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Tolerance-Based Time-Current Coordination

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SUMMARY

This paper describes a novel technique for representing time-overcurrent protection behavior using tolerance-response bands that are comparable to expulsion-fuse Time-Current Characteristics (TCCs). The advantage this new TCC representation method offers is more fault-interrupting devices can be time-current coordinated than would be typical with the present Coordinating Time Interval (CTI) method. Consequently this discussion presumes the convention of coordinating time-overcurrent protection using single, nominal, TCC lines, and a CTI fixed-time value, is reasonably understood. Recently, tolerance-response bands have been used for graphically representing and coordinating the numerous TCCs of a device that has revolutionized how the continued presence of medium-voltage feeder faults is determined. Identical to protective-relay performance specifications, this product's sensing and measurement tolerances, plus its fault-clearing time, have been combined to produce TCC tolerance-response bands for the wide variety of available protection characteristics. Therefore, this paper will discuss how TCC tolerance-response bands can be developed for any time-overcurrent element.

KEYWORDS

Tolerance-based coordination, Time-Current Characteristic (TCC), TCC tolerance-response bands, Coordinating Time Interval (CTI)

I. Background

Protective-relay and control time-overcurrent elements are conventionally coordinated using single, nominal, Time-Current Characteristic (TCC) lines and a fixed Coordinating Time Interval (CTI) time-value. CTI is frequently based on historical coordination experiences, and it traditionally accounts for the sum of an overcurrent element's current-sensing and measurement tolerances, its time-response consistency, and its associated fault-interrupter's maximum total fault-clearing time.

Once a CTI time-value is established, the single, nominal, TCC lines of upstream and downstream devices are separated by this CTI to ensure that overtripping of upstream devices doesn't occur in response to a common downstream fault.

When coordinating electromechanical relays, it was common practice to use a CTI of 20 cycles, or 0.33 seconds (60 Hz), to account for response tolerances between or among series devices using this technology. With the advent of solid-state and microprocessor relays, CTI typically has been reduced to 0.25 or 0.2 seconds when coordinating relays of this construction.

This subsequent reduction in CTI is principally due to improvements in protective-relay measurement, time-response, repeatability-tolerances, and reduced relay burdens. But fault-

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interrupting times have likewise dropped from 5 or 6 cycles to 2 or 3 cycles, which also have helped contribute to lower CTIs. Yet, the primary-current sensing-device is still usually the iron-core current transformer (CT) – the class C, or the 10P20.

CT or current-sensor error will be discussed in this paper, but the effects of CT saturation will not be addressed. When a CT saturates, its secondary-current is no longer proportional to its primary-current. This results in time-overcurrent elements frequently exhibiting a definite-time response to increasing primary-current. Further, CT saturation is more likely to occur due to the higher burden of electromechanical relays. As these relays (if present) are more apt to be at the furthest upstream protection position (the substation circuit-breaker), CT saturation (if it occurs), doesn't introduce any coordination issues because downstream devices generally continue to respond faster to increasing fault currents.

II. Alternative TCC Representation Method

The basis for using a tolerance-based, time-current coordination method is rooted in how expulsion-fuse TCCs are graphically characterized. With expulsion fuses, an operating-response band is developed using a fuse's minimum-melt and total-clear TCCs. The coordination of series fuses is accomplished simply by ensuring a fuse's slower (total-clear) and faster (minimum-melt) TCCs don't touch or cross adjacent upstream and downstream fuses for an appropriate level of fault current.

Instead of relying on a CTI fixed-time value, that is frequently based on historical performance (after all, using it usually prevents overtripping), a TCC tolerance-response band accounts for all the component tolerances contributing to the time-response of an overcurrent element. This means accounting for:

- CT or current-sensor error
- Overcurrent element
    - o Measurement inaccuracies
    - o Timing tolerances (including any fixed-time error)
- Fault-interrupter total fault-clear

Accommodating Primary-Current Sensing Response Tolerances

The relatively recent introduction of an alternative to medium-voltage reclosers uses Rogowski coils that are very precise and remain linear across an extremely wide range of currents. However, protection elements supplied by more conventional current sources, such as a class C or 10P20 CT, will require representation of their primary-current sensing-device tolerances.

The performance of typical iron-core CTs is worth understanding, and then resolving. Using the class C or 10P20 CT as an example, performance specifications essentially require the CT to have a 10% maximum ratio error at 20 times its rated primary-current.

Experience suggests most CTs and current sensors are reasonably accurate when sensing load currents. So it's sensible to believe the 10% error of a class C or 10P20 CT, if it's likely to occur, would appear at 20 times the CT's rated primary-current.

Some simply consider this error to be +/-5% throughout the range of primary-current. Consequently, the CT's secondary-current response tolerance contributes equal negative and positive percentage error to the total measurement tolerances of the TCC. However, it's highly unlikely a CT, which is a passive device, will ever produce more secondary-current than the applied primary-current.

To be fair, there are a couple of possible causes of a CT supplying more secondary-current than its specified ratio would indicate. One would be winding-turn errors introduced during manufacturing, and the other might occur when a CT's turns (wires) become shorted after being placed in service. As these causes are extremely rare, it's very sensible to presume positive CT error is extremely unlikely.

However, modelling the transition of sensing tolerances from 0% to a -10% for currents ranging from 1 to 20 times rated current also becomes a compromise when implemented using software-coordination tools. So what are the consequences of simply using a +/-5% CT error?

A +/-5% tolerance (instead of 0%) at typical current pick-up levels isn't likely to have a significant impact because the consequential response times are generally very long. As an example, and using an IEC Very Inverse TCC equation (because the math is fairly simple), let's presume we have a 600:5-ampere (120:1) class C or 10P20 CT; a relay with a pick-up of 600 amperes; and a time dial, or time-multiplier, of 1.0.

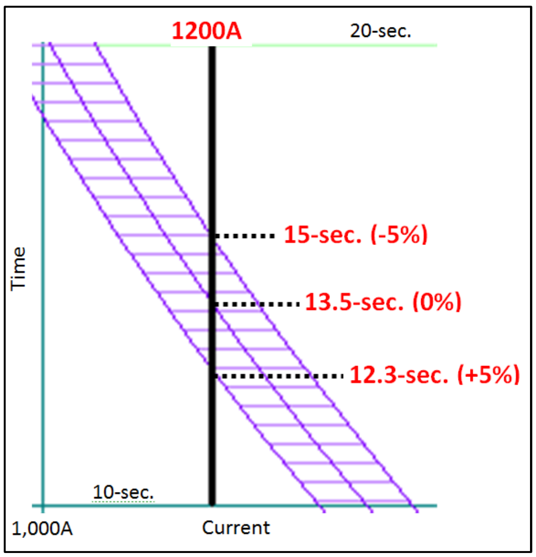

Figure 1.

The IEC Very Inverse equation is T (sec.) = 13.5/(I – 1) * TM, where I is the applied current divided by the pick-up current, and TM is the time-multiplier or time-dial setting. Using 1,200 amperes as the applied current, I = 2 (1,200/600), and with a TM = 1, this TCC produces a 13.5-second response time. This 13.5 seconds is also the response time presuming the 600:5-ampere CT has 0% error.

This is illustrated using the horizontal-hatched TCC band in the partial time-current plot shown in Figure 1. The center line of this TCC band is the Very Inverse TCC response with 0% CT error. At 1,200 amperes, this center line crosses the time-axis at 13.5 seconds.

The +/-5% CT error roughly contributes a +/-10% time-response at two times pick-up. This effect produces minimum and maximum response TCCs for our tolerance-response band that are very conservative, and helps accommodate load-current contributions at low fault-current levels.

And the effects of the +/-5% and -10% CT ratio error at 20 times rated current (12,000 amperes) are shown in Figure 2.

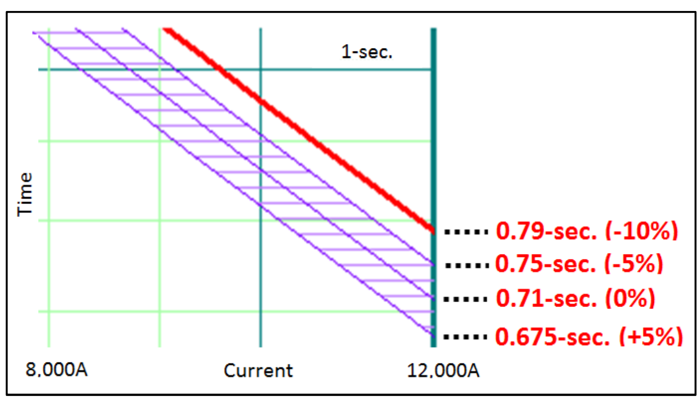

Figure 2.

To observe the effects these CT errors have on coordination, Figure 3 adds an upstream IEC Very Inverse TCC band. This vertical-hatched TCC band is also developed by plotting the effects a +/-5% CT error has on its TCC responses times.

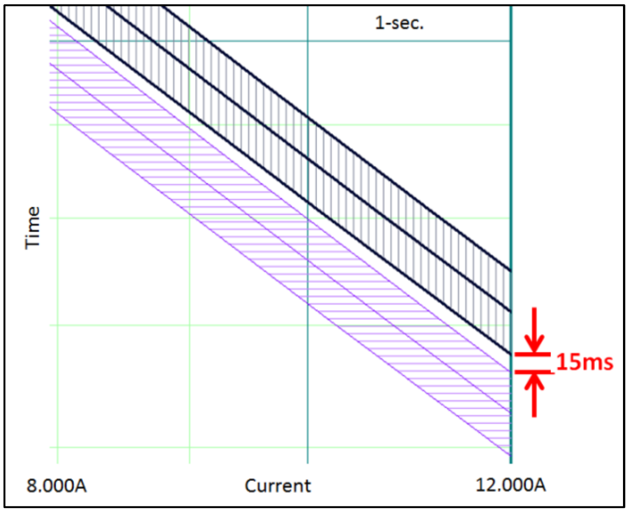

Figure 3.

Here, the two vertical- and horizontal-hatched TCC bands simply have been separated so they don't touch each other, as would be the practice when coordinating fuses. Their separation at 12,000 amperes is 15 milliseconds, which was achieved by using a time-multiplier of 1.0 for the upstream TCC band and reducing the time-multiplier of the previous TCC band to approximately 0.9.

Now the more probable -10% CT response of the downstream (horizontal-hatched) device is added in Figure 4. This -10% CT error is the solid line dissecting the bottom half of the vertical-hatched TCC band.

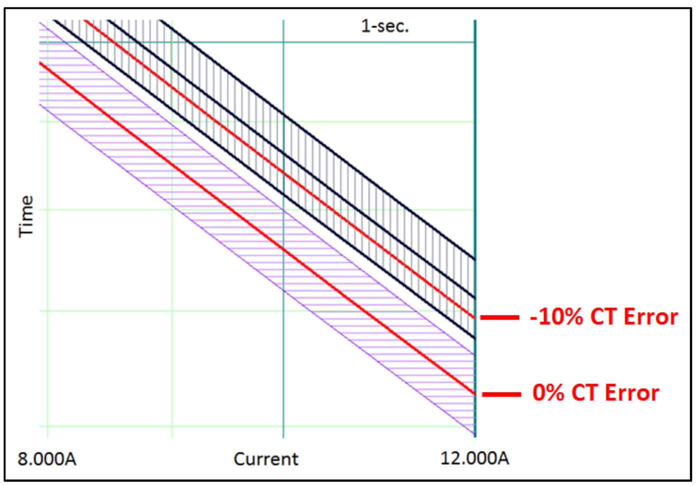

Figure 4.

It appears there is a coordination violation because the -10% CT error line crosses into the vertical-hatched TCC band. But this isn't an issue because the bottom half of the vertical-hatched band won't exist in service (the upstream CT cannot sensibly produce more secondary-current than its ratio allows).

Consequently, the lower half (+5% CT error) of the vertical-hatched band is removed in Figure 5 because its CT can't logically produce more current at 12,000 amperes.

The influence of the -10% CT error is then compared with the remaining vertical-hatched TCC band. The resulting analysis indicates there is a 19-millisecond margin between the more realistic -10% CT error line and the very conservative response of the vertical-hatched TCC's nominal line (0% CT error).

Consequently, using +/-5% CT error, and ensuring the resulting upstream and downstream TCC bands don't touch, indicates this method for resolving the 0/-10% CT error is very practical.

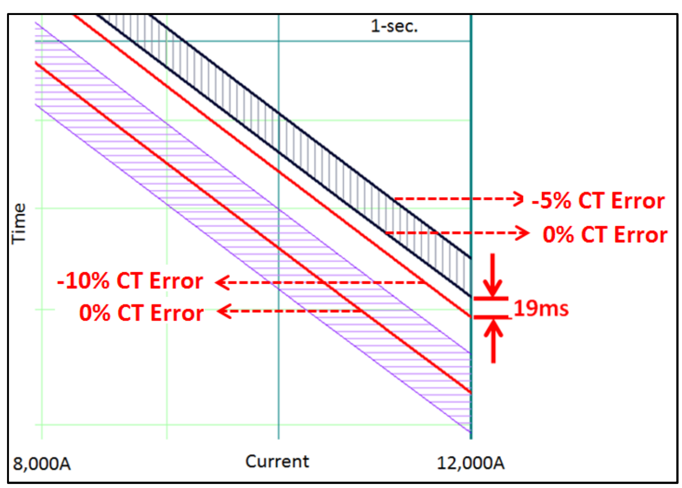

Figure 5.

However, the overcurrent element's measurement and timing tolerances, and the total fault-clear of its associated fault interrupter, must still be added. Once these influences have been included, the effects of CT error in developing TCC tolerance-response bands will be better appreciated.

Incorporating Protection Element Current Measurement Tolerances

The best way to determine a protection element's current-response tolerances is to refer to the manufacturer's specifications. However, the performance nuances of some overcurrent elements simply cannot be readily accommodated by most of today's software-coordination tools. This is because some protection-element responses can vary based on the measured current relative to the overcurrent pick-up setting. Fortunately, the consequences of not including some of these response irregularities are of little or no concern in achieving optimum time-current coordination.

A typical protective-relay specification will indicate an element's pick-up accuracy, which in some instances can include fixed-tolerance response influences. Also, a definite-time or instantaneous element's measurement accuracy may differ from those for inverse TCCs.

While some tolerances simply will indicate positive and negative percentages, others may append "+/-" current to these percentages to reflect fixed tolerances. As an example, pick-up accuracy may be stated as +/-4% of setting, plus +/- 0.07 amperes. Yet others might state a percentage and a current, or two percentages, but qualify both based on whether one is greater than the other. For instance, a current tolerance may be indicated as +/-0.6% of applied current, or +/-2% of rated (nominal) current, whichever is greater.

If the software-coordination tool doesn't enable the application of these more-complex tolerance values, most fixed-tolerance values can be accommodated using the CT's or current sensor's error. While using +/-5% error for the class C or 10P20 CT definitely mitigates fixed-value tolerances at higher currents, some differences can occur at lower pick-up current levels.

This potential shortcoming isn't usually a concern because achieving TCC coordination primarily occurs at higher currents. As an example, presume pick-up accuracy is specified as +/-4% of setting, plus +/-0.07 amperes (conventionally expressed in secondary-current). Using the previous 600:5-ampere (120:1) CT ratio example, +/- 0.07 amperes becomes +/- 8.4 amperes (primary).

The combination of specified +/-4% and +/-8.4-ampere fixed-current tolerances results in a pick-up range of 87.6 amperes to 112.4 amperes. Conversely, if +/-5% CT error and the specified +/-4% tolerance are only used, the pick-up range varies between +/-9.2% (1.04 X 1.05), or from 91 amperes to 109 amperes.

These effects may be better appreciated by viewing the partial time-current plot in Figure 6. The outer, wider lines near 100 amperes illustrate the +/-4% measurement error, plus the +/-8.4-ampere fixed-current tolerance (no CT error). The inner horizontal-hatched band shows the effects of using only the +/-5% CT error plus the +/-4% measurement error (no +/-8.4-ampere contribution).

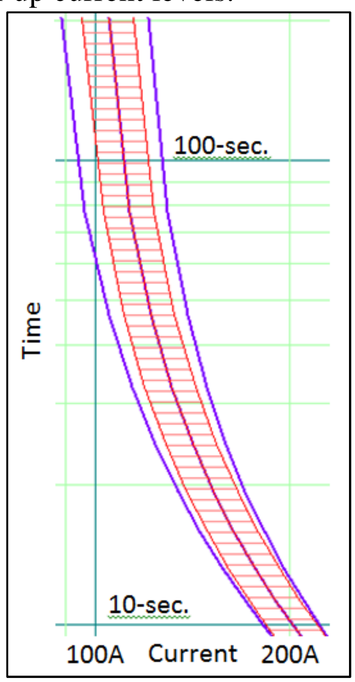

Figure 6.

While there appears to be an appreciable difference at pick-up between these two current-response representations, this is simply a graphical illusion. There is, in fact, only about a 3.5-ampere difference between each outer line and the maximum and minimum current responses of the horizontal-hatched TCC band. And we also notice this divergence has essentially vanished at 200 amperes.

Implementing Protection Element Time Tolerances

The manufacturer's relay specification also will provide indication of an element's timing tolerances. In some instances, this can include response influences caused by the time-multiplier and even the current-input signal level.

These tolerance values may also change depending on the protection element's characteristic. And, as with current tolerances, some timing tolerances will be more complex, stating a percentage and a time but qualifying both based on whether one is greater than the other.

Moreover, as with current tolerances, many software-coordination tools enable the application of both percentages and fixed-time tolerance values, and can automatically apply the greater or lesser of two related parameters. However, and unlike current tolerances, fixed-time tolerance values must be accommodated somehow.

As an example, an IEC Very Inverse TCC specification indicates a current measurement tolerance of +/-4%, and a timing accuracy of +/-4%, plus +/-25 milliseconds. Figure 7 is a partial plot near its 600-ampere pick-up with and without timing tolerances, but including the specified current tolerances plus the +/-5% CT error.

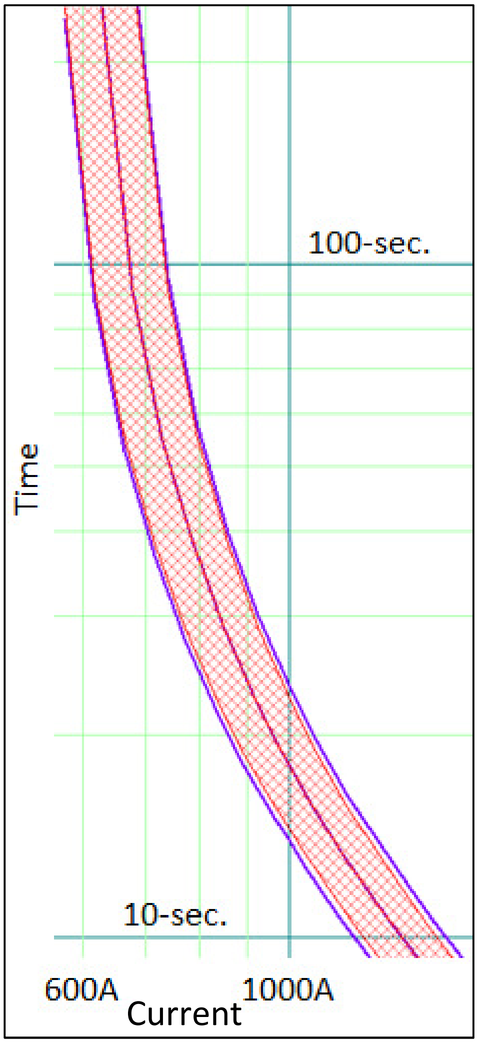

Figure 7.

There is no discernable difference between the plotted tolerances at or near pick-up. However, the crosshatched TCC (no timing tolerances) narrows as current increases near 1,000 amperes and beyond.

This separation becomes very pronounced at 20 times rated primary-current, as shown in Figure 8. Here, the time tolerances (upper and lower solid lines) account for 50 milliseconds faster

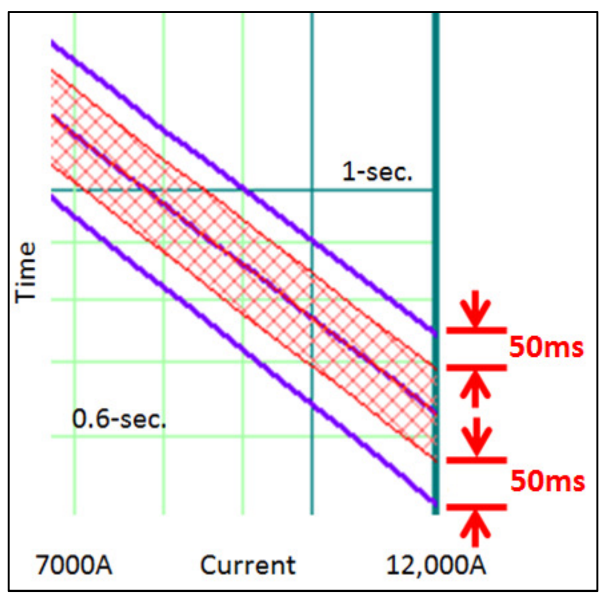

Figure 8.

and slower responses at 12,000 amperes when compared with only the current tolerances plus the +/-5% CT error (crosshatched TCC band).

Consequently, combining current and time tolerances becomes essential when coordinating upstream and downstream devices. Therefore, the plot in Figure 9 introduces an upstream device with the same specified tolerances just used previously. The only difference between the two TCCs is the top TCC (vertical hatching) is set to pick-up at 750 amperes and has a time-multiplier of 1.0.

The downstream TCC (horizontal hatching) pick-up and time-multiplier settings result in a 15-millisecond separation between it and the upstream TCC (vertical hatching) at 12,000 amperes.

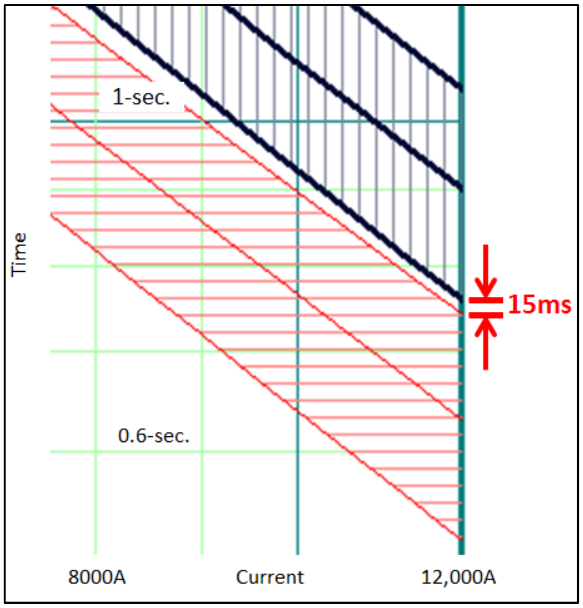

Figure 9.

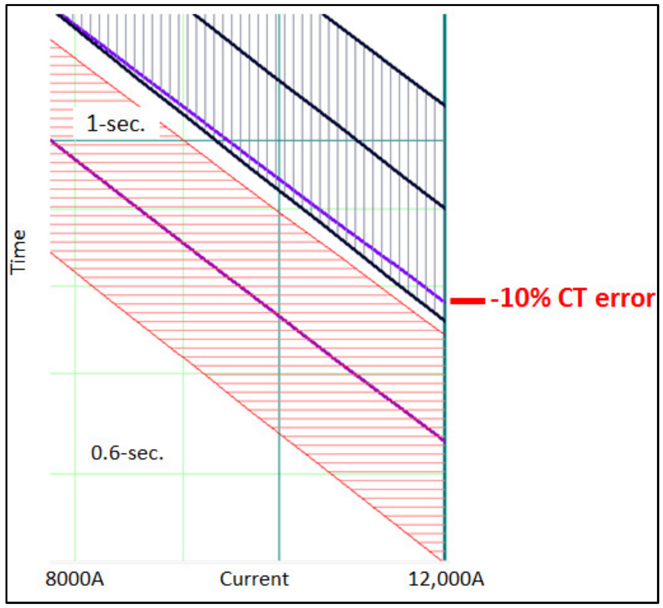

Figure 10.

Using a more realistic -10% CT error, plus the previous tolerances of the downstream overcurrent element, Figure 10 shows the influence of the -10% CT error (single line transitioning into the vertical hatching). However, as when plotting just current tolerances, we remember that a sizeable portion of the bottom half of the vertical-hatched TCC is equally unrealistic because it represents "+" CT error, which cannot sensibly exist.

Moreover, unlike when only current tolerances were illustrated previously, the effect of a possible -10% CT error is marginalized by the addition of "+" timing tolerances. So, using an appropriate CT error and the specified current and timing tolerances, and separating the resulting TCC tolerance-response bands, ensures there is adequate coordination margin between devices.

Addressing the Total Fault-Clear of the Fault Interrupter

We have finally arrived at the last component of the TCC tolerance-response band – the "+" fixed-time, total fault-clear of the fault interrupter.

Applying this positive, fixed-time tolerance is relatively easy, and today's breakers and reclosers are generally 2-cycle devices. However, existing legacy fault interrupters will vary in time, from a typical maximum of 5 or 6 cycles to a minimum of 3 cycles.

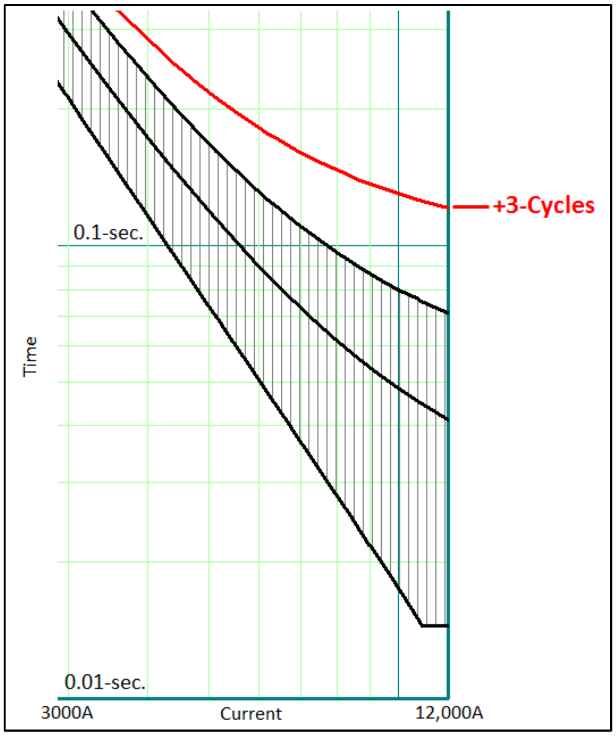

Figure 11.

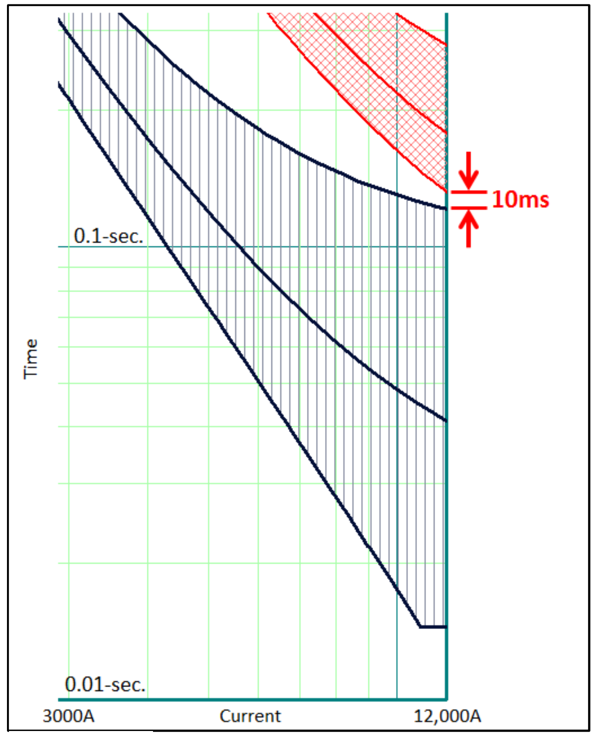

Figure 12.

The influence of total fault-clear is best illustrated by plotting a TCC specification with and without the additional fault-interrupting fixed-time. The TCC with the vertical hatching in Figure 11 is an IEEE Extremely Inverse curve with a pick-up of 600 amperes, includes a +/-5% CT error, uses a time-multiplier of 1.0, has +/-4% current-measurement and timing tolerances, and a fixed-time error of +/-25 milliseconds. The region between the uppermost single line and the line bounding the upper area of the vertical hatching is the effect of presuming a 3-cycle or 50-millisecond (60-Hz) total fault-clear.

As we are again interested in how this all affects coordination, we will now add an upstream device with the same specification, but a 750-ampere pick-up and a time-multiplier of approximately 3.6. The results, shown in Figure 12, indicate there is a 10-millisecond separation between the upstream and downstream TCC bands with all their tolerances considered.

Figure 13 shows the full plot of both TCCs from pick-up to 12,000 amperes. And Figure 14 is a plot of these same two TCCs displaying only their conventional, single, nominal TCCs and effective CTI. The resulting 137-millisecond effective CTI is a substantial improvement over the convention of using a CTI fixed-time of 250 milliseconds, or even 200 milliseconds, and is accomplished simply by using a very conservative tolerance-based TCC coordination technique.

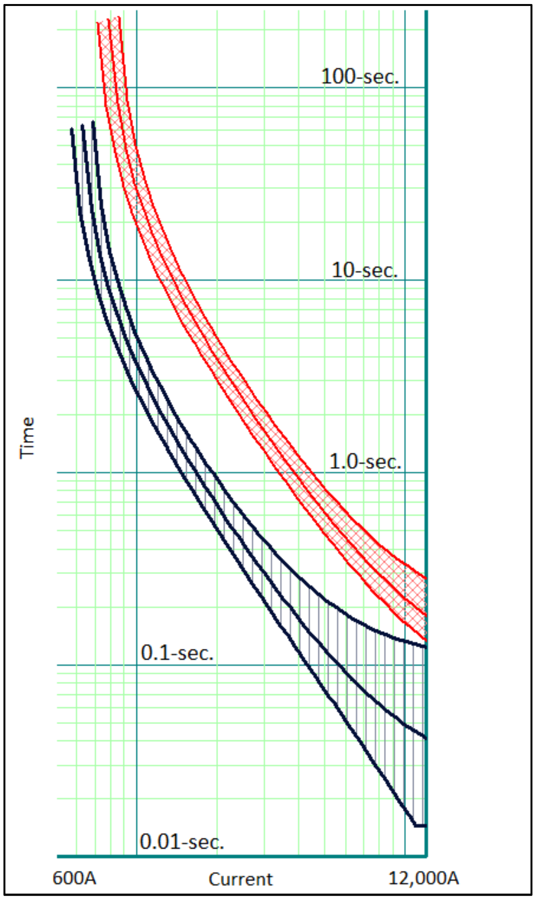

Figure 13.

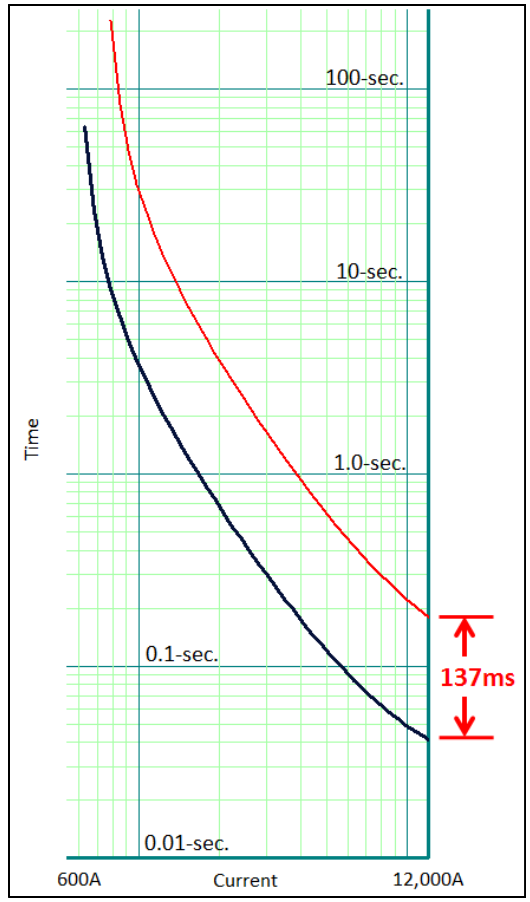

Figure 14.

III. A Final Note on the Effects of CT Error

The partial plot in Figure 15 shows a TCC tolerance-response band transitioning from inverse-time to definite-time. This transition is specified by the manufacturer and occurs at some multiple of the TCC's current pick-up setting. In these instances, CT error no longer affects the definite-time portion of the TCC, and the overcurrent element (and not the CT) determines the protection-response. Consequently, CT error does not contribute to the TCC tolerance-response band once the TCC has transitioned to this definite-time response.

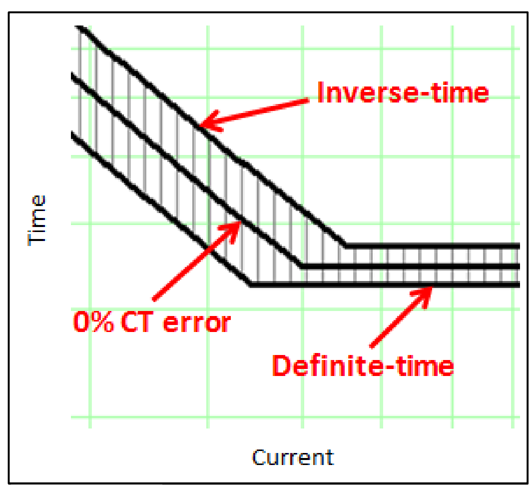

Figure 15.

IV. Conclusions

The illustration of tolerance-based TCC coordination conclusively demonstrates that time-overcurrent protection responses can be better modeled using cumulative response tolerances. Instead of simply relying on a single, nominal, TCC line and a fixed-time CTI, graphically coordinating comprehensive TCC response bands results in dramatically tighter TCC separation margins. And this was accomplished using a 3-cycle fault interrupter and relatively conservative, common protective-relay specifications.

However, the inverse shape of the TCC, current pick-up levels, time-multiplier settings, and the fault-current range also will govern whether tolerance-based TCC coordination appreciably reduces the separation margins produced by the conventional CTI method.

When using the tolerance-based TCC coordination technique, less inverse TCCs may occasionally result in separation margins comparable with those produced by the conventional CTI approach. However, the improved accuracy and linearity of primary-current sensing-devices, and a more precise (and ideally unified) system of protection and control components, coupled with contemporary fault-interrupting speeds, will significantly challenge this potential outcome.

Nevertheless, if increasing the number of series, coordinated, time-overcurrent devices is the ultimate objective, using the proposed tolerance-based TCC coordination technique can appreciably improve upon what can be achieved using the conventional CTI method.