary. It has a forced-air (FA) rating of 9375 kVA (125%). The transformer impedance is 7.5%, and the maximum three-phase secondary fault current is 478 amperes (2000 MVA), as seen on the primary side of the transformer. The transformer is connected delta grounded-wye.

Fuse: The transformer primary-side fuse is a 65E-ampere Standard Speed S&C SMD-2B Power Fuse rated 115 kV. The full-load current of the transformer, based on its force-air rating is 47 amperes. At this level of transformer loading, the primary-side fuse will be loaded to 72% of rating (47 amperes ÷ 65 amperes = 0.72). The preload adjustment factor, as determined from S&C Data Bulletin 210-195, is 0.88.

Feeder Recloser: The load-side recloser is a hydraulically-controlled Cooper Type W Recloser, rated 14.4 kV, 560 amperes continuous. The phase-trip pickup current is 280 amperes (140-ampere coil), and the operating sequence is one fast (A) and three slow (C) operations. The reclosing time interval between the fast operation and the first delayed operation is 0.5 second (instantaneous). Between the delayed operations, the reclosing time interval is 5 seconds.

Completing the Exercise Using Coordinaide

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you launch the program, you'll be directed to a second page containing a brief "Conditions of Use" disclaimer, followed by a short note detailing minimum web browser requirements and a link to a "Users Guide." One final click launches the program and takes you to the "General Information" page. Please follow these directions to select the primary-side fuse, the transformer, and the load-side recloser.

Step 1 — Enter General Information

- Project Name: *Fuse-Recloser Coordination Exercise (Cooling-Factor Method)*
- Date: [provided by Coordinaide]
- By: *Optional*

Step 2 — Enter System Information and Select Devices

- Three-Phase Voltage, kV: *115*
- Available Fault Current, Amperes RMS Symmetrical: *10000*
- Device #1 — *Power Fuse*
- Device #2 — *Transformer (Damage Curve)*
- Device #3 — *Recloser*

Click "Continue" after entering system information and selecting the devices. You'll be directed to the first "device" page.

Step #3 — Select and Enter Device Parameters

Device #1 — Transformer-Primary Fuse (Select Parameters)

- Manufacturer: *S&C*
- Type: *SMD-2B*
- Speed: *Standard*
- Voltage Range, kV: *115-138*
- Ampere Rating: *65E*

Click "Continue" after selecting the parameters for Device #1. The time-current characteristic curve for Device #1 will be displayed.

Device #2 — Transformer (Select Parameters)

- Three-Phase Primary Voltage, kV: *115* [Provided by Coordinaide]
- Three-Phase Secondary Voltage, kV: *13.2*
- Three-Phase Rating, kVA: *7500*
- Impedance, %: *7.5*
- Fault Current, Amperes RMS Symmetrical: *10000* [Provided by Coordinaide]
- Display Magnetizing Inrush Points? ○ Yes ● No (default)
- Connection: *Delta Grounded-Wye*

Click "Continue" after selecting the parameters for Device #2. The time-current characteristic curve for Device #2 will be displayed.

<u>Device #3 — Feeder Recloser (Select Parameters)</u>

- Coordinates With: ● Source-Side Device ○ Load-Side Device **See Note 1**
- Coordination Method: ● Cooling Factor ○ Conservative (default) **See Note 2**
- Manufacturer: *Cooper (McGraw): Hydraulic*
- Type: *W*
- kV Range, kV: *14.4* [Provided by Coordinaide]
- Phase-Trip Operating Sequence: *1 Fast / 3 Slow*
- Fast Curve: *"A"*
- Slow Curve: *"C"*
- Coil Rating, Amperes: *140*
- Fuse Preload, %: *72*
- Cooling Interval #1, Sec.: *0.5*
- Cooling Interval #2, Sec.: *5*
- Cooling Interval #3, Sec.: *5*
- Ground-Trip Operating Sequence: *Skip for this example*

Note 1: Since the recloser is on the load side of the primary-side fuse, select "Coordinates with Source-Side Device (default in this example)."
Note 2: Select "Cooling-Factor Method" to take into account the effects of cooling of the primary-side fuse during reclosing time intervals (contacts open) of the recloser. You are encouraged to repeat this example using the less precise conservative method, and then compare the results. See article dated October 30, 2006.

Click "Continue" after selecting the parameters for Device #3. The time-current characteristic curve for Device #3 will be displayed.

Step #4 — Go to "Results" Page

Click on the tab at the top labeled "Results." You'll be directed to a log-log grid with TCC curves of the devices you've selected.

If desired, you can change the current scale of the grid from the default, 5 to 100,000 amperes, to 0.5 to 10,000 amperes. You can also eliminate the hash-fill applied to the TCC curves, to make the plot more readable. And you can zoom in on a particular section of the grid by entering the upper and lower current and time values in the appropriate cells. To see a full-size TCC plot or full-size summary information, click on "Printer Friendly Graph" or "Printer Friendly Summary," as applicable.

Now let's review the TCC plot of the coordination example under consideration.

Device #1, the 65E-ampere Standard Speed primary-side power fuse, is plotted in red. Device #2, the transformer damage curve, is plotted in black. And Device #3, the load-side recloser, is plotted in orange. The two thicker orange curves are the recloser fast curve (A) and slow curve (C), respectively, based on TCC data published by the recloser manufacturer. The thin orange curve is the maximum-equivalent lockout curve of the recloser, reflecting positive tolerances.

The 65E-ampere Standard Speed power fuse provided excellent protection for the transformer as evidenced by the fact the total-clearing curve of the fuse crosses the transformer damage curve at current levels less than the maximum values obtained for any type of fault. This fuse has a published peak-load capability of 107 amperes, which means that the transformer can be loaded to nearly 280% of nameplate — well in excess of the desired OA/FA rating (125% of nameplate). And it provides *complete* coordination with the maximum-equivalent lockout curve of the recloser, since the minimum-melting time of the fuse at 478 amperes (0.42 second) is well above the maximum-equivalent lockout curve of the recloser at this current level (0.24 second). Note that the secondary-side recloser curves have been shifted to the right, by 15% in terms of current, to account for the primary-side to secondary-side current imbalance that would exist were a phase-to-phase ungrounded secondary-side fault to occur.

As this exercise illustrates, including the effects of cooling of the transformer primary-side fuse during the reclosing time intervals (contacts open) may allow you to confirm that the fuse initially selected, in fact, coordinates with the recloser, even though the conservative coordination method (the subject of the article dated October 30,2006) might suggest otherwise. Furthermore, by using the cooling-factor coordination method, you may be able to select a smaller primary-side fuse rating, or a fuse having a faster speed characteristic, or both, for even better transformer protection.

Primary Fuse (65E-ampere standard speed)

Maximum equivalent recloser "lockout" curve using cooling-factor method

Through-fault protection curve for delta-grounded-wye connected transformer

Recloser "C" Curve

Recloser "A" Curve

Three-phase secondary-side fault (478 amperes)

Time in Seconds

Current in Amperes at 115 kV