CT Saturation in Industrial Applications –
Analysis and Application Guidelines

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1. Introduction

It is possible that relatively low-ratio CTs are applied for protective relaying of small loads fed from switchgear and motor controllers of relatively high short-circuit capacity. Assume the worst-case scenario of 64kA available fault current from bus feeding a small motor load of normal current below 50A. In theory, CTs rated as lows as 50:5 and relay class C10 may be applied for protection purposes.

Realizing that 64kA of fault current is 1080 times the rated current of the 50:5 CT, the magnitude of the problem is evident. Protection class CTs are designed to work in the linear range, with minimal errors and minimal waveform distortion, only up to 20 times the rated nominal current with the burden as defined by the relay class (saturation voltage) of the CT per IEEE Std. C57.13.

Well-established and relatively accurate equations are available for calculation of the actual maximum primary current for saturation-free operation under any specific burden, any specific X/R ratio, and any specific residual flux in the CTs. This engineering practice is of little help here: A CT fed with a primary current hundreds of times its rated current will saturate severely - only relatively short duration peaks of limited current will be observed from the secondary of the CT. These peaks can be as low as 5-10% of the ratio current, and will last a small fraction of the half-cycle, down to 1-2ms in extreme cases. As a result only a very small portion of the actual ratio current is presented to protective relays fed from such severely saturated CTs. In terms of the true RMS value, the secondary current may be as low as 1-2% of the expected RMS secondary current.

On the surface it may seem that a severe problem takes place here – the fault current is so high that it virtually stops the CT from passing the signal to the relay. The relay does not see enough proportional secondary current during severe faults in order to operate its short circuit protection. The upstream relay, using CTs of a much higher ratio, measures the fault current more accurately and trips. Zone selectivity is lost because the poor low-ratio CT was "blinded" to the fault.

It is justified to assume that vast majority of industrial applications are not supported by computer simulation studies (EMTP) of saturated CTs, or any lengthy and sophisticated CT analysis. At the same time there is a population of relays installed on high capacity buses and fed from low ratio CTs. An obvious question arises: why does the above problem not demonstrate itself in the field?

In this paper we will analyze the problem in detail and explain its underlying mechanics. Several GE Multilin's relays are analyzed in terms of their response to heavily saturated waveforms. A formal, compact and easy to grasp method is shown to present complex relations between the CT response and the response of any given relay. Based on this graphical method one can quickly evaluate the problem (do I have a problem when using relay X, with CT Y, under fault capacity Z, and overcurrent pickup setting Q?), and clearly see alternative solutions if a problem truly exists (i.e. definition of a method to match relays with CTs).

This paper illustrates that many unknowns in analysis do not have significant impact on the outcome. Reasonable conclusions will be evident from the results, even though broad assumptions are made in the model.

This exploratory analysis shows that severely saturated CTs only slightly reduce short circuit tripping capabilities of GE Multilin's relays. Given the typically applied settings, there is no danger of a failure to trip from intantenous overcurrent functions even in extreme cases of very high short-circuit currents and low-ratio CTs.

2. Severe Saturation of Low-Ratio CTs

Well-established engineering practice exists for CT selection to ensure saturation free-operation of protection CTs at a given short circuit level, CT burden, X/R ratio and assumed residual flux. In the context of this paper, it is assumed that this engineering technique is not applied, and severe saturation will occur for short circuits within the protected zone (motor, feeder, cable or bus).

Analytical analysis of a saturated CT is not practical. Only "time to saturation" may be approximated with relative ease, and is used in some protection applications. More detailed analytical analysis is not in the realm of practical engineering.

Computer simulations are the only efficient way to extract the required information on secondary signals. These are burdensome for everyday engineering in the industrial domain. This paper uses computer simulation to derive simple and practical analysis and engineering charts to address the problem.

Figures 1 and 2 below present plots of the proportional secondary CT current, and the simulated secondary current for a 50:5, C10, CT with a 0.2ohm resistive burden under the fault current of 10 times nominal current (without and with full dc offset, respectively). This poor performance CT with this particular burden saturates slightly under 500A ac current (Figure 1), and accordingly more when full dc offset is present in the primary current (Figure 2). This document uses a digital model of a CT. More information on the model and its validation can be found in Section 7.

Figures 3 and 4 present the performance of the same CT under the fault current of 200 times the nominal, i.e. 10kA. Now, the saturation is much more severe.

This paper focuses on extreme cases of CT saturation, with primary current as high as 1000 times the rated value. Figures 5a through 6b present a series of secondary currents superimposed on the ratio current. The primary current ranges from 200 to 1500 times the CT rating (10kA to 75kA in this case). All traces are rescaled to the peak of the ratio current for easy visualization (in this way all currents have the same graphical scale). Figure 5 is for symmetrical currents, and Figure 6 for the fully offset currents.

These figures illustrate severity of the problem. The secondary current is as low as 5-8% of the expected ratio current, and exhibits spikes shorter than 1ms when the fault current is as high as 75kA. Please note that this 50:5, C10, CT has a burden of 0.2ohms, virtually making it into an IEEE C57.13 "C5 relay class" equivalent.

It is important to observe that the secondary current, despite being extremely low compared with the fault current, is still very large compared with the CT and relay ratings:

> For example, consider a fully offset 75kA current and a 50:5, C10, CT of Figure 6b. The peak value of the secondary current is only about 5% of the peak value of the fault current, but this translates to 0.05*75kA*$\sqrt{2}$ / (50:5) = 530A peak secondary, or 530A peak/($\sqrt{2}$ *5A) = 75 times rated value of the relay. This is a substantial current considering a typical conversion range of a microprocessor-based relay is 20-50 times the rated current. Figure 7 shows the relation between the peak value of the secondary current, and peak value of the ratio current for the simulated CT (10kA-75kA range).

Consider however, that it is the short duration of the peaks of the secondary current, not the low magnitude of those peaks that is important from the point of view of the signal strength delivered to the relay.

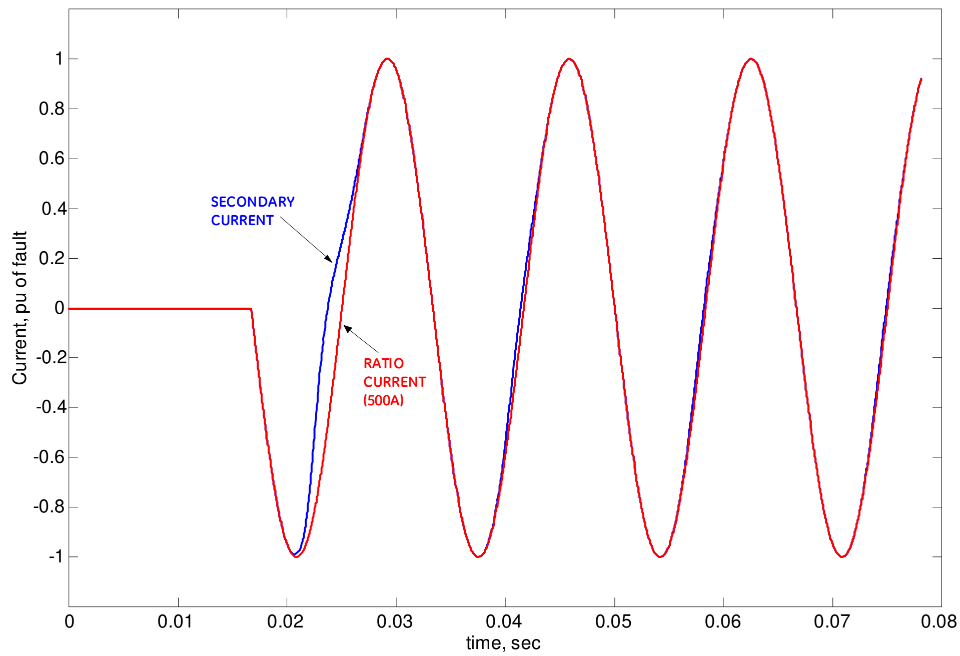

Fig.1. 50:5, C10, CT with a burden of 0.2ohms under fault current of 500A (symmetrical).

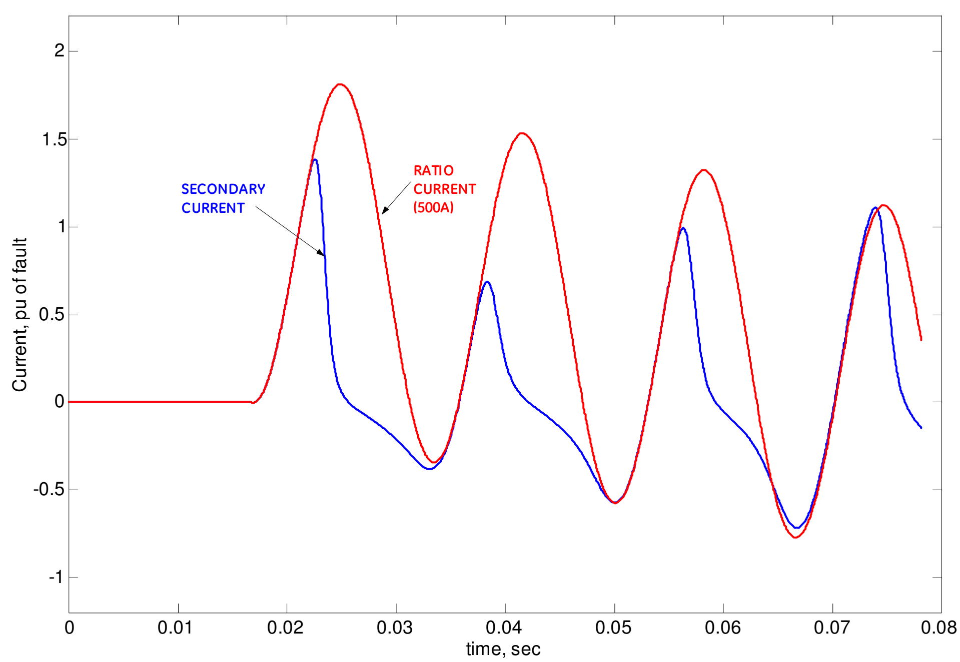

Fig.2. 50:5, C10, CT with a burden of 0.2ohms under fault current of 500A (fully offset).

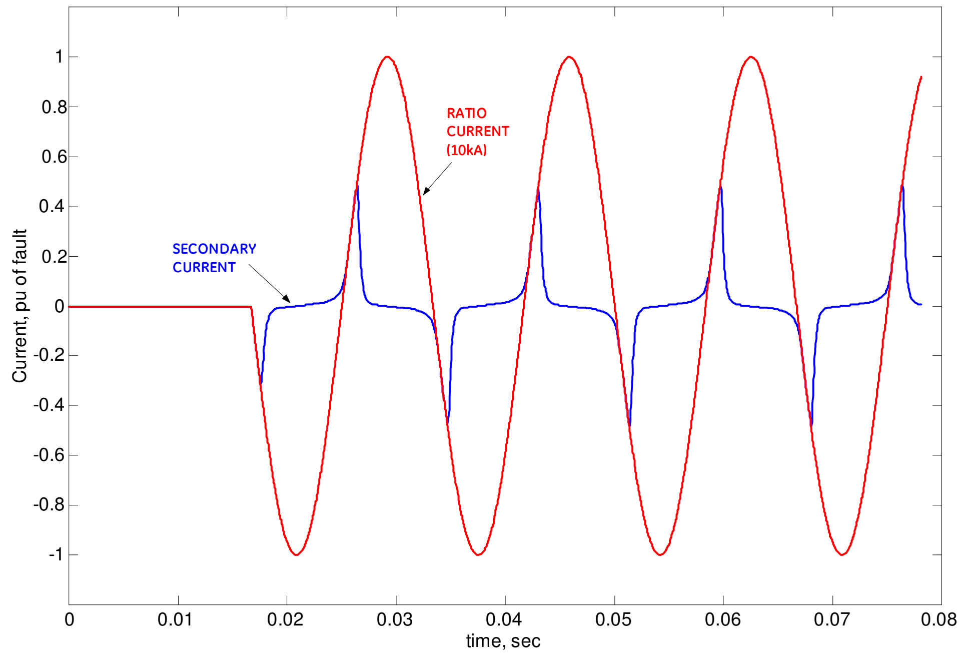

Fig.3. 50:5, C10, CT with a burden of 0.2ohms under fault current of 10kA (symmetrical).

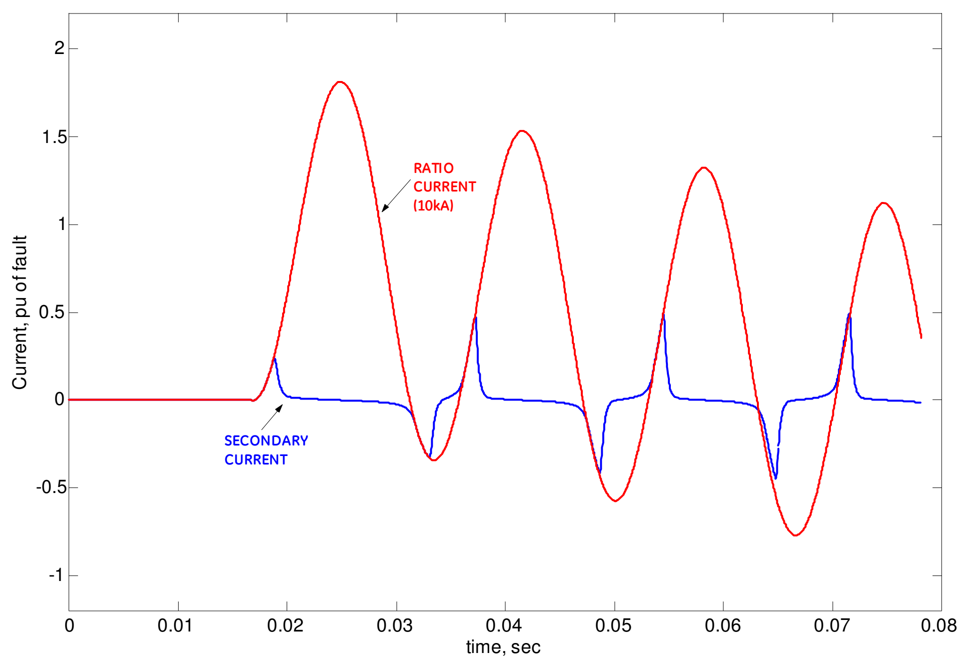

Fig.4. 50:5, C10, CT with a burden of 0.2ohms under fault current of 10kA (fully offset).

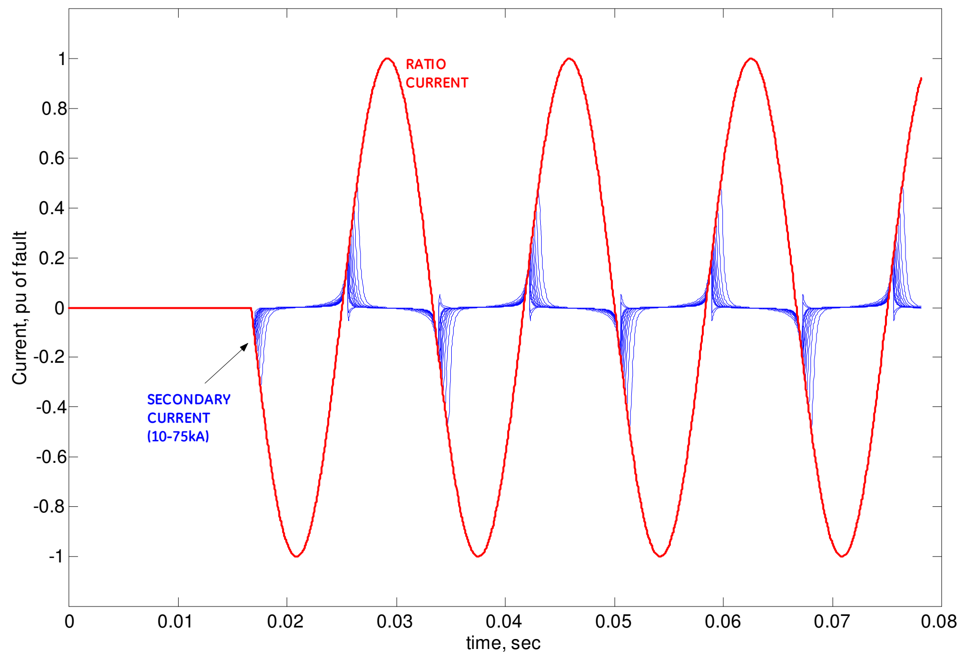

Fig.5a. 50:5, C10, CT with a burden of 0.2ohms under fault current up to75kA (symmetrical).

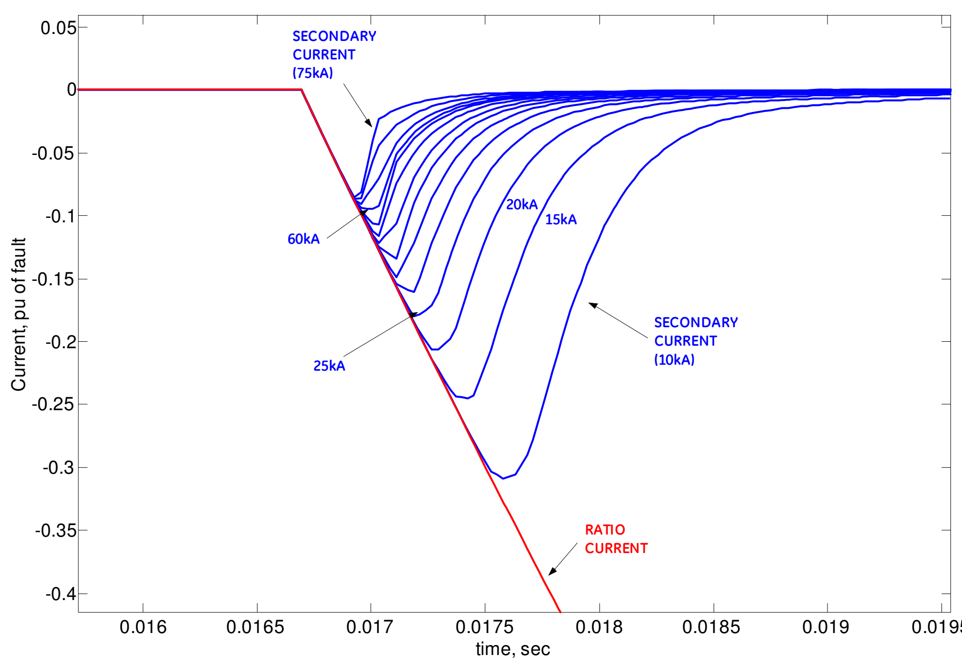

Fig.5b. 50:5, C10, CT with a burden of 0.2ohms under fault current up to75kA (symmetrical). First half-cycle of the secondary current.

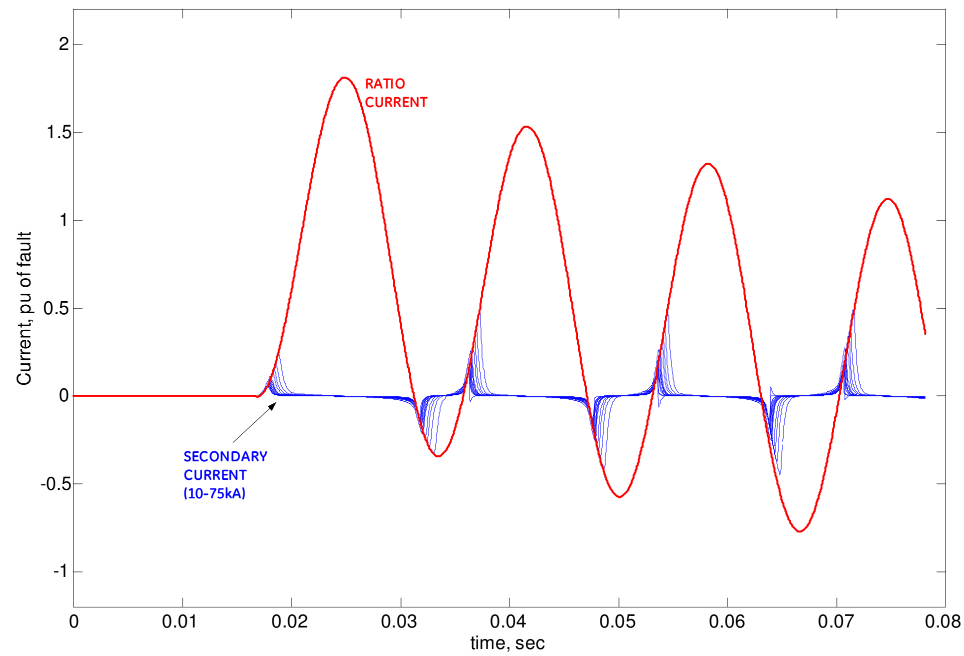

Fig.6a. 50:5, C10, CT with a burden of 0.2ohms under fault current up to75kA (fully offset).

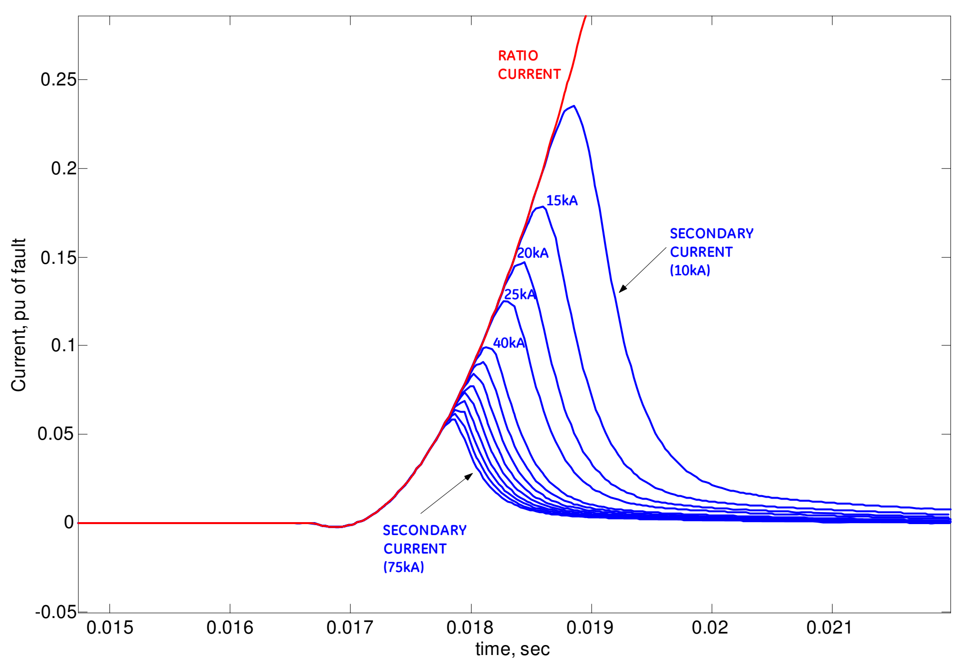

Fig.6b. 50:5, C10, CT with a burden of 0.2ohms under fault current up to75kA (fully offset).
First half-cycle of the secondary current.

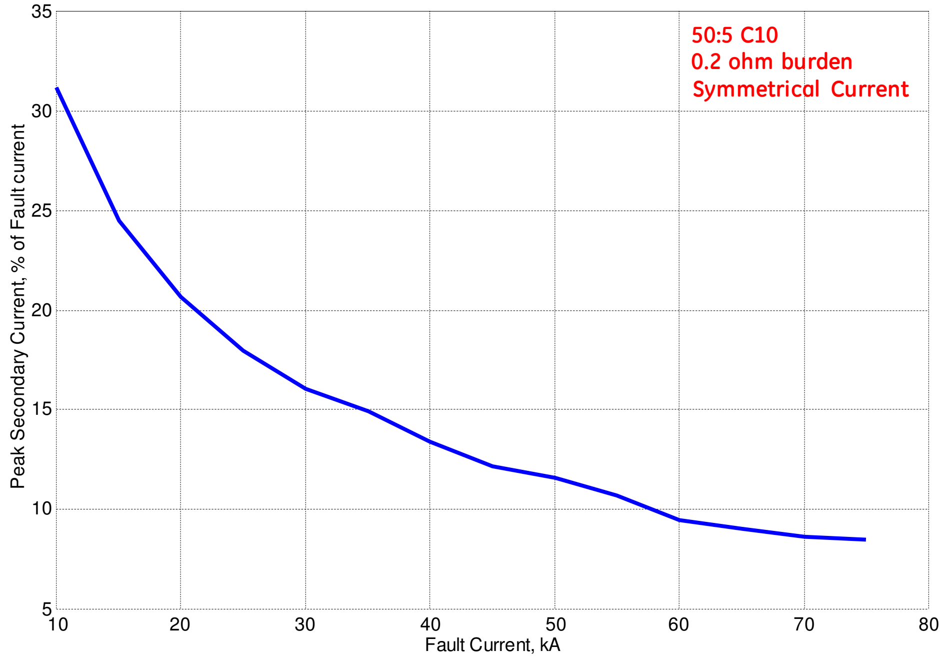

Fig.7a. 50:5, C10, CT with a burden of 0.2ohms: relation between the peak secondary current and peak fault current (symmetrical waveform).

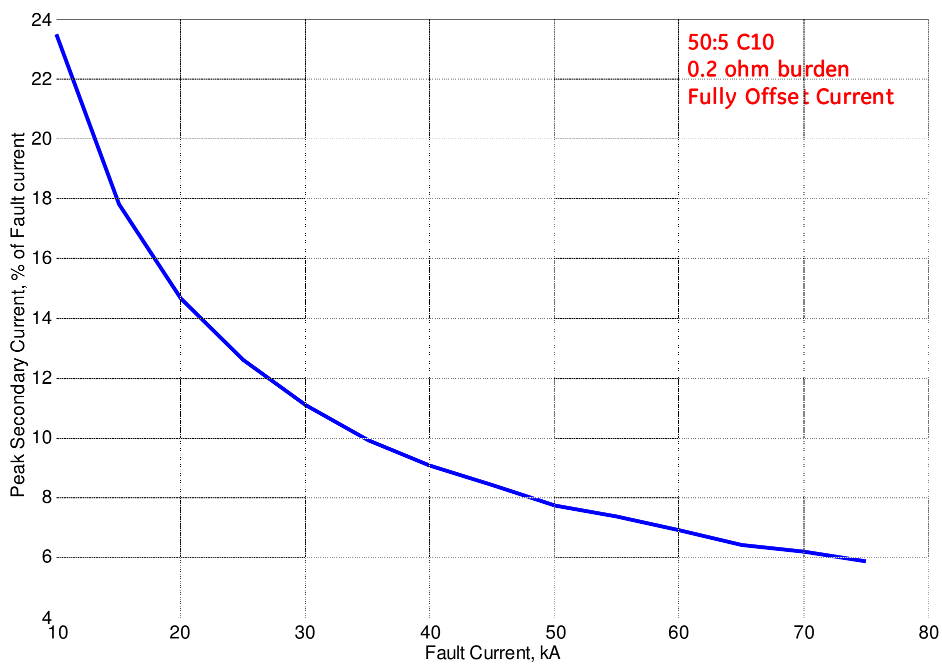

Fig.7b. 50:5, C10, CT with a burden of 0.2ohms: relation between the peak secondary current and peak fault current (fully offset waveform).

3. Microprocessor-Based Relays and Saturated Current Waveforms

As explained and illustrated in the previous section, low-ratio CTs pass proportionally less and less signal energy to the relay when the primary current increases dramatically. In an extreme case of the fault current being 1000 times the CT rating, only a small percent of this current, in the form of short spikes, would be delivered to the relay. This section explains and illustrates how a typical microprocessor-based relay responds to such waveforms. Response of Instantaneous Overcurrent functions is of primary interest.

With reference to Figure 8 a typical relay incorporates input current transformers (galvanic isolation), analog filters (anti-aliasing), A/D converter, magnitude estimator possibly with digital pre-filtering, and an Instantaneous Over-Current (IOC) comparator.

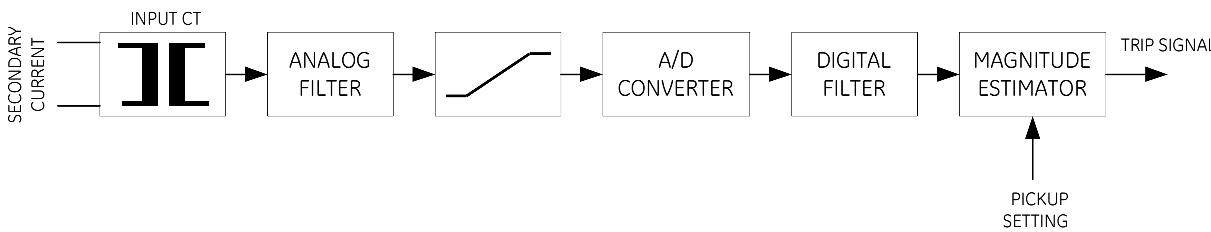

Fig.8. Signal processing chain of a typical relay.

3.1. Impact of Relay Current Transformers

In general, the relay input CTs may saturate adding to the complexity of the analysis, and to the scale of the problem. However, saturation of relay input CTs may be neglected for the following reasons:

The secondary current is substantially reduced under severe saturation of main CTs. Moreover, saturation of the main CT makes the secondary current symmetrical eliminating the danger of exposing the relay input CT to decaying dc components. And thirdly, the secondary current has a form of short lasting spikes. This limits the flux in the cores of the relay inputs CTs.

For example, consider the case of Figure 5. Under say 75kA of symmetrical fault current the secondary current is approximately a series of triangular peaks of about $0.08*75kA*\sqrt{2}$ / (50:5) = 848A secondary, lasting approximately 0.5-1ms. Assuming 1ms duration of these spikes, the true RMS of this secondary signal is only 120A, or 24 times the 5A rated of the relay input.

In reality, the relay input CT would have some impact on the response of the relay. Frequency response, i.e. ability to reproduce the short lasting input signal, may play a role.

The theoretical analysis of this paper neglects the impact of relay input CTs it is believed to be small. This is confirmed through testing of actual relay hardware.

3.2. Impact of the Analog Filter

Analog filters are implemented in order to prevent aliasing of higher frequencies on the fundamental frequency signal. Typically, a second order filter is used with a cut-off frequency of about 1/3rd of the sampling rate.

Analog filters have a positive impact on the response of the relay to heavily saturated current waveforms. Due to its intended low-pass filtering response, the analog filter reduces the peak values of its input signal and lengthens the duration of such spikes. In a way, the analog filters smoothes out the waveform by shaving its peaks and moving the associated signal energy into the area of lower magnitude. This phenomenon is illustrated in Figure 9. Given the fact that the peak magnitude of spikes is well above the conversion level of the relay, and as such it is not used by the relay when deriving the operating quantity, the operation of shifting some signal energy from the peaks into the low magnitude area would increase the operating signal, and improve the overall response of the relay.

Figure 9 assumes a linear analog filter, i.e. a filter that would not saturate despite of the high magnitude of its input. Most filters, however, are designed using active components (operational amplifiers) and will saturate on waveforms such as the one of Figure 9. Figure 10 shows response of a simplified model of such filter (clamping of the input signal to a linear filter). As seen in the figure, the signal is reduced even more. What is important, the analog filter shifts some portion of the signal energy into the low magnitude region when it is measured and utilized by the relay.

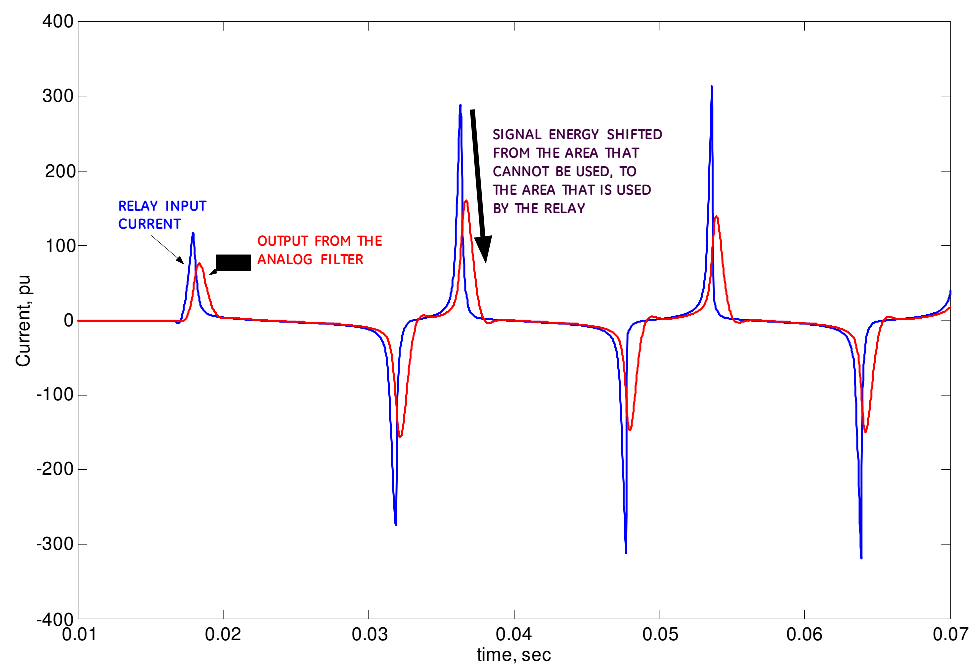

Fig.9. Impact of a linear analog filter on the saturated current waveform (64kA fault current; C10, 50:5, CT with 0.2ohm burden).

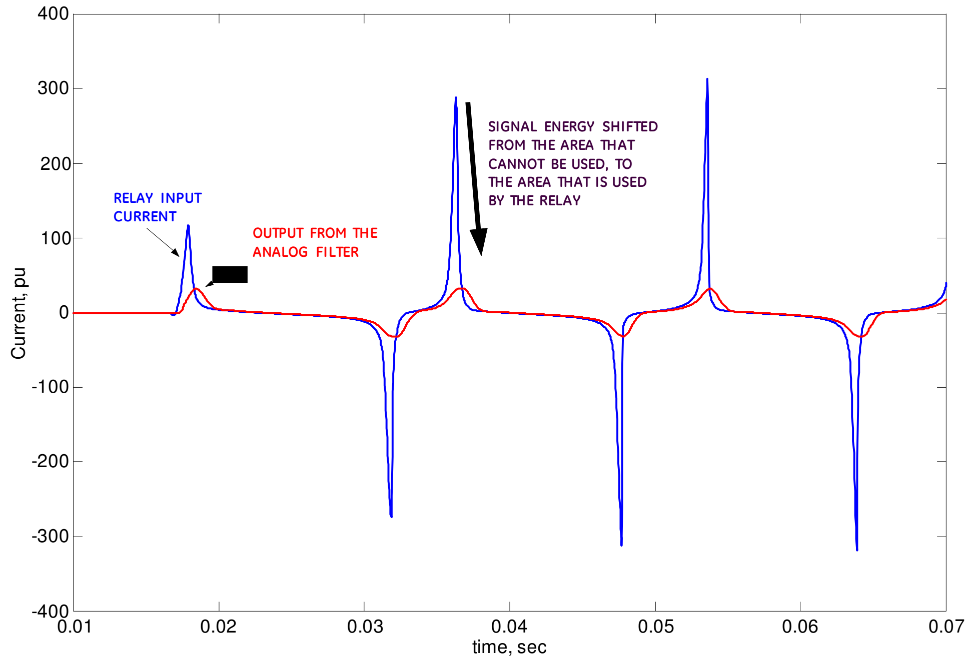

Fig.10. Impact of a linear analog filter on the saturated current waveform (a simplified model of a non-linear filter).

3.3. Impact of the A/D Converter

The impact of the A/D converter is twofold. First, any converter has a limited conversion range where signals above a certain level are clamped. This is similar to the response of the analog filter in front of the A/D converter (saturation of the amplifiers). The conversion range of today's relays is typically in the 10-50 span. For example, the GE 469 Motor Management Relay clamps the inputs at $28.3 * \sqrt{2} * 5A = 200A$ secondary peak, assuming the 5A rated current.

Figure 11 illustrates the impact of the A/D clamping on the signal processed by a given relay. The second aspect related to the A/D conversion is a limited sampling rate. Today's relays sample at rates varying from 8 to 128 samples per cycle. Industrial relays tend to sample at 8-16 times per cycle.

Given the short duration of the signal pulses produced by a heavily saturated CT, location of A/D samples on the waveform plays an important role. Consider Figures 12 and 13. In Figure 12 the samples lined up in a way that 3 samples in each cycle "caught" the peaks of the signal. In Figure 13 the samples lined up in a way that only 2 samples in each cycle aligned with the peaks. This will result in different values of the operating signal for the IOC function. In the analysis, the worst-case must be considered, and in this context, Figure 13 presents the worse condition.

It is also intuitively obvious that higher sampling rates give better chance to “integrate” the short lasting signal pulses and yield a higher operating signal, and thus better relay performance. This is illustrated in Figure 14 where the sampling is increased from 12 to 16 samples per cycle (s/c).

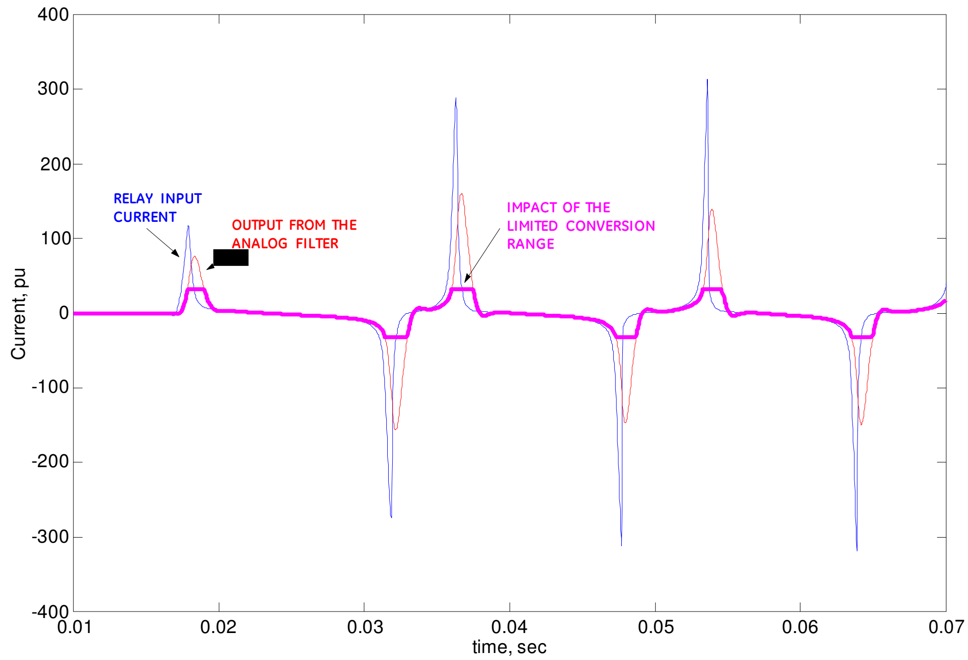

Fig.11. Impact of the A/D converter – clamping (case of Fig.9).

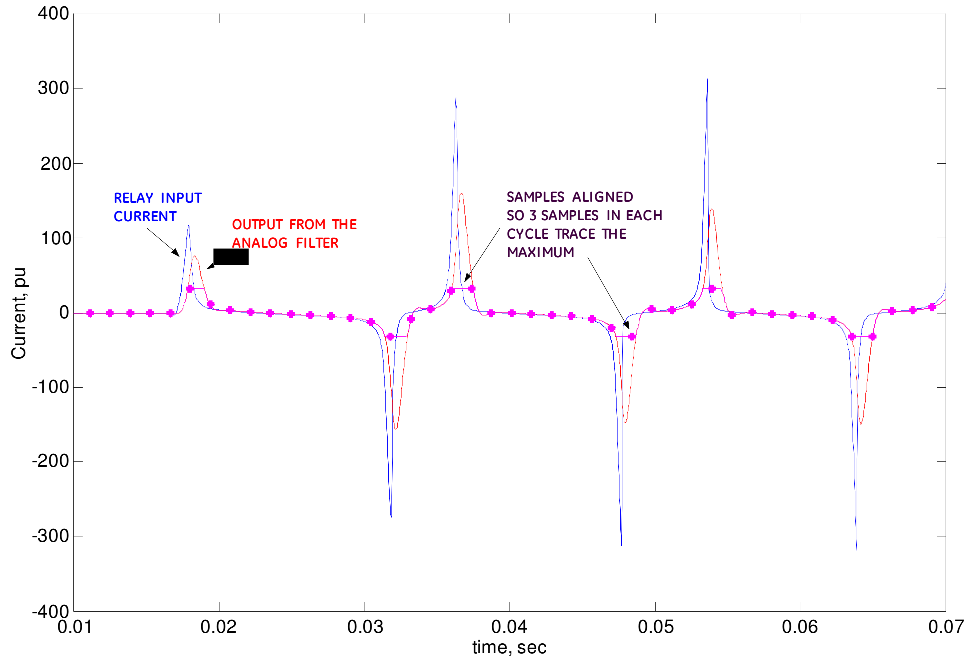

Fig.12. Impact of the A/D converter – sampling (case of Fig.9).

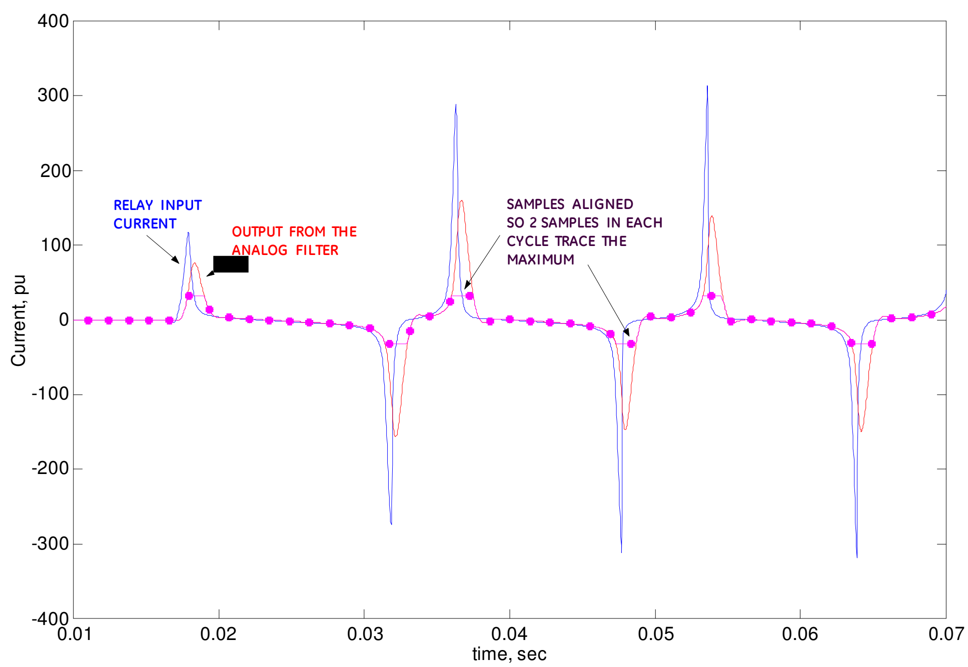

Fig.13. Impact of the A/D converter – samples aligned differently compared with Fig.12.

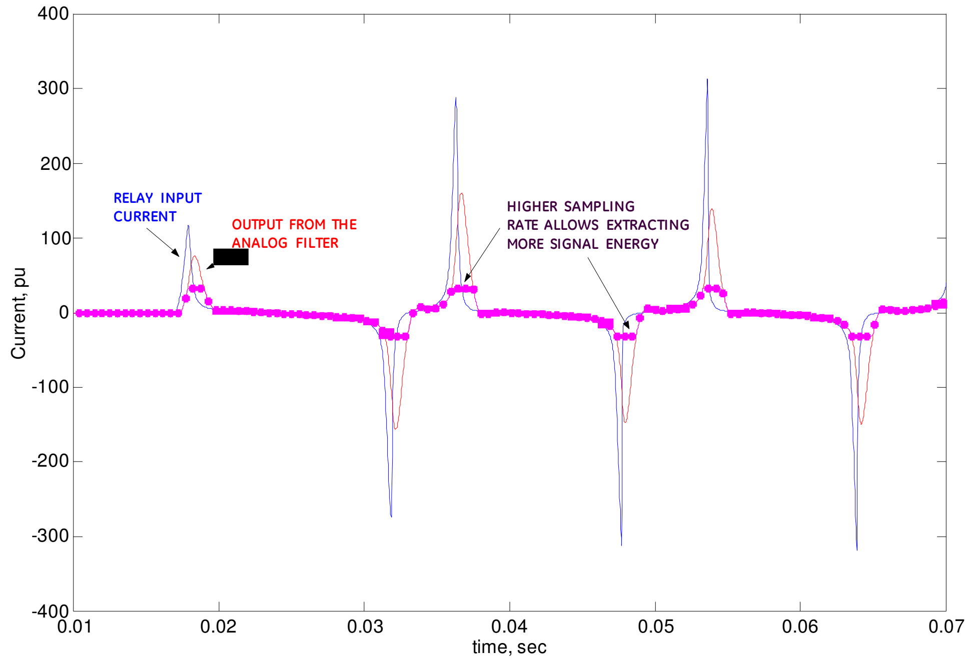

Fig.14. Impact of the A/D converter – higher sampling rate (case of Fig.9).

3.4. Impact of the Magnitude Estimator

Microprocessor-based relays calculate their operating signals, such the current magnitude for the IOC function, from raw signal samples. This process of estimation can include digital filtering for removal of the dc offset that otherwise would result in an overshoot. Typically a Fourier-type or RMS-type estimators are used.

The former extract only the fundamental component from the waveforms (60Hz) through a process of filtering. This would result in a much lower estimate of the magnitude if the waveforms were heavily distorted.

The latter extracts the total magnitude from the entire signal spectrum yielding a higher response under heavily saturated waveforms. The difference can be tenfold in extreme cases such as the ones considered in this paper.

Figure 15 shows an example of the estimation of a true RMS value. Please note that the relay is subjected to 64kA of fault current, and measures “only” 10-15 pu of current (50-75A secondary, or 500-750A primary). This is only about 1% of the true current, but still 10-15 times relay rated current.

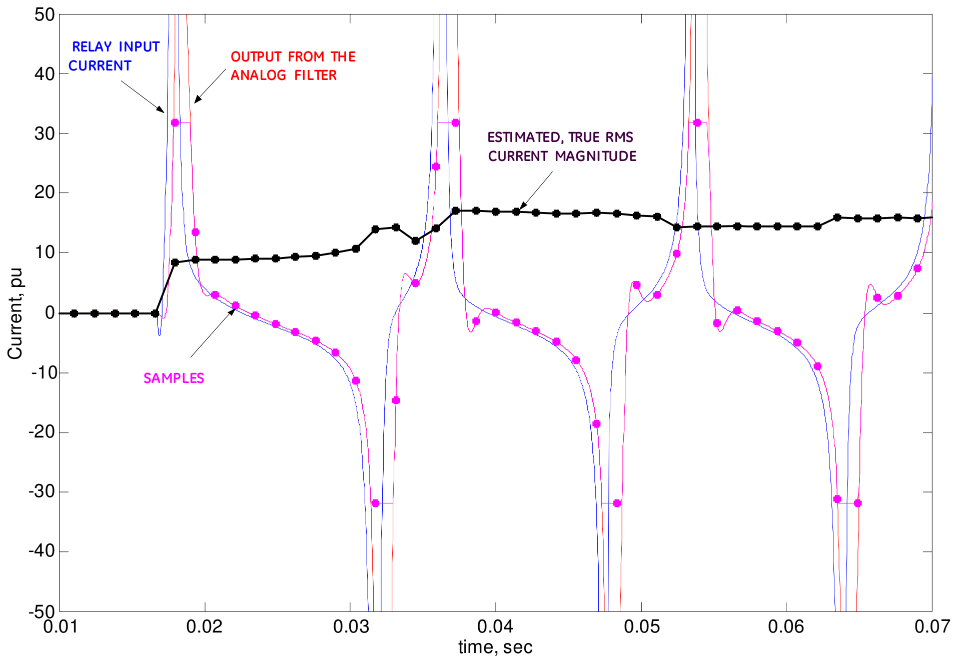

Fig.15. Example of amplitude estimation – true RMS algorithm (case of Fig.9).

3.5. Impact of the IOC Comparator

The derived operating current signal is compared against a user set threshold. Extra security may be implemented by requiring several consecutive checks to confirm the trip ("security counters"). This impacts when and for what current the relay would operate.

Another aspect is the rate at which the operating conditions are checked. They may be executed with each new sample, every other sample, once a cycle, etc. ("protection pass"). This again impacts if and when a given function operates if the current is not steady.

Intimate knowledge of the relay inner workings is required to analyze this, as well as the previously discussed aspects of the relay response.

The next section proposes a methodology for reduction of the many factors impacting response of a given relay to waveforms produced by a given CT in order to facilitate practical analysis and application in the field.

4. Method of Quantifying Response of IOC Protection Under CT Saturation

This section presents a methodology for reduction of the many factors impacting response of a given relay to waveforms produced by a given CT in order to facilitate practical analysis and application in the field.

As shown in the previous subsection, any given relay reduces the signal coming from the CT to a series of pulses. These pulses are further limited in magnitude by the conversion range of the relay, while their duration is impacted by the natural inertia of the analog input circuitry of the relay (input transformers, analog filters). As a result considerable variability is removed in the A/D samples in response to the CT parameters. Additionally, a typical relay applies averaging when deriving its operating quantities (such as the true RMS). This reduces variability even further.

The above observation facilitates the following method of quantifying response of any given relay to any given CT. The method starts with a portion to be completed by relay manufacturers as follows:

1. Assume a nominal burden of a given CT. Under different burden, a given CT could be always re-rated by the application engineer based on the known principles.
2. Simulate the CT with and without dc offset in the primary current. Assume a typical X/R ratio for industrial applications (X/R = 15). Repeat for different ratios if required.
3. Vary the ac component in the primary current from the CT rated value up to 64kA.
4. Use a digital model of a given relay, or the actual relay, to find the operating quantity of an IOC function for a given fault current. When simulating, consider the minimum measured value within the timing spec of the IOC function. When testing the actual hardware, look for consistent operation within the timing specification of the relay.
5. Vary the alignment of samples with respect to the waveform in order to get the worst-case scenario. When simulating, explicitly align the samples in different patterns. When testing the actual relay, repeat the test several times to make sure the relay operates consistently.
6. The value found in step 5 is the highest setting that could be used for the IOC function to guarantee operation within the timing specification for a given fault current. This pair of fault current / maximum pickup setting becomes a point on the 2D chart.
7. Repeat the above for various fault currents. The obtained points constitute a characteristic for the considered CT and relay.
8. Repeat the above for various CTs obtaining a series of characteristics for the considered relay.

Figure 16 below shows the important signals for a certain relay fed from a 50:5 C10 with 0.2ohm burden under the symmetrical fault current of 1kA (or 20 times rated). Please note that this particular plot is for a burden different than nominal. The Figure shows that the relay would operate for this case within the timing specification as long as the setting is below 8pu. The (20pu,8pu) pair becomes a dot on the chart.

Figure 17 shows the same relay and CT under the current of 10kA (or 200 times rated). The Figure shows that the relay would operate for this case within the timing specification as long as the setting is below 15pu. The (200pu,15pu) pair becomes a dot on the chart.

Figure 18 shows the same relay and CT under the current of 50kA (or 1000 times rated). The Figure shows that the relay would operate for this case within the timing specification as long as the setting is below 14pu. The (1000pu,14pu) pair becomes a dot on the chart.

Repeating this for various fault currents, with and without dc offset, while varying the alignment between samples and waveforms, and plotting these as dots on the chart would divide the fault current / pickup plane into three regions: solid operation (A), intermittent or slow operation (B), and no operation (C) as depicted in Figure 19.

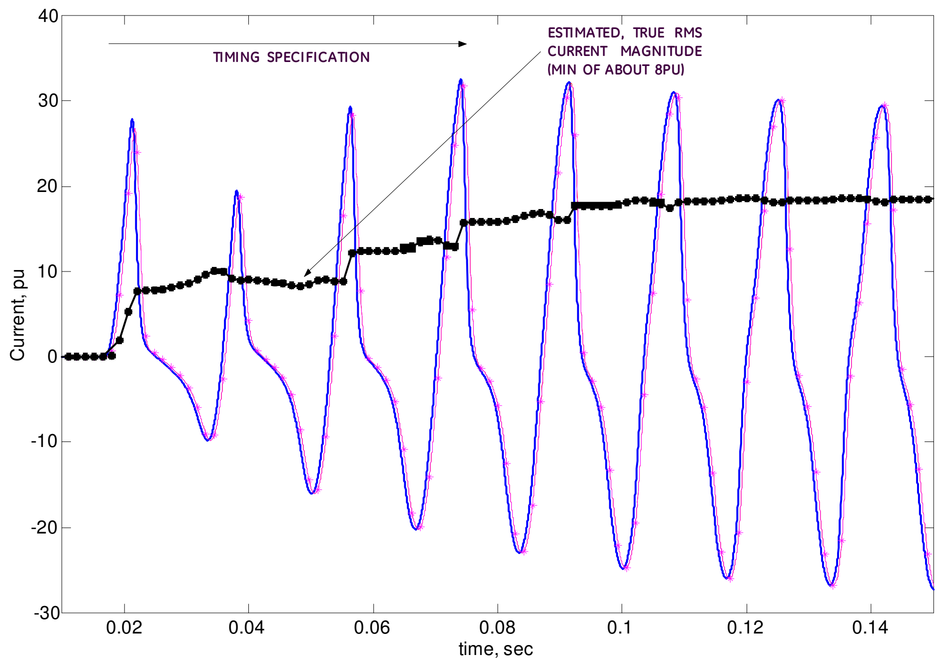

Fig.16. 50:5, C10 CT feeding a relay. Fault current of 1kA (20 times rated).

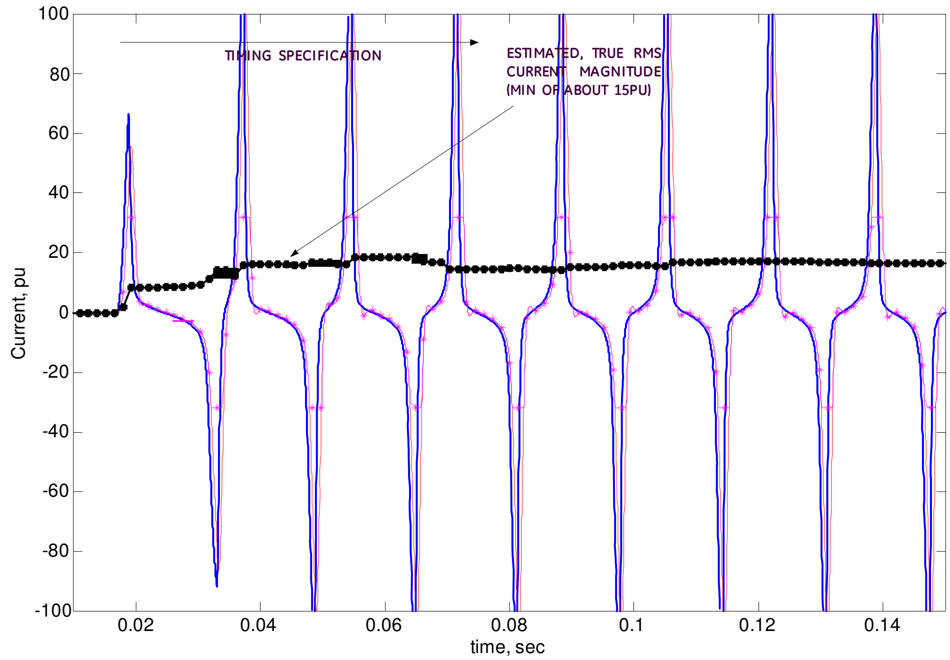

Fig.17. 50:5, C10 CT feeding a relay. Fault current of 10kA (200 times rated).

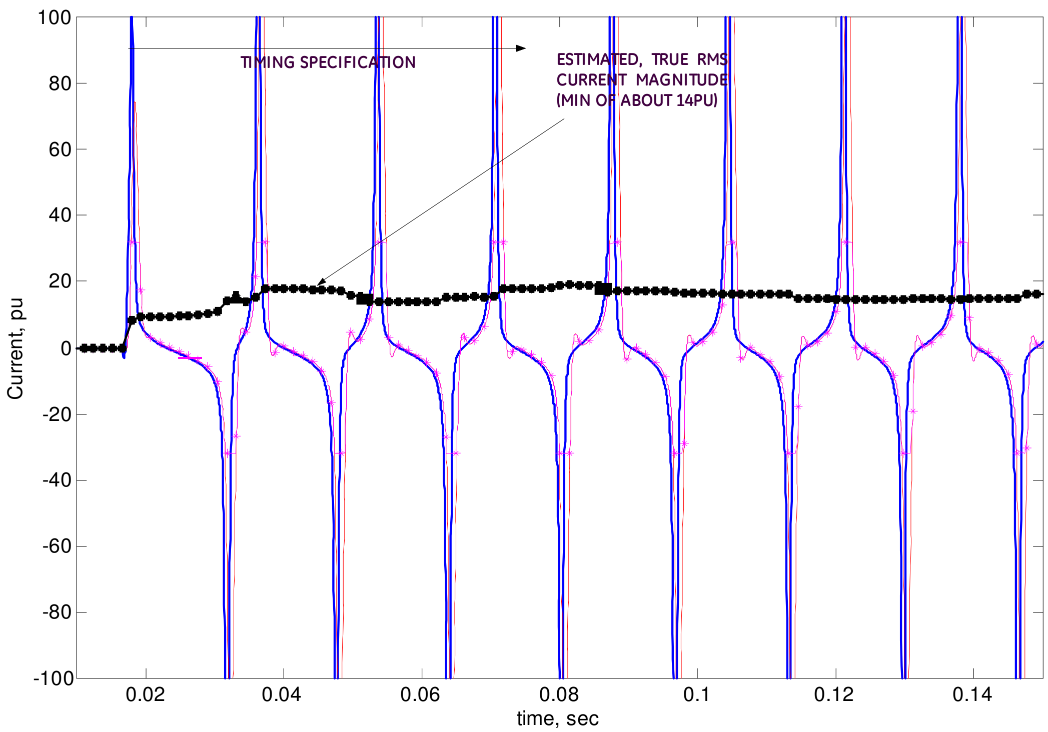

Fig.18. 50:5, C10 CT feeding a relay. Fault current of 50kA (1000 times rated).

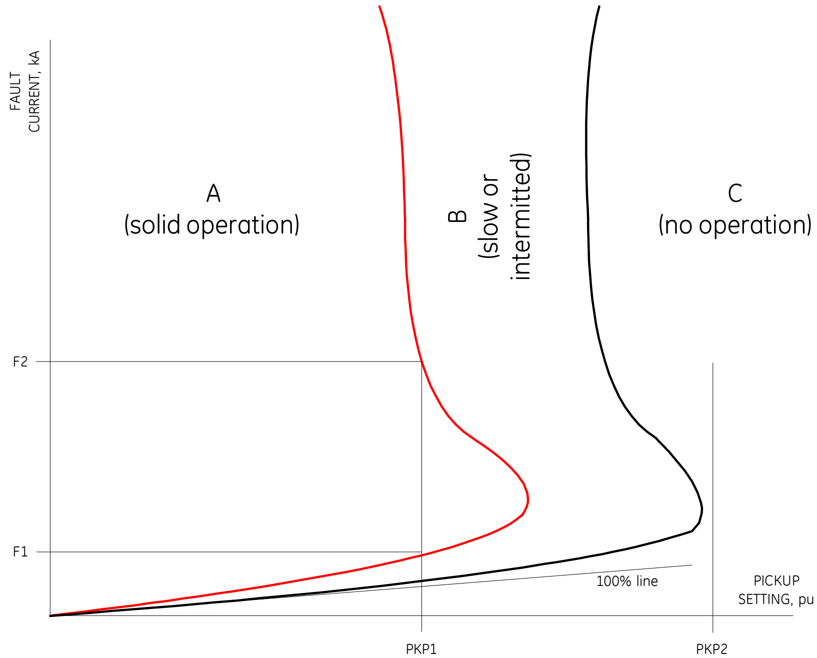

Fig.19. The concept of "fault current – IOC pickup" curves.

The fault current – IOC pickup curves are interpreted as follows: if the CT were perfectly linear, and the relay had an infinite conversion range, the relay would see exactly 100% of the actual primary current, and would operate if the fault current equals the entered IOC setting. This would constitute a straight line as shown in Figure 19. Due to CT saturation and the finite relay range, the relay sees less than the actual (ratio current), and thus needs more current than 100% of the setting in order to operate. Therefore, the curves climb up away from the 100% line.

If set to PKP1, the relay would operate as long as the fault current is above F1 value (crossing the pickup line), and the fault current is below F2 value (severe saturation decreasing the relay operating current below the pickup value).

If set to PKP2, the relay would never operate, because the operating value never goes above the PKP2 value: first, the current is to small; next the current is too large causing enough saturation to keep the operating quantity low.

Solid (guaranteed) operation of the IOC functions is of primary interest here. Therefore, the left line dividing solid operation form the intermitted operation shall be provided to the users as shown in Figure 20. Charts for different CTs shall be included on the same graph.

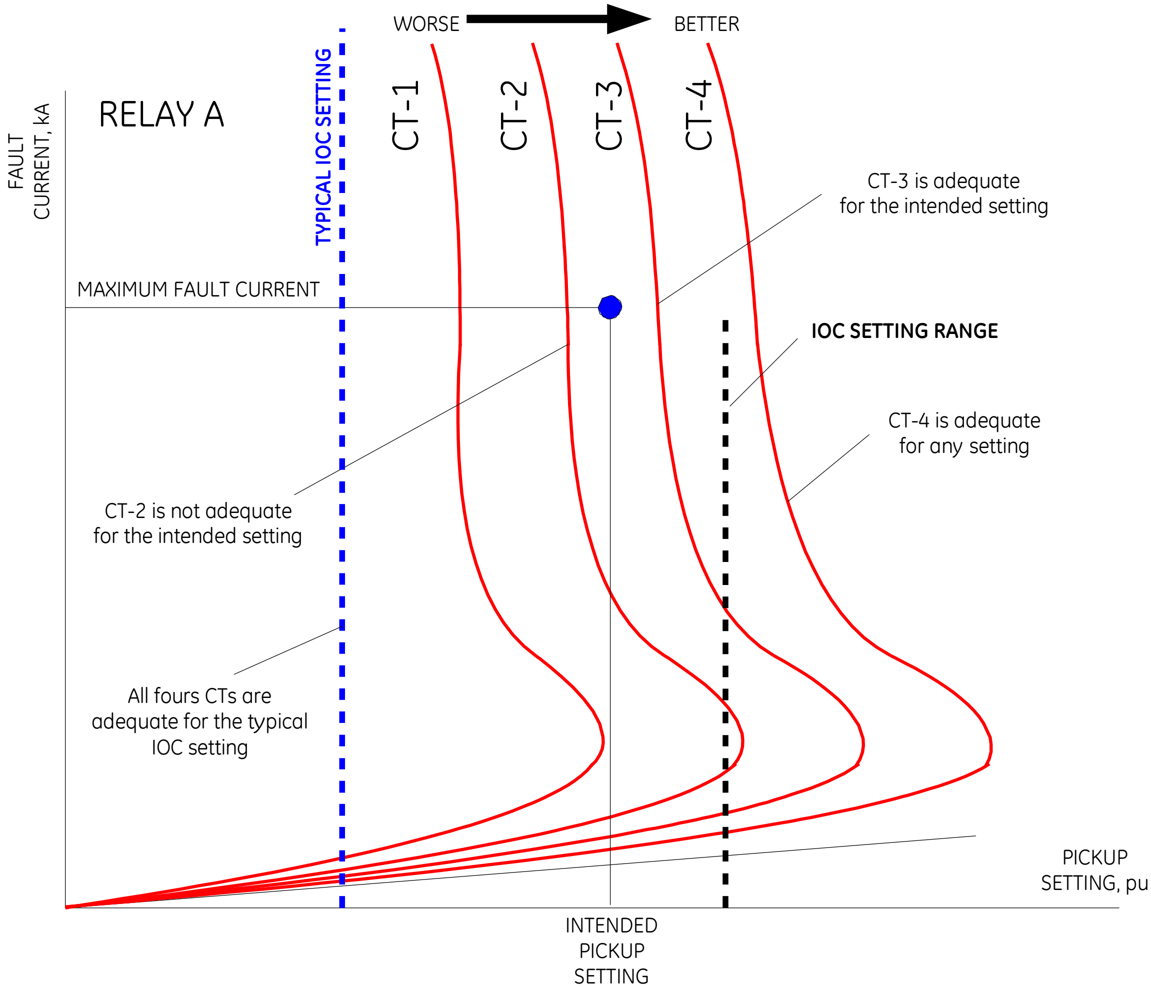

Fig.20. The concept of fault current – IOC pickup curves: Selecting CT for a specific relay, specific maximum fault level and specific pickup setting.

The user applies the chart as follows.

For an intended pickup level the user reads the fault current from the curve. If a fault of this magnitude happens, this particular relay fed from this particular CT would see just enough current to operate. This point defines the boundary of safe operation. If the actual maximum fault current is below that value, the application is safe; if above, the relay may trip slow or not at all for currents above the value from the chart.

If the application has a problem, the user could use a better CT. A family of curves shall be provided for various CTs. A CT shall be selected with the characteristic to the right of the intended pickup – maximum fault current point.

Please note that given the maximum fault current in Figure 20, CT-4 is adequate for any setting value (the CT-4 curve is located to the right from the maximum relay setting line). The CT-4 of this example is the lowest class / ratio CT that does not limit at all application of this particular relay. Vast majority of CTs of a given series fall into this category, and the curves are really needed only for the CTs below this borderline case.

Please note that given the typical IOC setting of 12pu or so used for short circuit protection of motors, all four CTs in the example of Figure 20 are adequate (even the CT-1 curve is located to the right from the typical setting line).

To understand better application of the curves, consider a relay and two CTs as in Figure 21. Assume a setting of 19pu is to be used on this particular relay fed from CT-1 on the bus with short circuit capacity of 50kA. Because the 50kA/19pu point is outside the CT-1 curve, this application is not secure. With this setting the relay would operate reliably up to the fault current of 15kA. This CT could be used with settings below 17.5pu.

If the 19pu setting is a must, and the short-circuit capacity is 50kA, CT-2 shall be used. It's curve is to the right of the 50kA/19pu point, meaning the relay would always operate for faults fed from this bus with a setting of 19pu.

Assume the CT-2 is used with this relay: The highest setting one could apply under any practical fault level is 21pu.

As illustrated above, the proposed fault current – pickup chart is a powerful tool to evaluate and adjust applications of IOC protection with low-ratio CTs.

The method can be used not only to match CTs to relays, but vice versa as well. For a given CT a series of curves can be produced that show the maximum allowable IOC setting for different relays and different fault current levels.

The CTs on the fault current – pickup charts shall be presented assuming nominal burdens. For varying burdens, the CT will get re-rated by an application engineer based on the well-known principles. For applications with long leads, the charts play a role in selecting proper wires in order to meet the required performance.

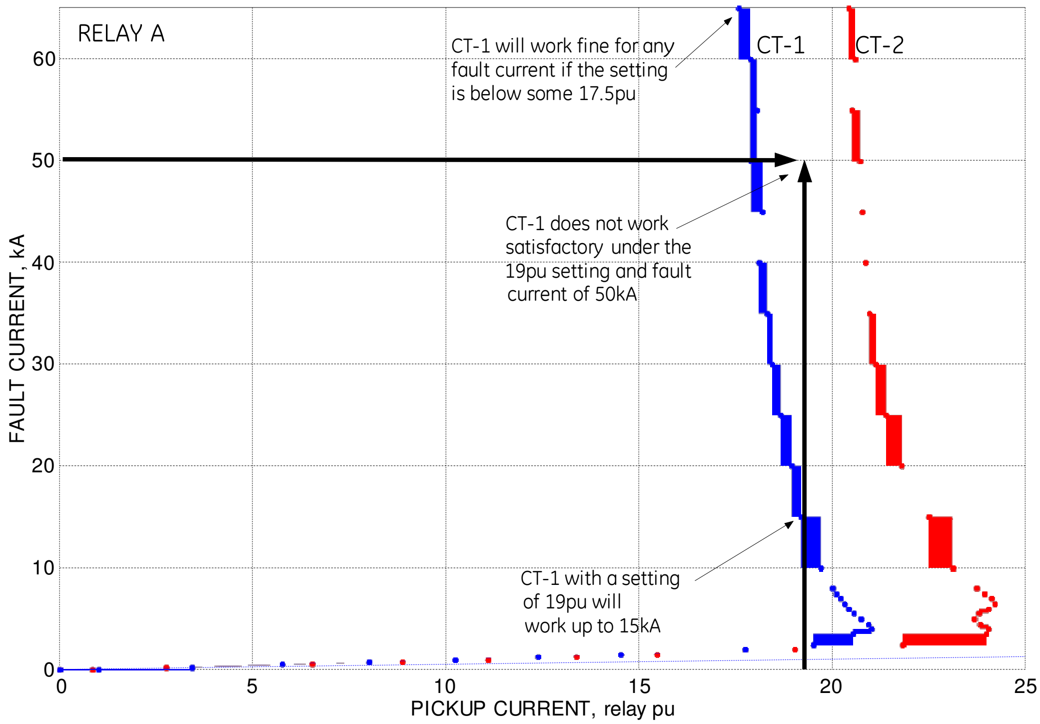

Fig.21. Using the fault current – pickup setting charts.

5. Analytical Analysis of Selected MULTILIN Relays

Several MULTILIN relays have been evaluated based on the approach outlined in the previous section. The evaluation assumes simplified model of relays giving consideration to their actual analog filters, conversion ranges, sampling rates, digital filtering and phasor estimators.

The analysis has been presented for 2 selected CTs (50:5, C10, 0.2ohm burden, and 50:5, C20, 0.2 ohm burden). Note, that these are relatively poor performance CTs. With the burden of 0.2ohms, the first CTs is equivalent to a "C5 class".

Figures 22 through 26 present the fault current – pickup charts for the 469, 489, 369, 239 and 750 relays.

It is clear from the figures that using very low-ratio CTs prevents applying the relays with settings above some 80% of the setting range. For example, with the 50:5, C10, 0.2 ohm CT applied in a 64kA switchgear, the 469 can be set as high as 17pu. The typical setting is considerably lower (some 12pu) which makes the application secure.

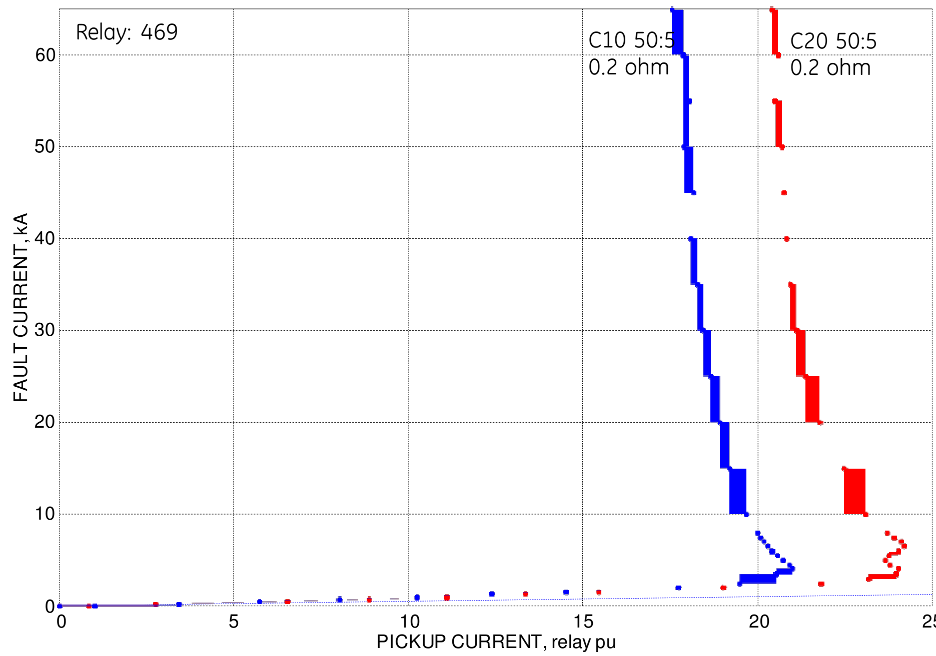

Fig.22. Fault current – pickup charts for the 469 relay (f/w 5.0, h/w rev. I) and two sample CTs (relay setting range for IOC is 20pu). Application in 60Hz systems.

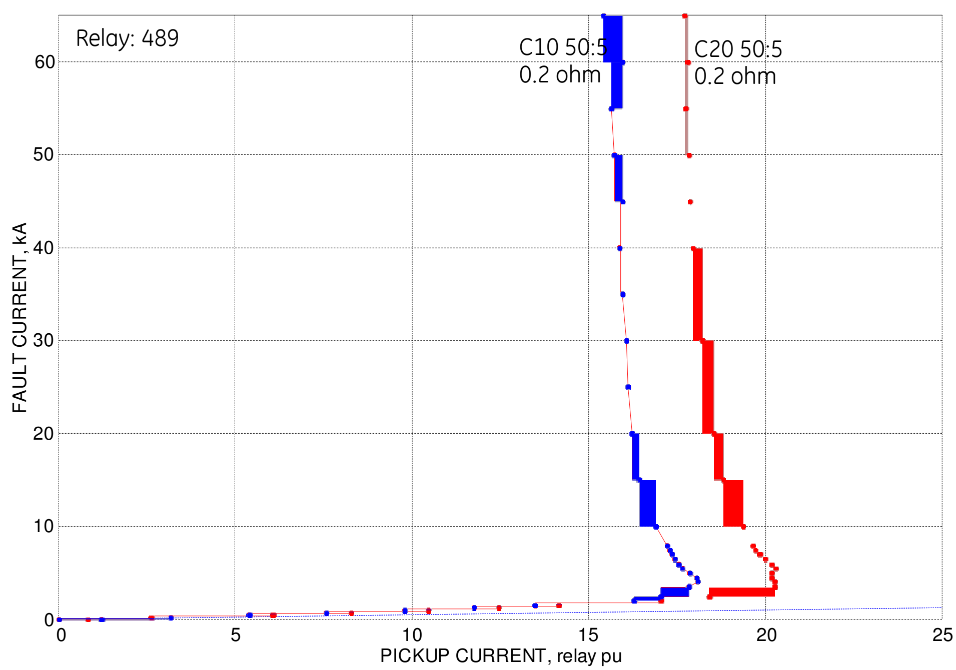

Fig.23. Fault current – pickup . charts for the 489 relay (f/w 1.53, h/w rev. I) and two sample CTs (relay setting range for IOC is 20pu). Application in 60Hz systems.

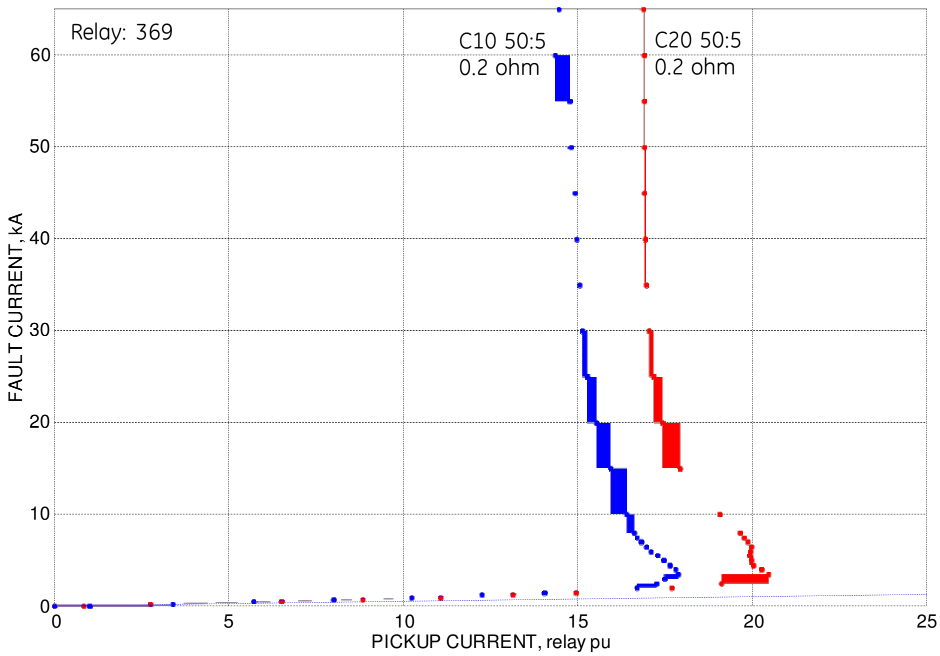

Fig.24. Fault current – pickup charts for the 369 relay and two sample CTs (relay setting range for IOC is 20pu). Application in 60Hz systems.

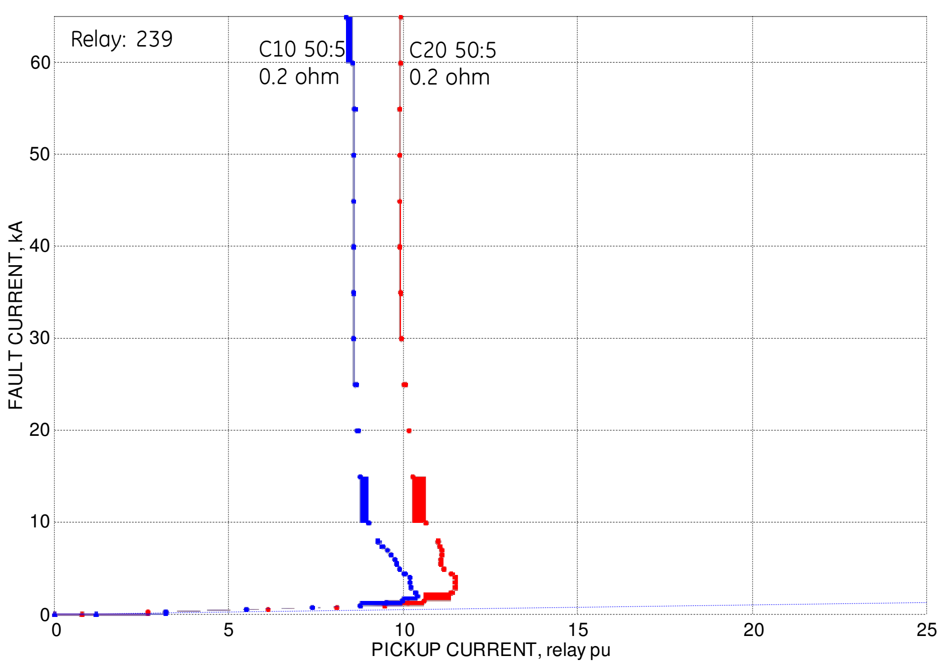

Fig.25. Fault current – pickup charts for the 239 relay and two sample CTs (relay setting range for IOC is 11pu). Application in 60Hz systems.

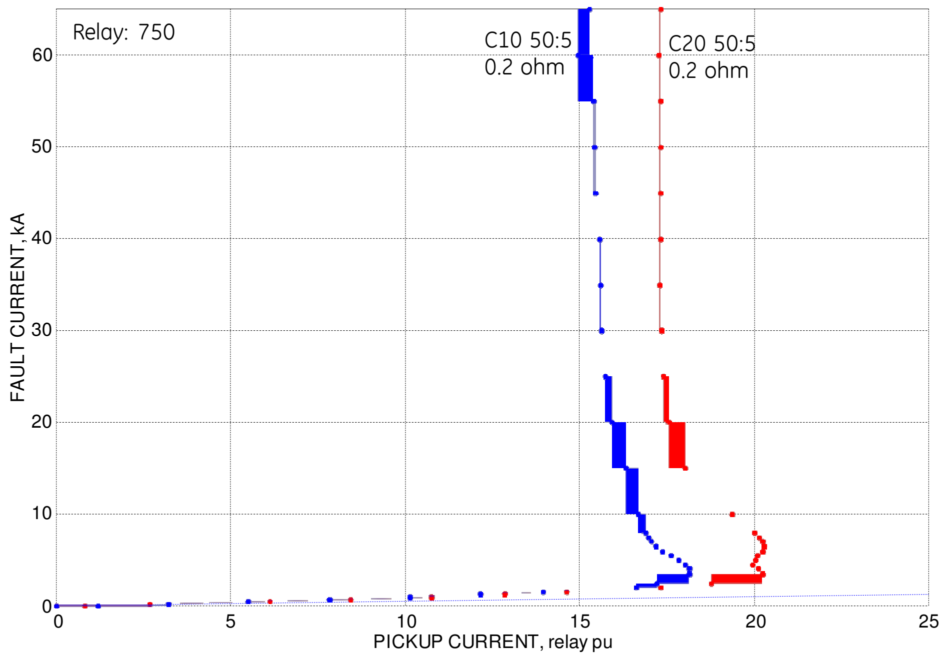

Fig.26. Fault current – pickup setting charts for the 750 relay and two sample CTs (relay setting range for IOC is 20pu). Application in 60Hz systems.

6. Test Results for Selected MULTILIN Relays

The analysis of section 5 has been validated on the actual relay hardware. Figures 27 and 28 present results (for currents up to 200 times the rated) for the 469 and 369 relays. It could be seen that the theoretical prediction and response of the actual relay match well in the tested region of the chart.

The relays have been tested as follows: A given saturated waveform is played back to the relay; an IOC setting is decreased from the maximum available on the relay to the point when the relay starts operating consistently, and all responses are within the published trip time specification. This setting is considered a solid operation point. The fault current – solid operation pickup point is put on the chart, and the process continues with the next fault level.

The relays were tested using playback of waveforms generated from a digital model of the CT. This model was verified as well in order to gain absolute confidence in the accuracy of the presented charts.

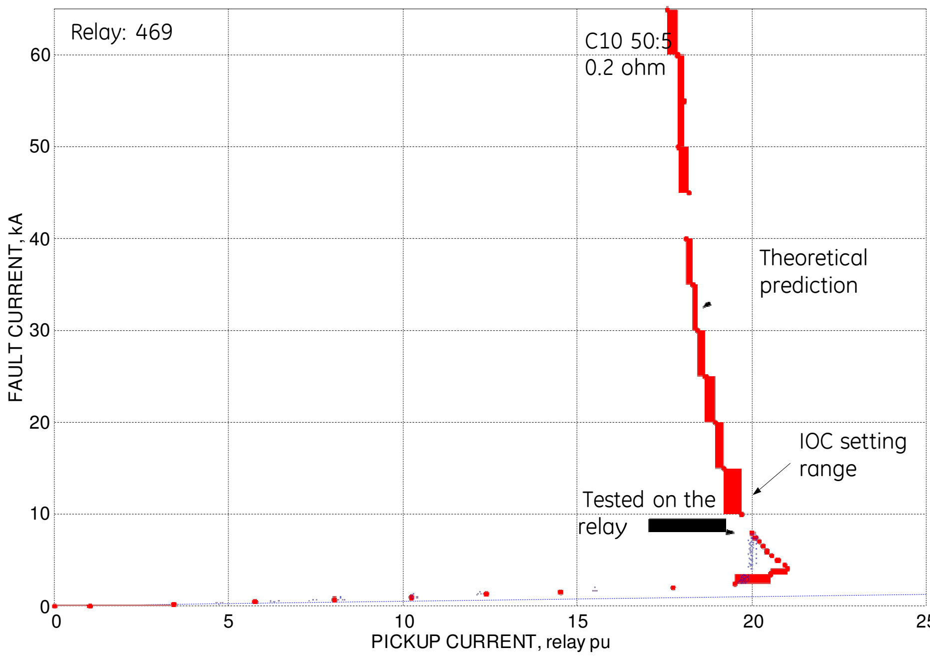

Fig.27. Fault current – pickup charts for the 469 relay (f/w 5.00, h/w rev. I) and a sample ITI CT (theoretical analysis vs relay test results). Application in 60Hz systems.

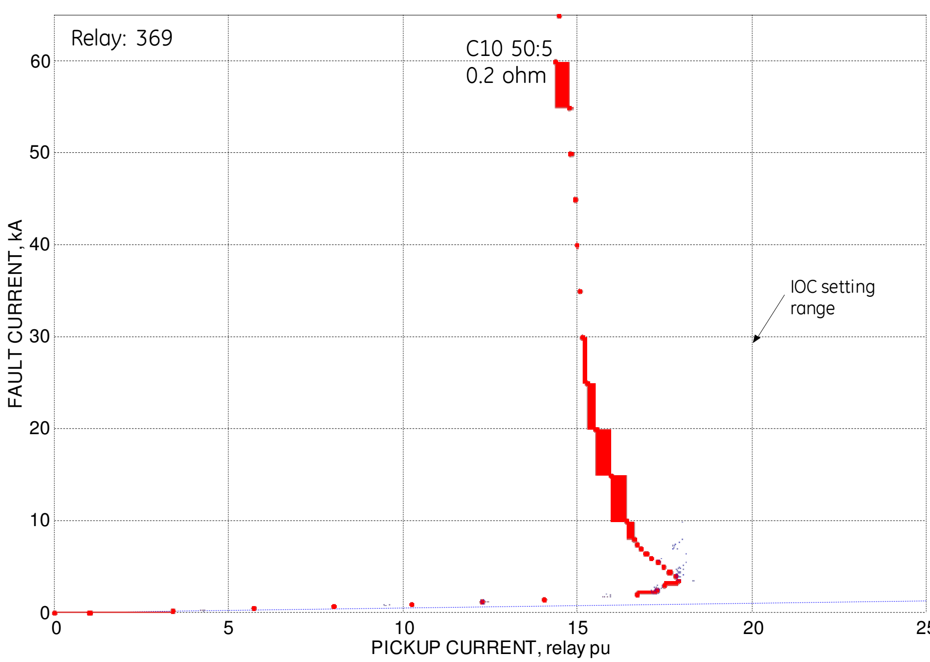

Fig.28. Fault current – pickup charts for the 369 relay and a sample CT (theoretical analysis vs relay test results). Application in 60Hz systems.

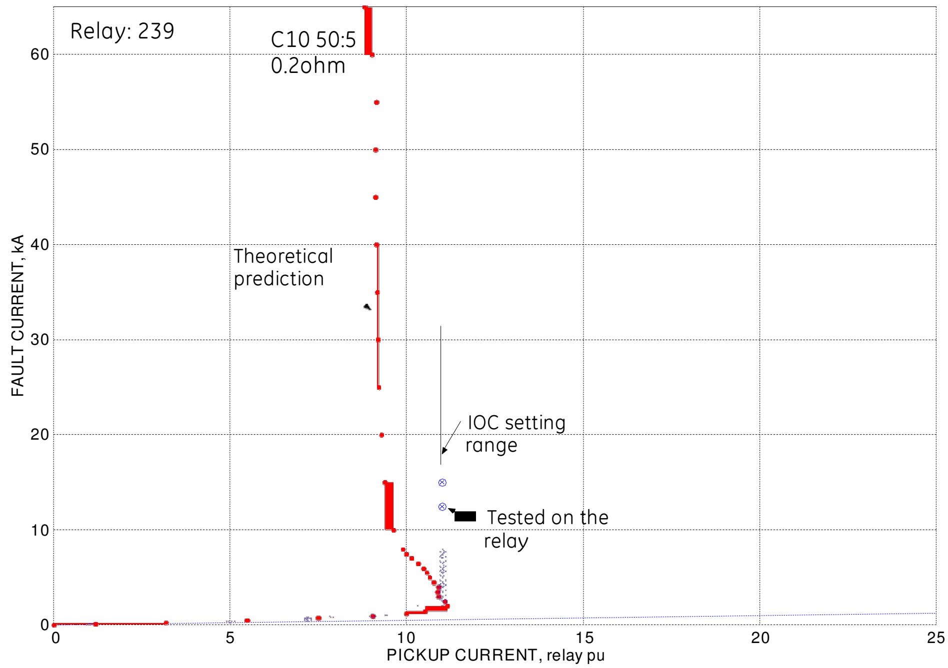

Fig.29. Fault current – pickup charts for the 239 relay and a sample CT (theoretical analysis vs relay test results). Application in 60Hz systems.

7. Validation of the CT model

Using an adequate CT model is critical to the accuracy of the analysis. CT modeling techniques are relatively precise when applied in the typical signal ranges, i.e. under currents up to few tens of the CT rated current. This paper assumes currents in hundreds of the rated value, and therefore calls for cautious approach to CT modeling.

The CT model used in this study is supported by the IEEE Power System Relaying Committee, and has been verified by multiple parties. It is justified to assume, however, that the verification was limited to relatively low current levels. The model shall be verified on fault currents as high as 800 rated in order to make sure the unusually high flux densities, and other aspects do not change the nature of the CT response compared with more regular situations. This must be done using actual CTs and high power testing equipment.

This section compares test results of a 50:5 C10 and a 50:5 C5 CT with the waveforms obtained from the digital model, in order to validate the model. The comparison is done for currents being hundreds of the CT rated.

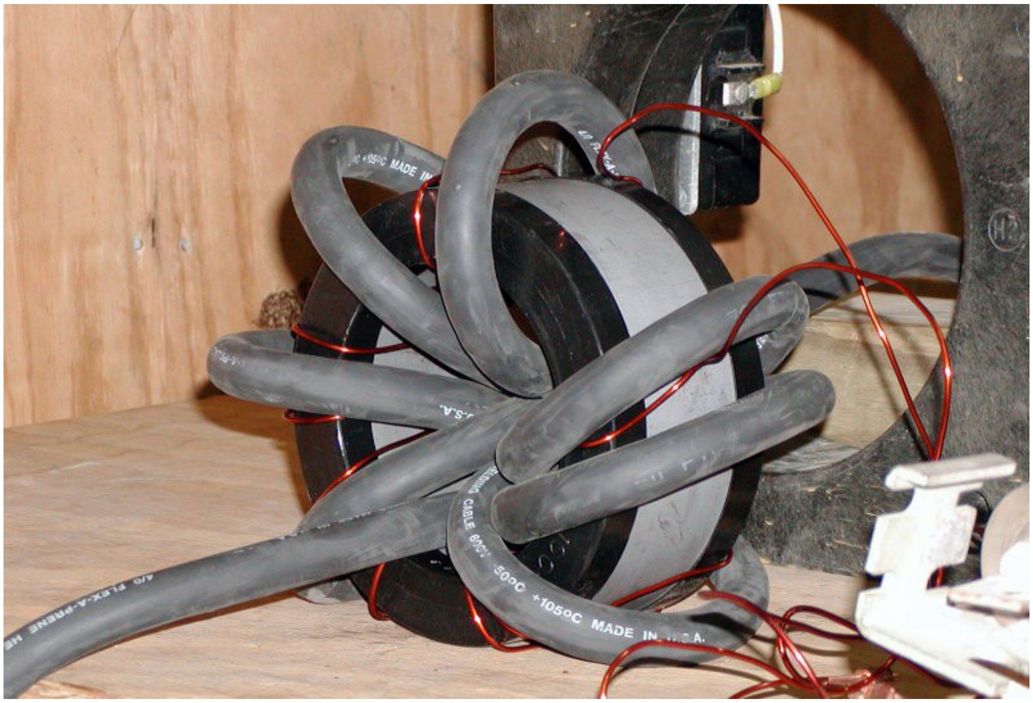

Fig.30. 50:5 C5 CT under test. Multiple primary turns (8 cable loops indicated) used to simulate effectively higher primary current. The reference CT is visible to the right of the CT under test.

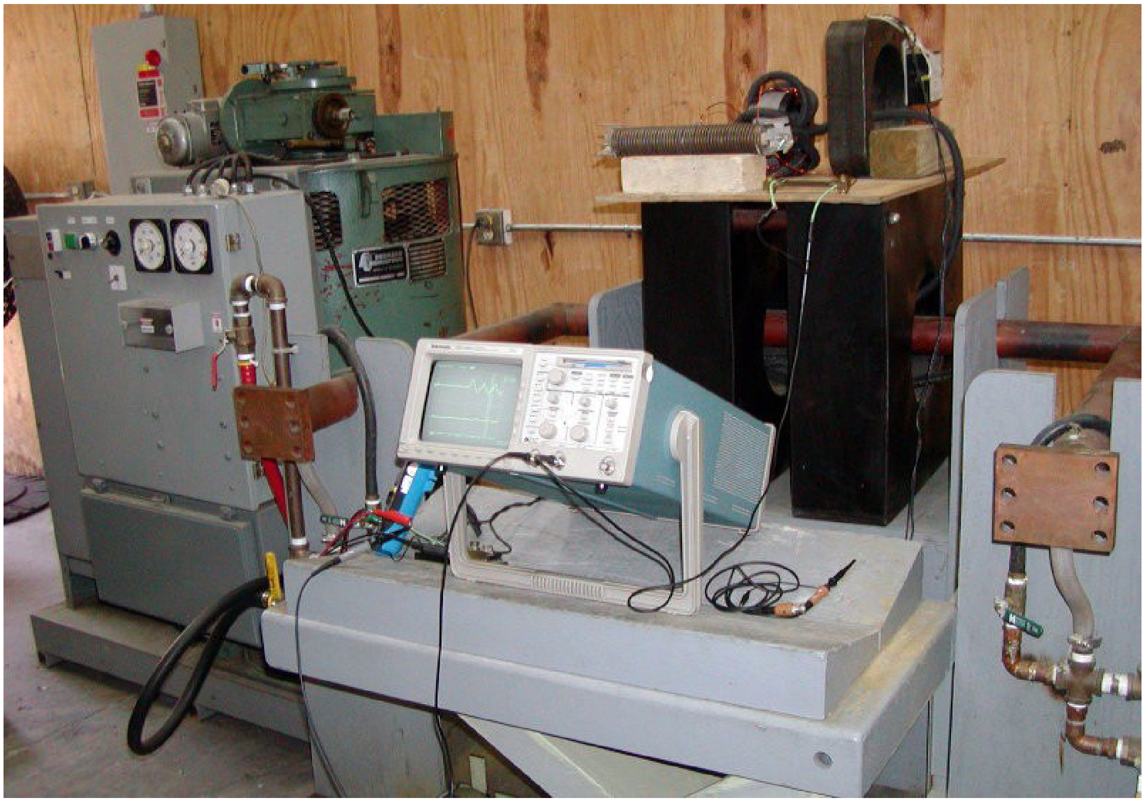

Fig.31. Test setup.

The tests have been done in the high power lab of GE Multilin's Instrument Transformers (ITI) division in Clearwater, Florida. Figures 30 and 31 show a CT under test, and the test setup, respectively. A current source capable of driving 5kA of current is connected to 4 primary turns on the C10 CT. A current source capable of driving approximately 3.6kA of current is connected to 11 turns on the C5 CT. This is equivalent to testing the C10 CT with 20kA of primary current, and the C5 with 40kA of primary current. A 0.2ohm burden resistor is applied to both transformers.

A digital scope is used to record traces of the ratio and secondary currents. A 0.3B1.8, C100, 4000:5 CT is used as a reference CT measuring the primary current.

The tested CTs are demagnetized before each test in order to facilitate the simulation by making the residual flux known (zero).

Figure 32 presents the actual (measured) magnetizing characteristics for the two CTs under test.

Figures 33 shows the primary currents: measured and simulated for a sample 20kA test of the C10 CT.

The current source used in the test cannot be controlled as to the dc offset. Therefore, the primary waveform in the digital simulation has been matched post-mortem to reflect the test waveform.

Subsequently, such primary waveform has been used to exercise the digital model of the CT producing the secondary waveform depicted in Figure 34. The tested and simulated secondary currents waveforms are inverted in the figure to better indicate the narrow current pulses that otherwise would overlap closely and be difficult to read.

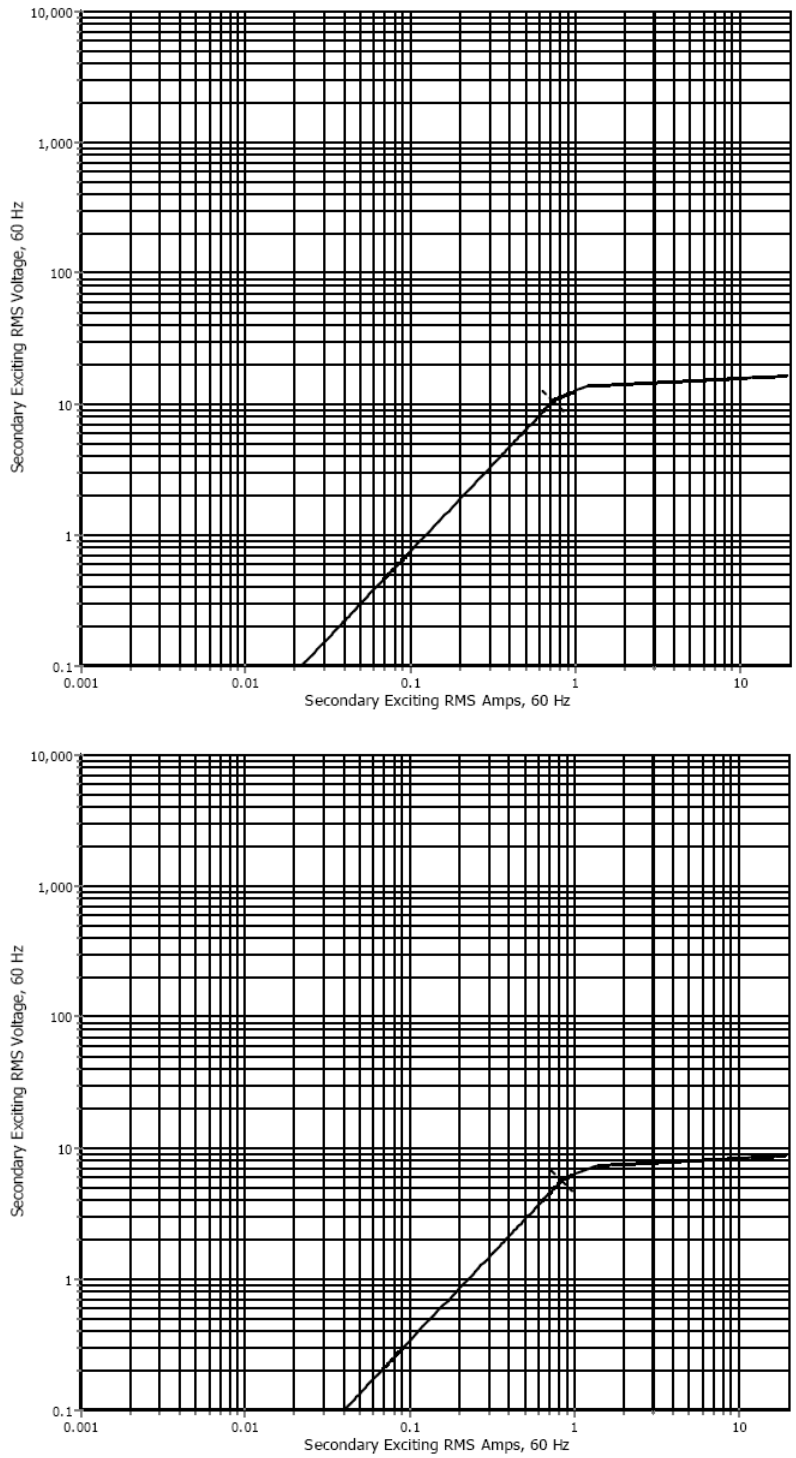

Fig.32. Magnetizing characteristics of the C10 (top) and C5 (bottom) CTs used in the tests.

The primary current of Figure 33 is distorted and does not follow a classical exponential dc decay model. This is because of the type of the current source used. The dc constant and distortions are of secondary importance, however, because of the high value of the current.

As seen in Figure 34, the model and actual CT tests match well. The model seems to yield a slightly lower magnitude of the secondary current, and at the same time, slightly narrower pulses of the current. The difference in magnitudes seems to be within 10-15%, and is not critical as this level is several times above the relay cut-off value already. The lower magnitude and width of the pulses as simulated by the digital model make the analysis of this report conservative – the actual CT would deliver more energy to the relay compared with the simulated CT.

Figure 35 shows a 10kA test of the C10 CT. Again, the model and the test results match well.

Figure 36 shows a 32kA test of the C5 CT. This approximates a 64kA test of a C10 CT. As seen in the Figure, the CT still delivers current pulses of 300A secondary. Again – the digital model seems to return current pulses of shorter duration, making the analysis of this report conservative.

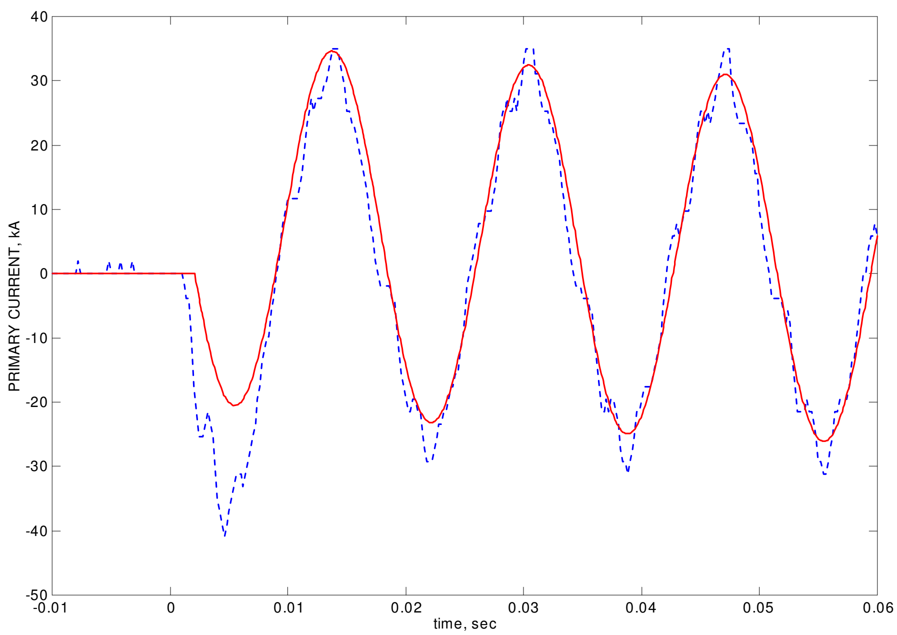

Fig.33. Case 1 – primary currents: test (dotted blue) and simulation (red). A 20kA test of the C10 CT.

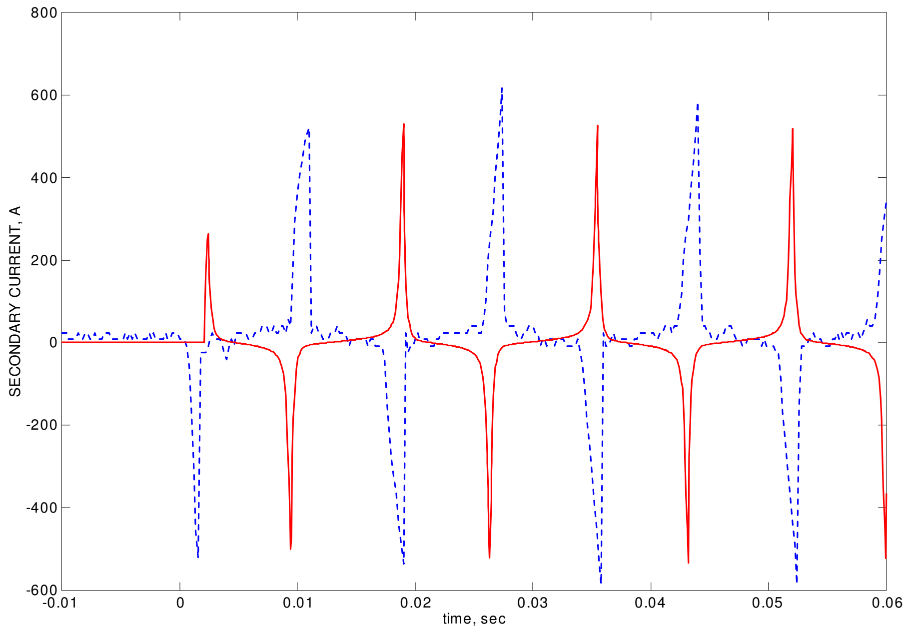

Fig.34. Case 1 – secondary currents: test (dotted blue) and simulation (red). The currents are inverted for better visualization. A 20kA test of the C10 CT.

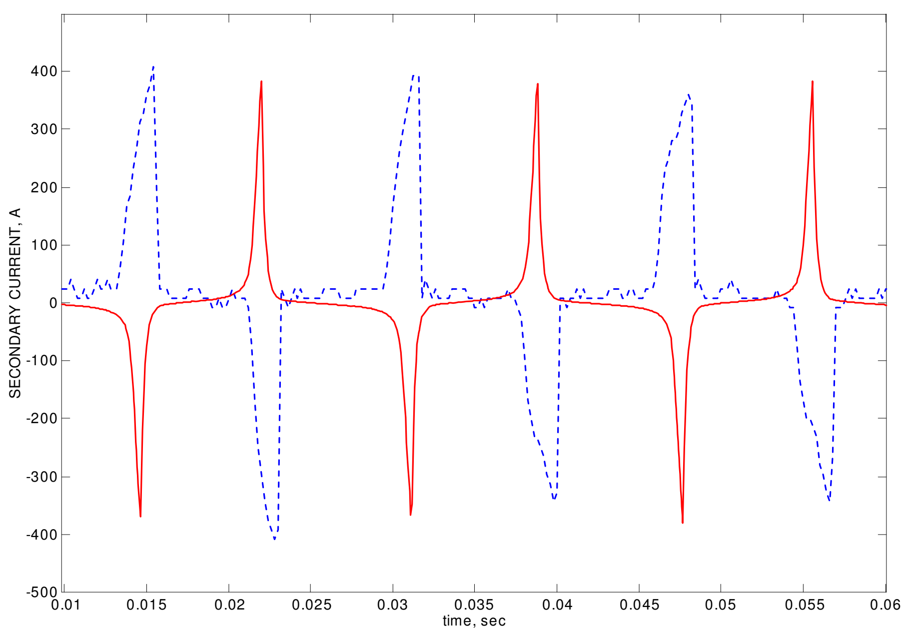

Fig.35. Case 2 – secondary currents: test (dotted blue) and simulation (red). The currents are inverted for better visualization. A 10kA test of the C10 CT.

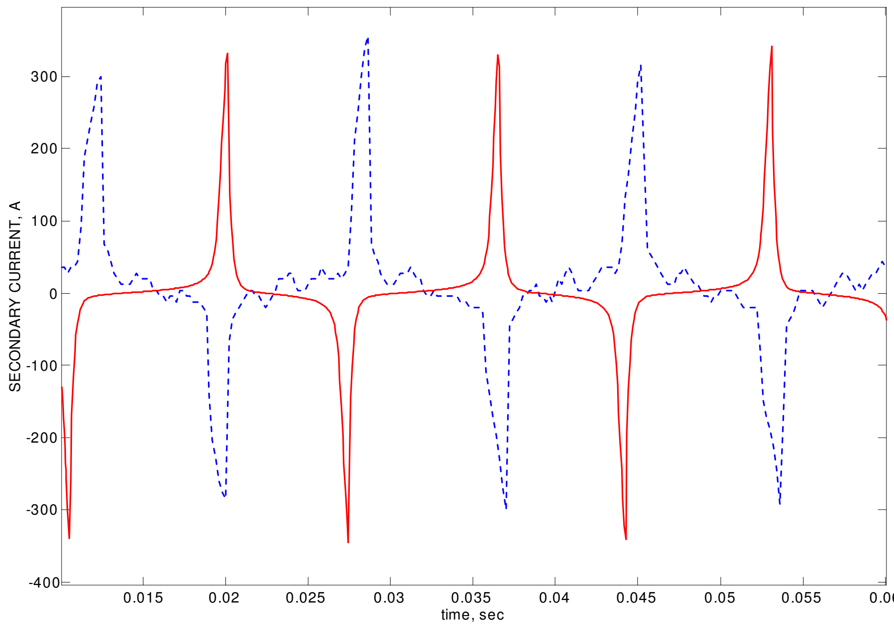

Fig.36. Case 3 – secondary currents: test (dotted blue) and simulation (red). The currents are inverted for better visualization. A 32kA test of the C5 CT.

8. Conclusions

This document explains issues associated with instantaneous overcurrent protection in industrial applications when feeding protective relays with low-ratio CTs. Extreme cases of CT saturation have been considered to the extend of 64kA of fault current measured by a 50:5, C10 CT.

A methodology has been provided for practical field engineering of CT and relay applications. Simple to understand and apply charts could be developed as illustrated in this report to quantity a problem, and rectify it if necessary. The proposed methodology eliminates many variables from the analysis, does not require users to apply any sophisticated tools, and is easy to use.

Results of analysis and testing indicate that the combination of low-ratio CTs and very high fault currents could prevent the user from entering very high IOC settings. For a given relay, working with a given CT, in a system with a given maximum short circuit level, a maximum IOC setting can be found for which the relay will operate within its timing specifications. If a higher setting is required, the relay may respond outside of the spec or restrain itself from tripping. That region of inadequate operation is relatively limited, and occurs only for absolute extreme cases of low-ratio CTs and high fault currents. Moreover, the practical settings are outside of the affected region.

This explains why one does not encounter this problem in the field. On the surface the problem seems to be very serious – the secondary currents are extremely low compared with the ratio currents. However, these secondary currents are still high enough to activate relays given their practical setting ranges.

The above could be better understood when realizing the source of the problem. A given CT saturates heavily because its ratio is selected to match relatively small load current. If the load current is small, the overcurrent pickup threshold for short circuit protection is small as well (it is a fixed multiple of the load current). The magnitude of extremely high fault currents is a hundreds times, or close to a thousand times the rated current, but this means it is tens or hundreds times the pickup settings. Under such high multiples of pickup, a relay has a large margin between the operating current and the setting. The operating signal will have to be decimated by tens or hundreds times by CT saturation and limited conversion range of the relay, to cause the relay to fail.

It must be emphasized that there is a dramatic difference between relays using Fourier-like approach (cosine and sine filter), and relays based on true RMS value. The latter behave significantly better as illustrated in this report.

This report uses the standard IEEE burden of 0.2 ohms for illustration. The actual burden in typical industrial applications is significantly lower, making sample results of this report conservative. In actuality the problem is less significant.

Using this methodology, users of GE Multilin's relays can apply them safely and confidently in applications where fault currents exceed rated currents by hundreds of times, even if low-ratio CTs have been used.