Harmonic Sharing for Effective Detection of Transformer Inrush Condition in Differential Protection Schemes

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Differential protection generally is considered to be the "best" protection for any given zone-of-protection on a power system. It is sensitive, secure and faster than other options. It is particularly appealing for protection of power transformers, due to their critical nature in the power system configuration. Fast clearing is desired to minimize damage for internal faults. Security is important, since a transformer will need to be tested after an operation (no reclosing). Transformer differential protection generally has been recommended for transformers 10MVA and above (4,5), but the economics of multifunction, numeric relay platforms and the overall decrease in cost per function has led to expansion of differential protection to circuits where it previously was not justifiable.
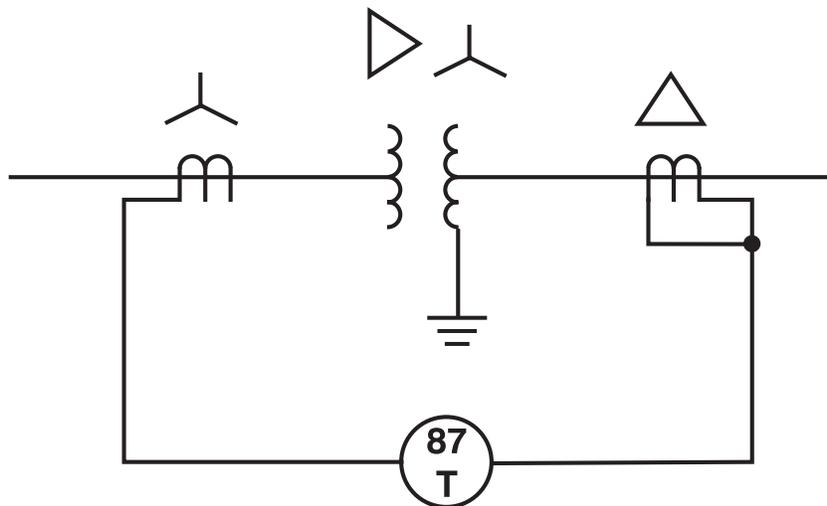

Fig 1: Transformer differential protection - one line

The nature of power transformers creates several complications for the application of phase differential relays. The relay scheme must compensate for the differences between the magnitudes of the measured currents on each transformer winding and the phase angle shift associated with the transformer connections. Additionally, the zero sequence source provided by a grounded WYE transformer winding must be accounted for in the scheme. This historically has been accomplished using CT ratios, Relay TAP settings and CT Connections. Additionally, the relay scheme must accommodate errors due to differences in CT performance, which may result from unequal accuracy classes, different connected burdens, or saturation due to DC offsets. Through current restraint (Percentage restraint) has been used effectively to provide security for these concerns.

One of the major concerns when applying differential protection to power transformers is ensuring security during transformer energization. Transformer energization creates a true unbalance (differential condition), but is *not* a fault, and the differential relay must not trip. Security of transformer differential protection schemes is dependent on detecting the magnetizing inrush currents of the protected transformer and associated blocking of differential operation due to inrush related, non-fault, unbalance currents.

The inrush waveform is highly distorted and rich in harmonics. Years of evaluation have shown that transformer inrush creates currents with high second harmonic content (6,8). The evaluation of harmonic content in the energization currents has been the primary means of inrush detection in transformer differential relays for many years and several generations of protective relay technologies. The vast majority of transformer differential relaying schemes use the amount of harmonic content of the measured waveform to determine that an energization is taking place. The normal differential element is blocked for this condition, also known as Harmonic Inhibit. Faults during energization are detected by supervising the restrained element with an unrestrained element, set above the largest expected energization magnitude.
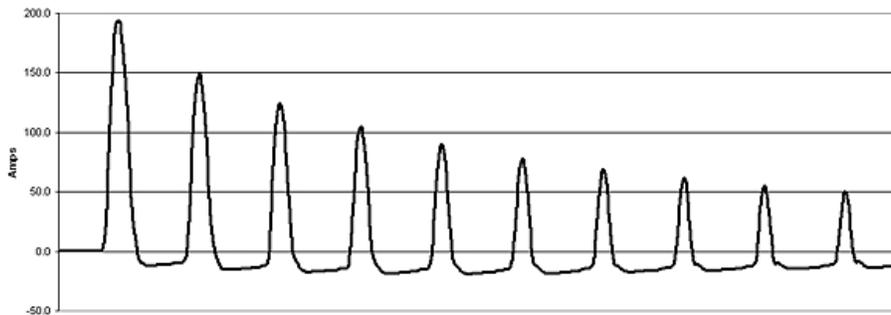
Fig 2: Transformer Inrush (One Phase)

Thresholds for defining energization generally have been fixed between 12% and 32%, depending on relay type. One Study (7) determined that magnetizing inrush waveforms would include at least 17% second harmonic. Recent transformer designs, however, may have inrush currents with 2nd harmonic content as low as 7% (2). Undesired operations of differential relays during energization (a.k.a. False Trips) have been encountered by many utilities. Historically (in the electromechanical implementation), transformer differential relays have been applied as single-phase elements, with a separate relay for each set of transformer windings. Phase shift compensation was accomplished through the CT connections. Inrush detection was limited to evaluating the harmonic content of the currents available within the specific relay element. In addition to the previously noted issues with harmonic levels, it is possible for the subtraction effect of the relay connection to reduce the amount of second harmonic currents seen by the relay (1). One of the complications of energization currents is that transformer inrush is not a consistent condition. The currents will vary from one energization to the next. Perhaps more significantly, inrush is not a balanced condition. The energization currents are not equally distributed between the individual windings. This can complicate the process of identifying inrush in a relay system, if a specific phase does not have sufficient harmonic content to be recognized as energization.
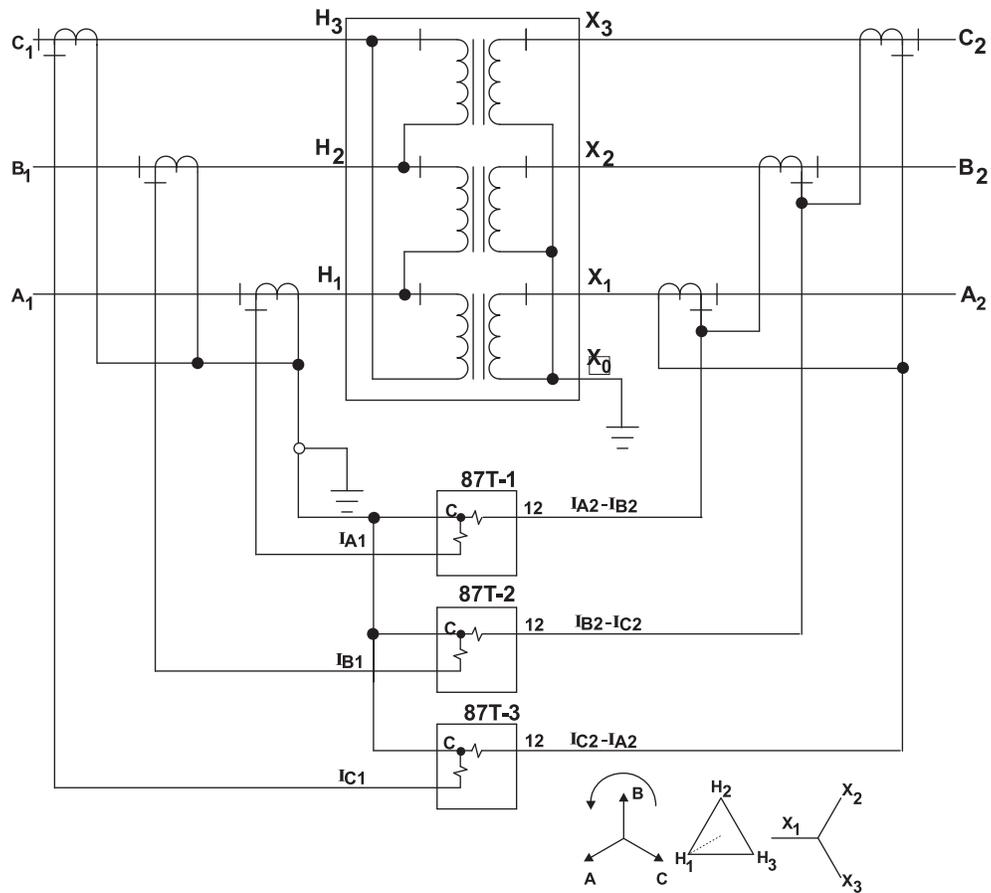
Fig 3: Transformer differential Single Phase Relay Configuration

The advent of solid state and numeric technologies has allowed refinement of this technique to optimize security while maintaining sensitivity. One of the primary differences in these newer relay implementations is three-phase packaging. That is, a single relay unit will include all three of the phase differential elements in one relay unit. Besides the space and economic benefits, this allows the opportunity to look at the all of the currents associated with an event to more effectively determine if an unbalance is due to an energization event. Another dramatic advantage of numeric relay systems is the ability to record system events, allowing analysis and evaluation. All of the waveforms presented in this paper are derived from relay data recordings.
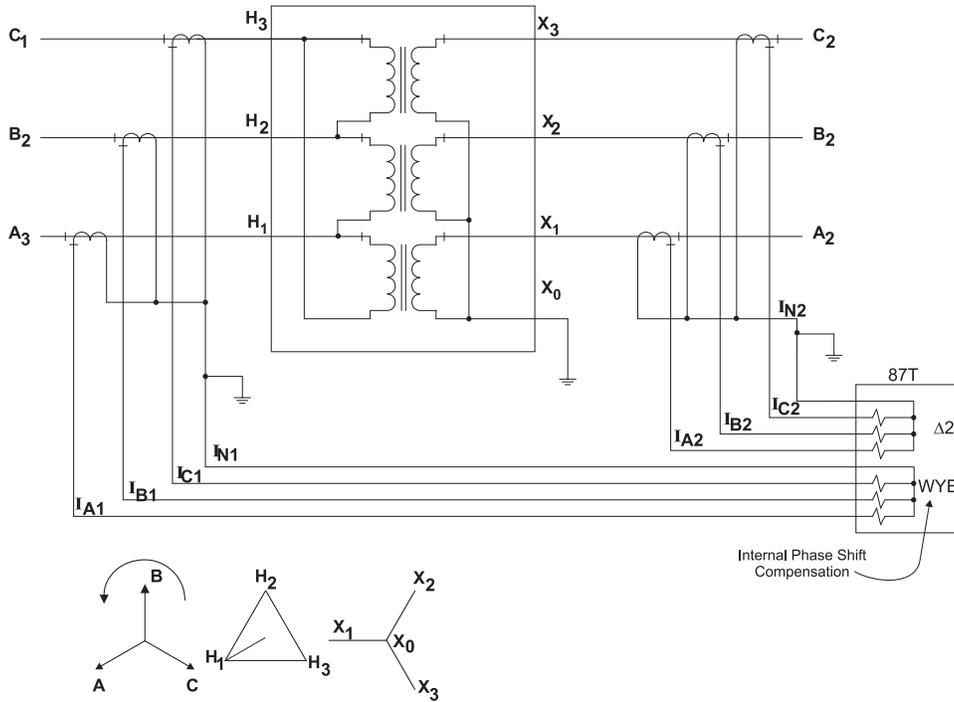
Fig 4: Transformer differential Three Phase Relay Configuration

Having all of the signals available in the relay allows each protective element (phase) to look at the overall system conditions. For example, if any of the phase elements detects an inrush condition, it could send a blocking signal to the other phases, to ensure that they properly restrain. This generally is known as cross blocking. While secure, it does raise the possibility of undesired restraint if a transformer is energized while faulted. Another technique is harmonic sharing.
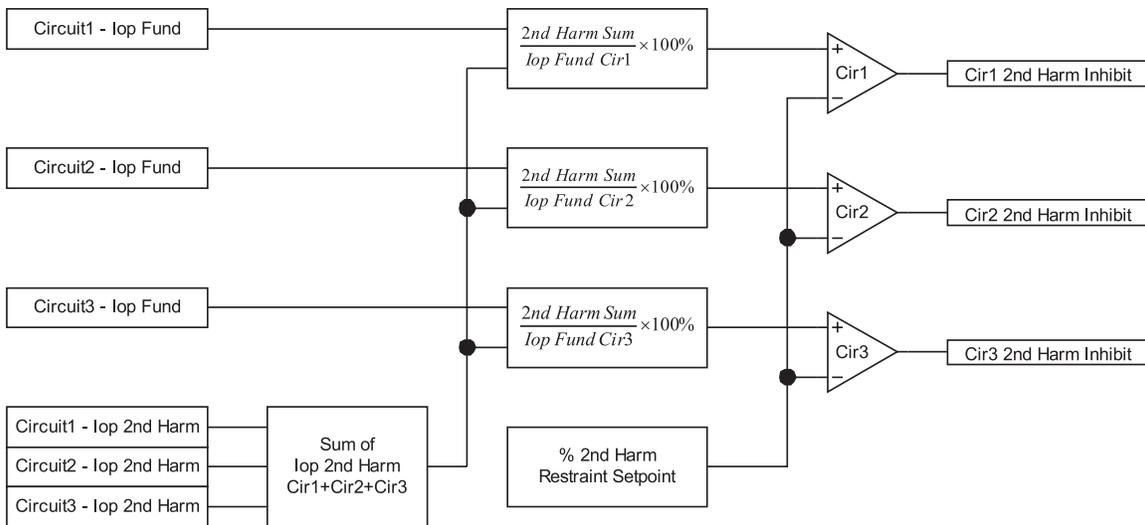
Fig 5: Harmonic Inhibit Detail

For this technique, the incoming currents are filtered to extract the fundamental signals (for faults and load) and the second harmonic signal (for inrush). The 3 inrush signals

(2nd harmonic) are then summed to create a single harmonic signal, representing the overall inrush currents. The inhibit threshold is adjusted to accommodate the larger overall signal resulting from the summing. For example, 18% summed harmonic is used rather than 12% independent harmonic. Each phase element of the 87T function compares its specific fundamental current with the summed harmonic signal and makes an independent decision whether to inhibit for energization. This provides improved security for situations with unreliable harmonic content. Sensitivity is maintained for faults during inrush conditions, as the fundamental current in the faulted phase (unbalance) should easily override the sum of the second harmonic currents associated with energizing the unfaulted phases.

Several examples are included to clarify these points. Each is taken from data records from numeric relay systems, with the data exported from COMTRADE format, and imported into Excel spreadsheets. Summaries of each case are provided at the end of the paper.

Case 1 – Typical Energization:
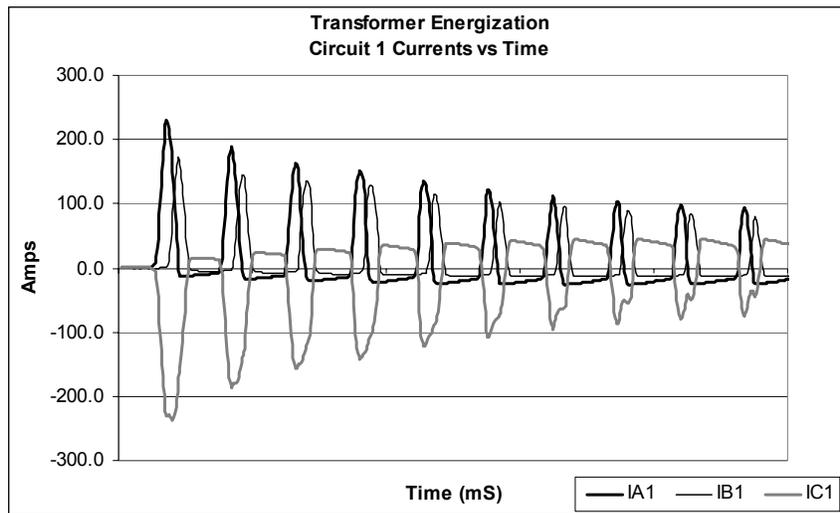
Fig 6: Transformer Inrush Current Case 1

The waveform above shows an energization of a 67/12.47kV, 18MVA transformer recorded by a numeric relay. The transformer is energized from the high voltage side, with the secondary side open. The Circuit 2 currents (LV side) are zero, so the Circuit 1 currents will reflect as the differential current. The unbalanced nature (phase-to-phase) of the inrush currents can be seen in this case. The A and C phase inrush currents are close in magnitude (within 3% at first peak); while the B phase peak is significantly less (27% less). There is significant CT saturation evident on the C phase signal, including a substantial offset of the "flat spot". The transformer was energized with an open secondary, so the Circuit 2 signals are not shown. They are accounted for in the spreadsheet calculations and the associated charts.

Figures 7 and 8 show the signals developed internal to a numeric relay for the Fundamental and the 2nd harmonic unbalance currents (Iop). These are the unbalance magnitudes that define the operation of the relay. They are plotted with the same scale

for easy comparison, but the specific values are not included as they relate to internal calculations. The differential relay will determine if a specific situation is transformer inrush, based on the ratio of the harmonic current to the fundamental current. Note that the restrained trip element of a differential relay must be delayed long enough for the second harmonic unit to accurately measure the 2nd harmonic content (approximately 1 cycle).
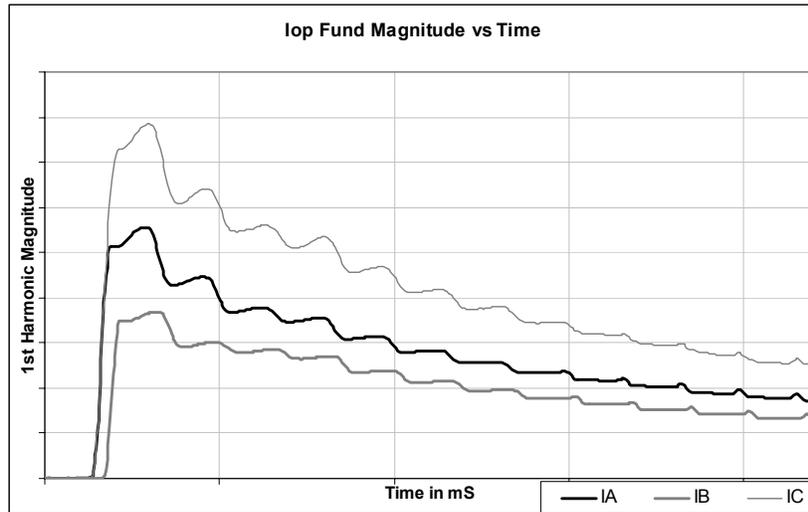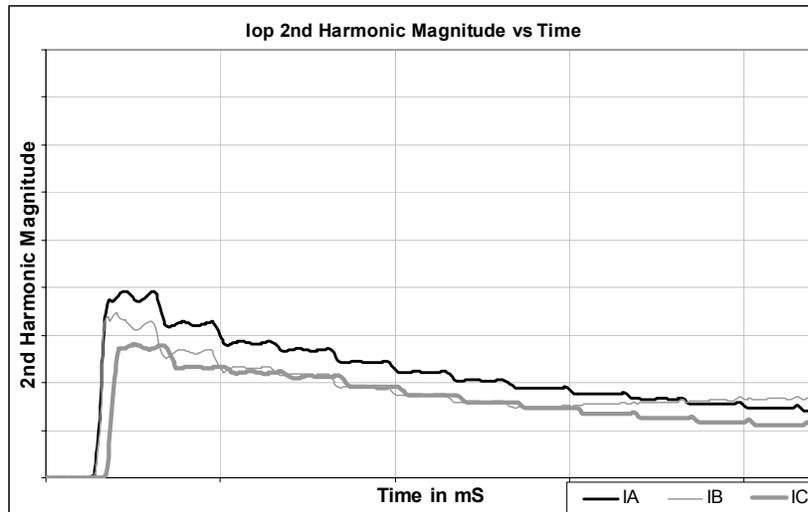

Fig 7: Fundamental Unbalance Current - Case 1

Fig 8: 2nd Harmonic Unbalance Current - Case 1

Figure 9 shows the percent 2nd harmonic signal associated with the first energization (case 1), without harmonic summing. After the initial "noise" associated with the DFT signal processing, each of the phases has well above the typical thresholds of around12% second harmonic. C phase, the lowest, has a second harmonic signal that is 35-40% of the fundamental signal. Notice that this is the phase with the significant saturation. A and B phase have more second harmonic signals greater than 75% of the associated fundamental.
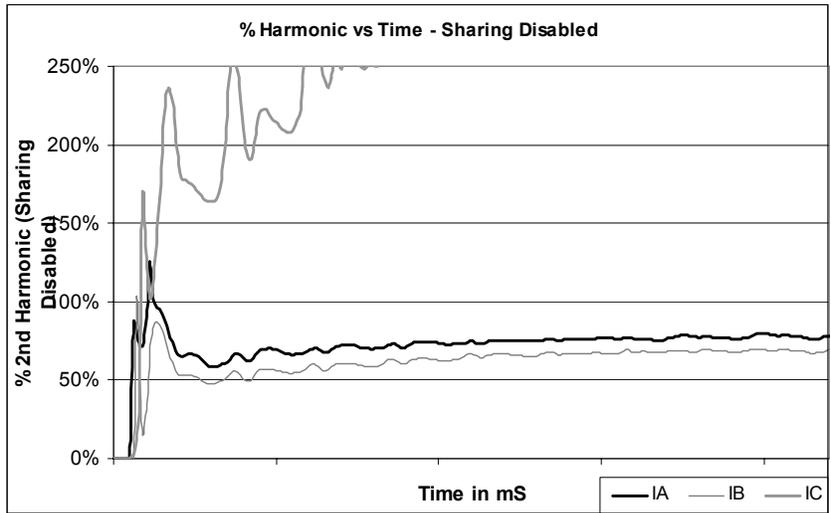
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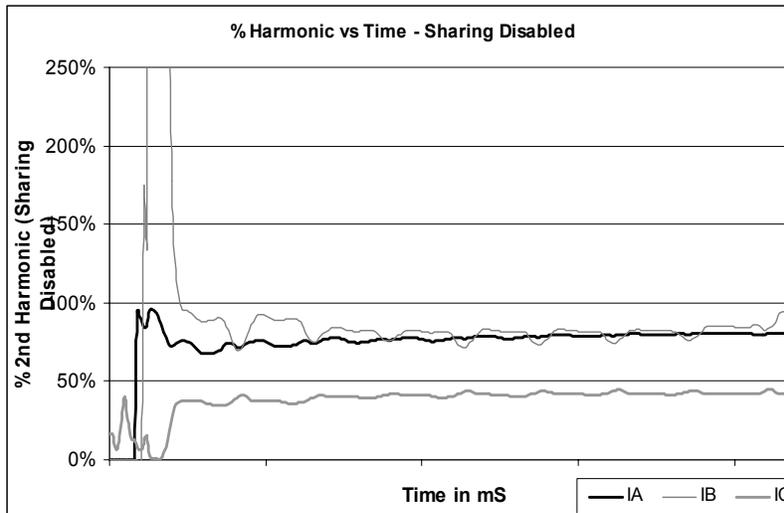
Fig 9: Second Harmonic Content - Case 1 (Without Sharing)

Case 2 –Typical Energization:

The waveform below (Case 2) is another energization of the same transformer, again with the secondary side open. Note that the inrush characteristics differ between energization cases. This time, the overall peak is about 20% lower than before and the decay is faster (at 9 cycles, it is ½ the previous case). A and B phases are almost equal (within 0.5% at first peak), and C phase is dramatically less (58% less). The C phase signal has both positive and negative peaks (bi-polar).
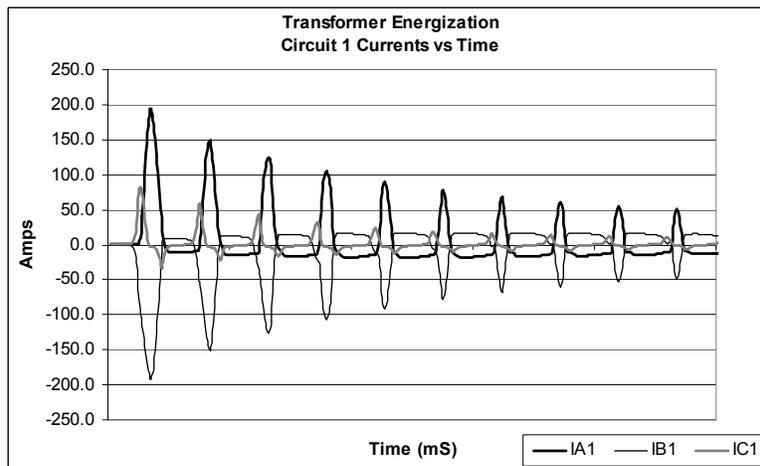
Fig 10: Transformer Inrush Current Case 2

Analysis of this case shows that, again, there is plenty of harmonic content to properly inhibit. Phases A and B have more than 50% second harmonic, compared to the associated fundamental currents. Phase C has dramatically higher second harmonic. This is a combination of the relatively higher second harmonic (due to the bi-polar waveform) and comparatively lower fundamental current. See Case 2 summary for details.

% Harmonic vs Time - Sharing Disabled

Fig 11: Second Harmonic Content - Case 2 (Without Sharing)

Case 3 –Typical Energization:

The waveform below is another energization of a distribution type transformer. This is a different location than the previous cases, but a similar system configuration. Again, the secondary is open, and Circuit 2 currents are zero. The inrush is typical in most regards, but closer examination shows a couple of differences. Note that there is a small "blip" of A and B current before the energization, and that the C phase current doesn't start until about ½ cycle into the event. There also is a significant DC offset (decaying) to the C phase bi-polar waveform

**Transformer Energization
Circuit 1 Currents vs Time**
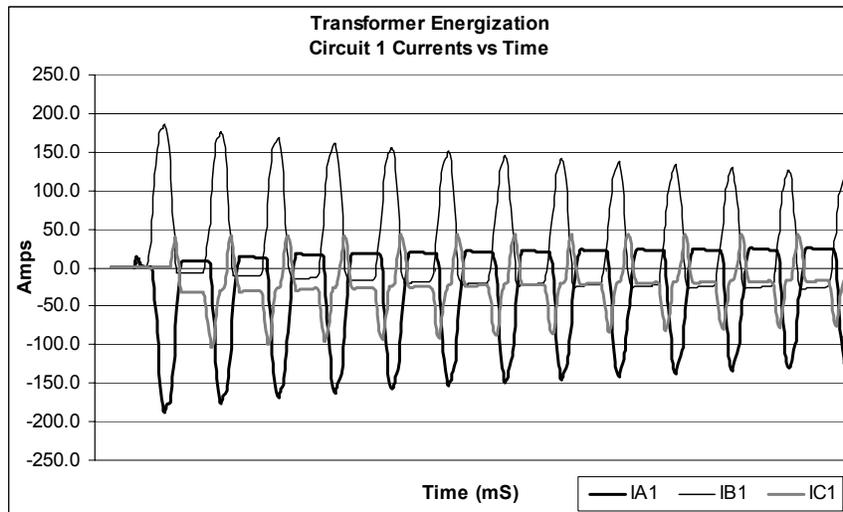
Fig 12: Transformer Inrush Current Case 3

Evaluation of the waveforms shows that the C phase fundamental rises much faster than the associated harmonic signal, resulting in an extremely large % harmonic signal during the transition. There is less harmonic signal in Phases A and B than the previous cases, but still well above the typical 12% threshold. See the case studies at the end of the paper for more details.
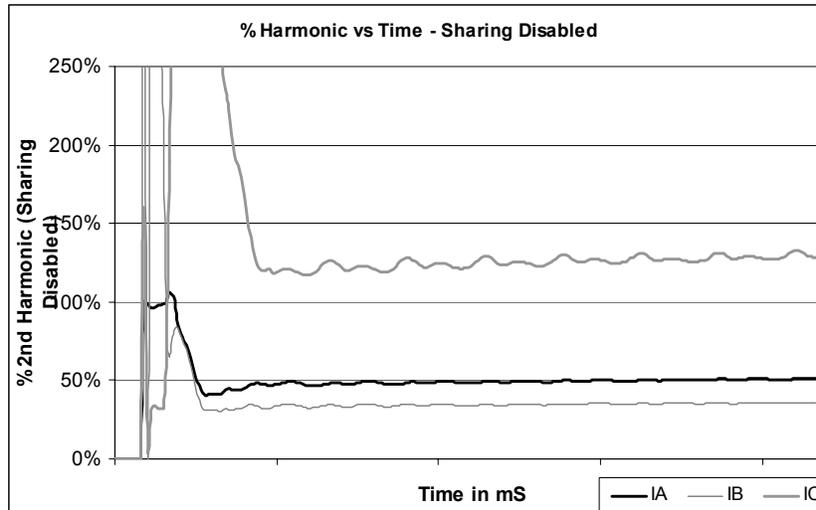
Fig 13: Second Harmonic Content - Case 3 (Without Sharing)

Case 4 – Energization with Low Harmonics:

The next set of waveforms is from a 69/12.470kV, 15/20/25MVA transformer connected to a radial distribution system. While this transformer is energized with the loads open, there is a station service transformer connected to the transformer secondary, but outside the zone of protection. So when the main transformer is energized, the station service transformer also will be energized. While the station service transformer is outside the differential zone, there may be some degree of sympathetic inrush from the distribution transformer. This installation had problems with tripping during energization, and the user switched to a numeric relay specifically for data recording to analyze their situation. The two figures below show an inrush condition, with both circuits (Circuit 1 is HV, circuit 2 is LV) included.
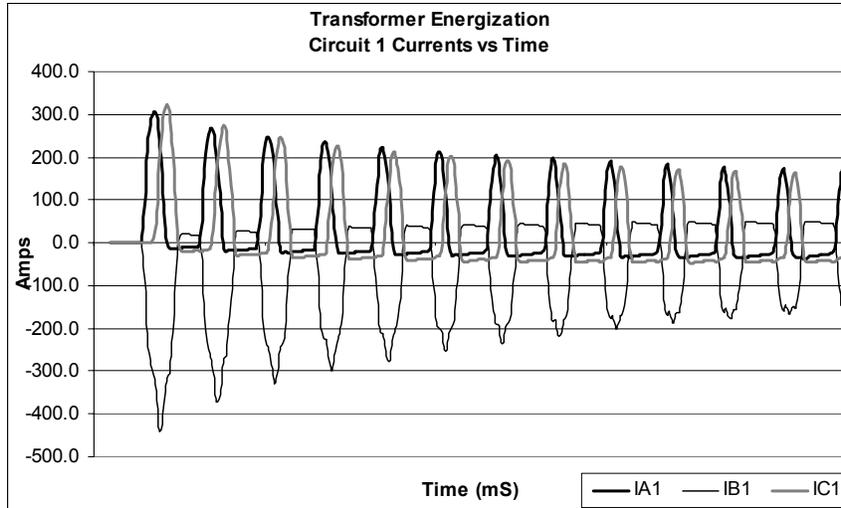
Fig 14: Transformer Inrush Current, High Voltage Side - Case 4
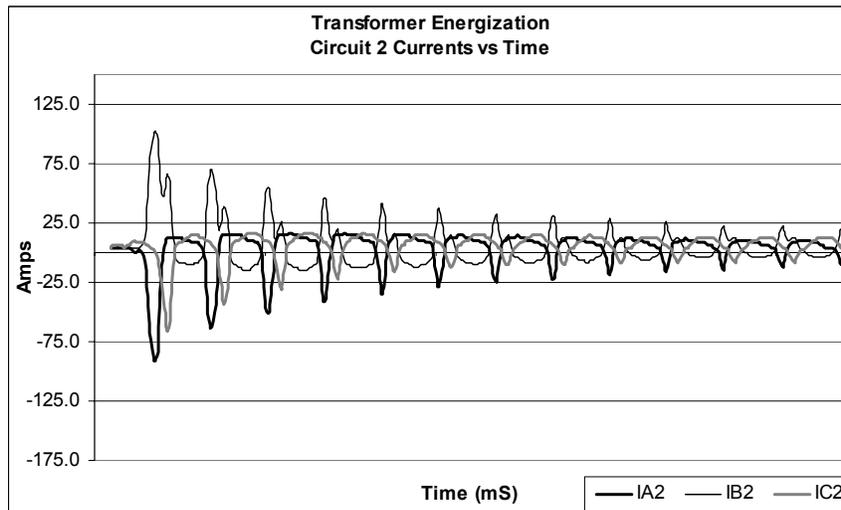
Fig 15: Transformer Inrush Current, Low Voltage Side - Case 4

Both of these waveforms show significant distortion. There is substantial DC offset to all three phases of both HV and LV side. Also, the B phase signal on the HV side, in particular, shows significant saturation. Evaluation of the signals internal to the relay shows typical fundamental unbalance current signals, but very low 2nd harmonic signals. See case summary at end of paper for details. As a result, the B phase element's percent harmonic, without sharing, is well below normal thresholds, around 7-10%. This is likely the cause of the insecurity. Note the C phase signal is lower than usually seen (20-25%), but still comfortably above the threshold.
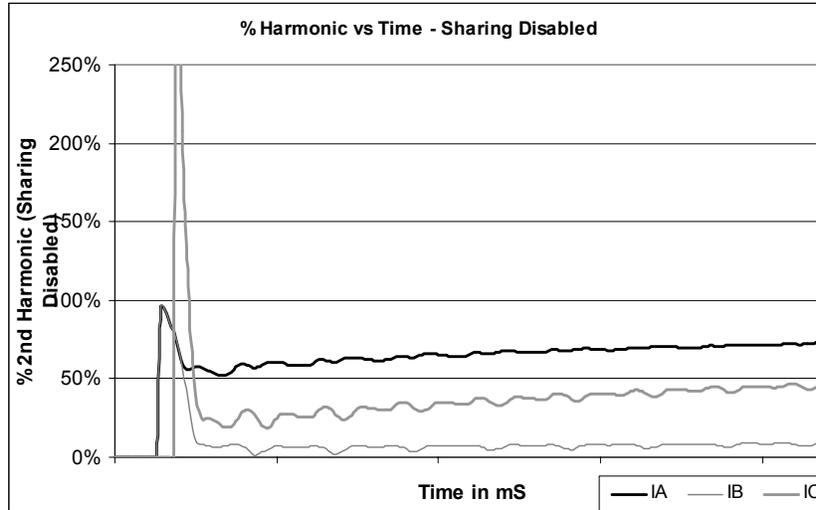
Fig 16: Second Harmonic Content - Case 4 (Without Sharing)

By implementing harmonic sharing, as discussed previously, we create a single, "known good" harmonic signal. Each phase element of the differential relay uses this summed signal to make its independent restrain decision. In this case, the difference is dramatic.
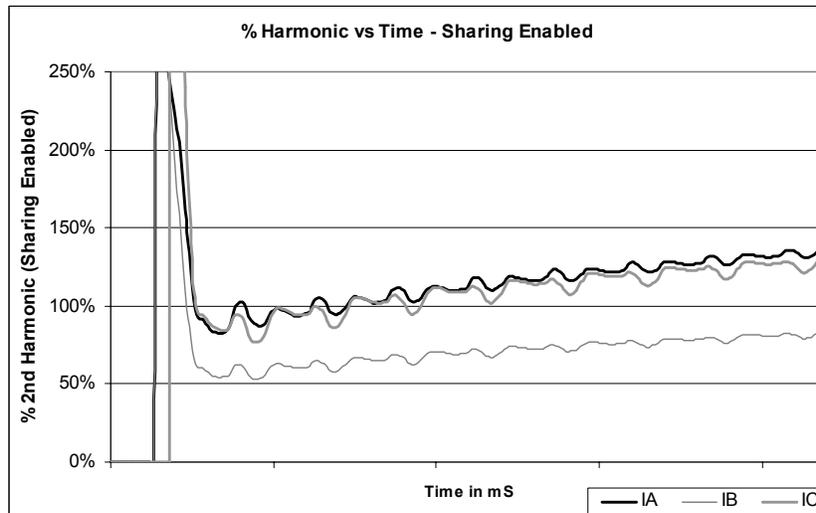
Fig 17: Second Harmonic Content - Case 4 (With Sharing Enabled)

With harmonic sharing, the overall percent harmonic signal is significantly higher. The problem B phase rises from under 10% second harmonic to over 50% second harmonic. Even with the higher threshold of %18, the safety margin exceeds 2:1, compared with being insecure with sharing disabled.

Additional Cases

There are additional test cases appended to the paper, as further examples of energization phenomena. This includes data recorded from a basic numeric overcurrent relay, applied on a transformer primary. Note that no cases were available for true trip conditions, such as a transformer failure, or closing into a transformer fault. The authors would welcome the opportunity to evaluate data records from any numeric relay users.

Summary

The availability of data recording in numeric relay systems has provided a whole new level of data for analyzing relay operations, and evaluating system conditions. The additional capabilities of numeric systems can allow improved protection capabilities. The use of harmonic sharing in transformer differential protection gives the ability to improve security for some inrush conditions, while maintaining sensitivity.
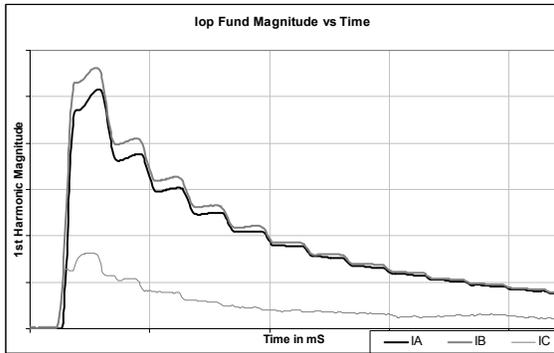
Case 1, file 0407161337.xls

67/12.47kV 18MVA D-Y   Internal compensation. 3.88A full load (200/5 CT) = 155A FL.
Energization peak is 238A. Note: Plenty of harmonic content, (minimum is ~40% w/o
sharing), but C phase is lower that A&B.

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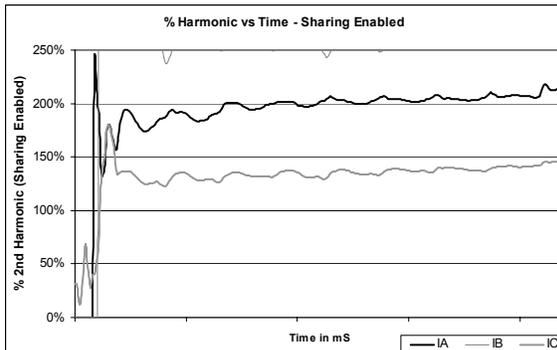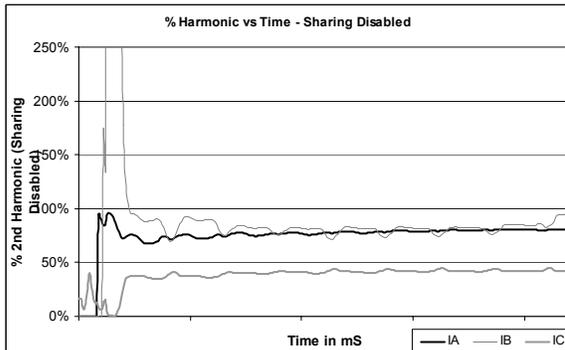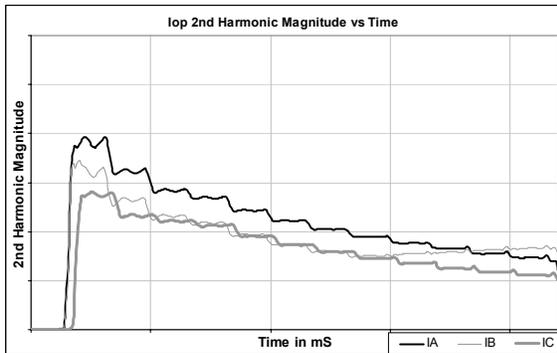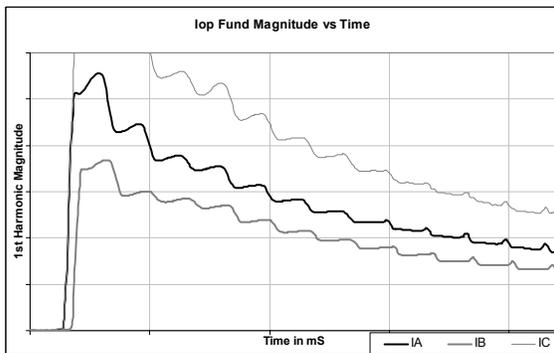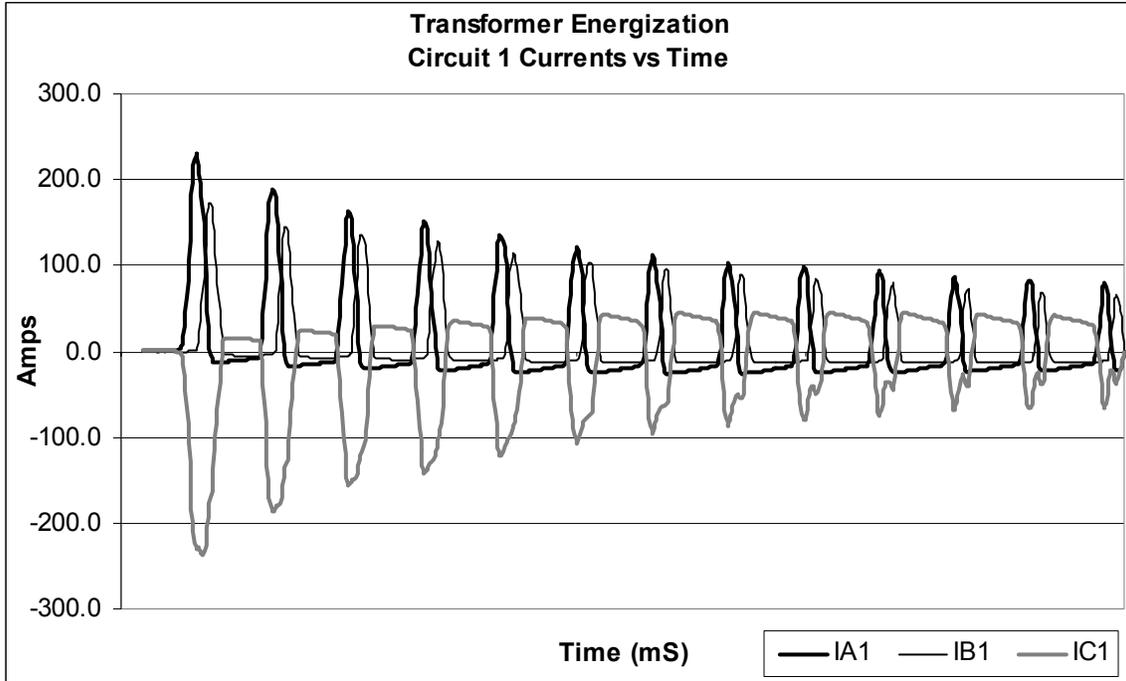
Case 2, file 0408141424.xls

67/12.47kV 18MVA D-Y Internal compensation. 3.88A full load (200/5 CT) = 155A FL. . Energization peak is 194A. Note: Very little C phase fundamental content, but plenty of harmonic content, minimum is ~40% w/o sharing.
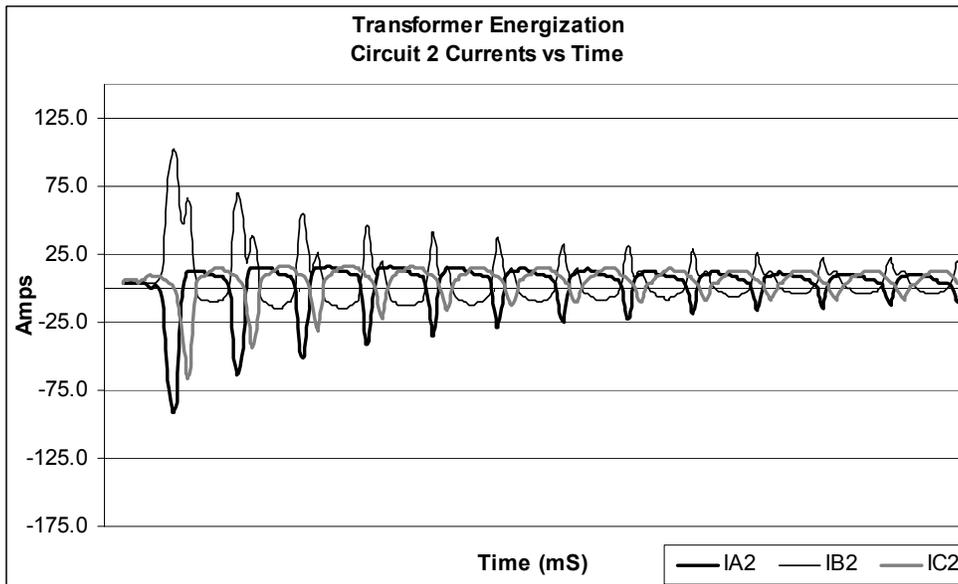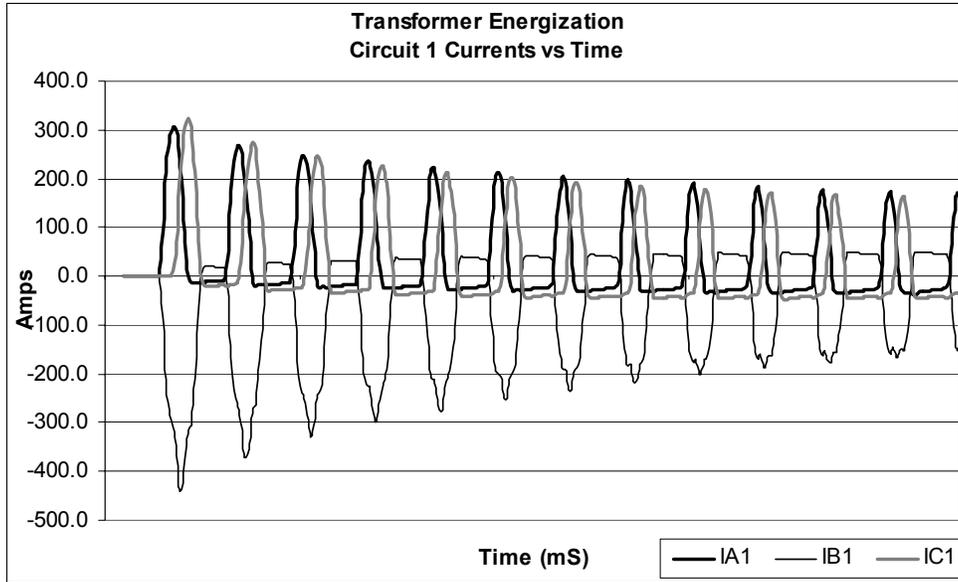
Transformer Energization
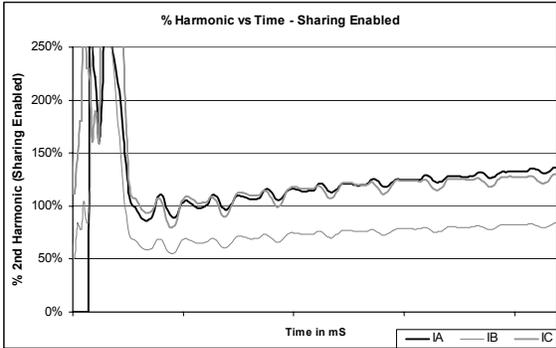**Circuit 1 Currents vs Time**

Iop Fund Magnitude vs Time

Iop 2nd Harmonic Magnitude vs Time

% Harmonic vs Time - Sharing Disabled

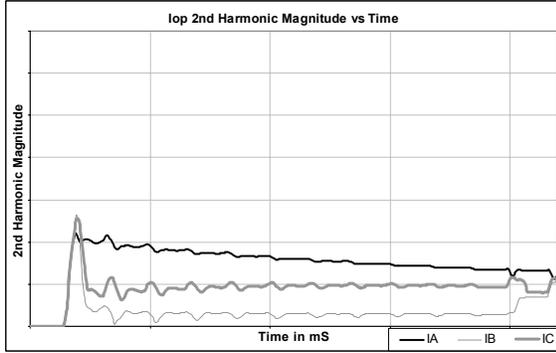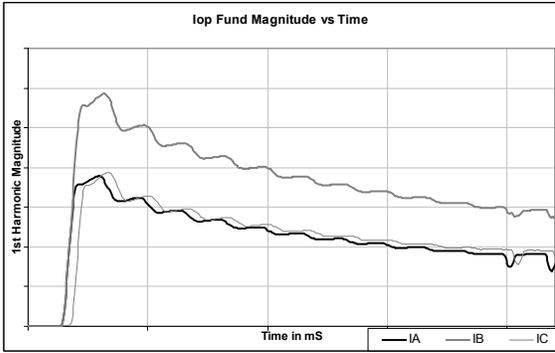% Harmonic vs Time - Sharing Enabled
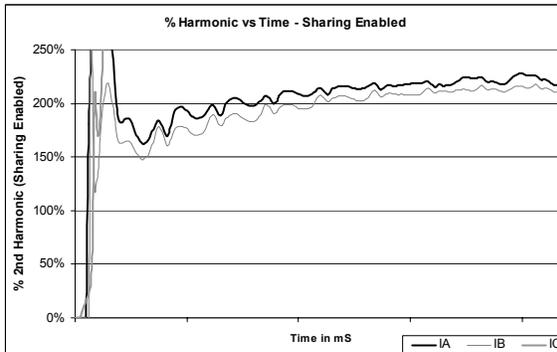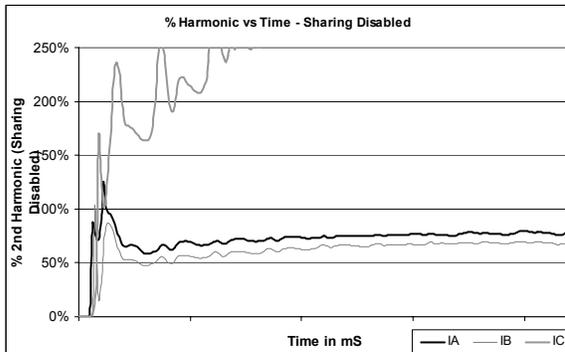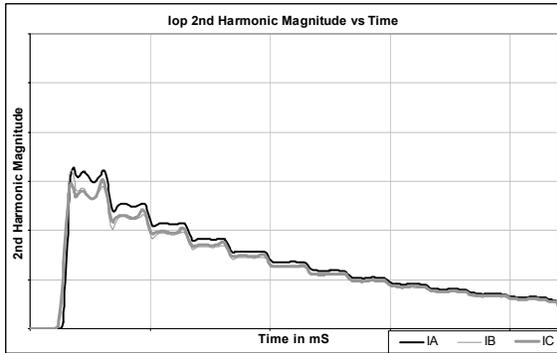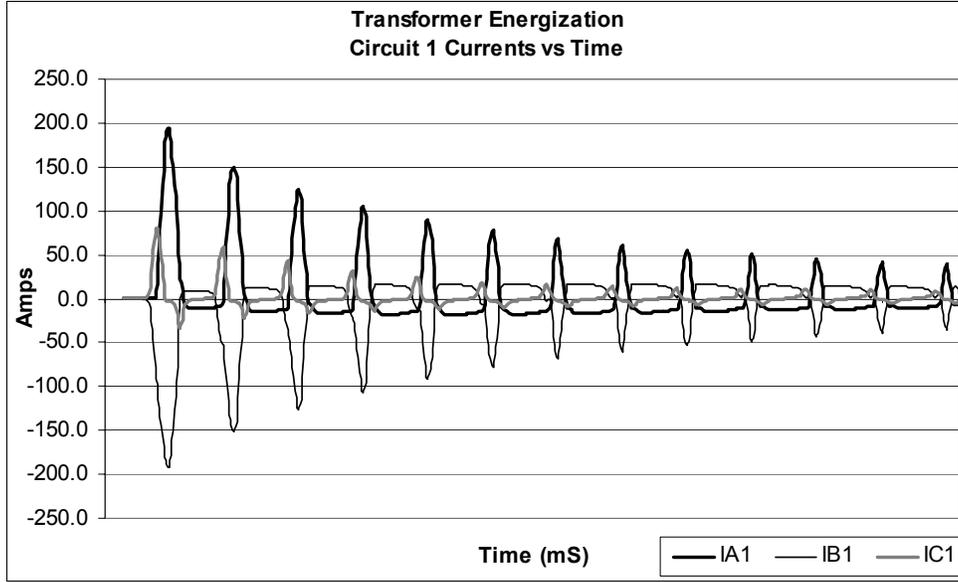
Case 3, file 0301010023.xls

Details Unknown. Note: C Phase waveform is "slow" rising…. Note dig in Harmonic Inhibit signal early on. ASIDE: There were security issues w/ this transformer.
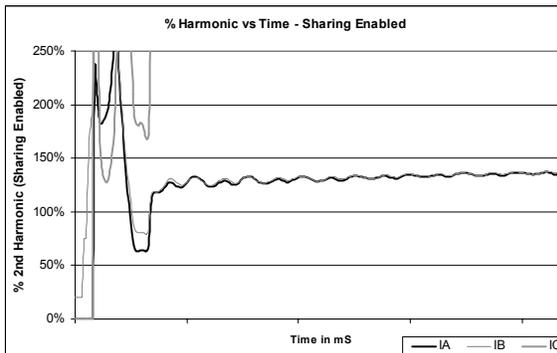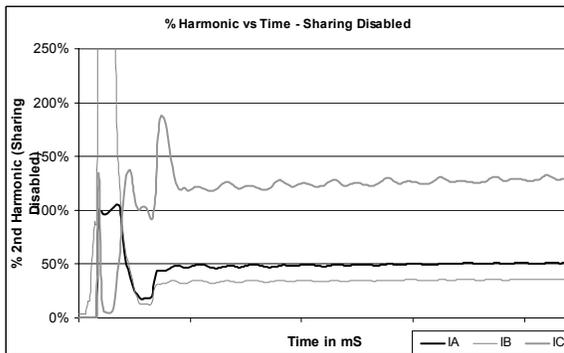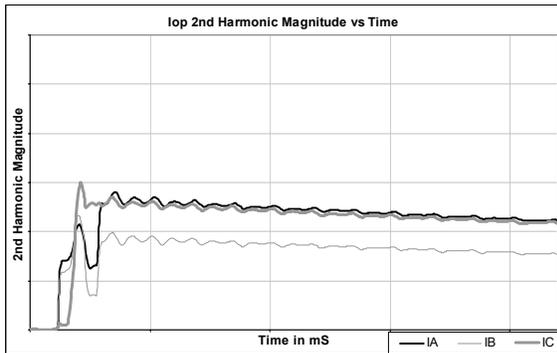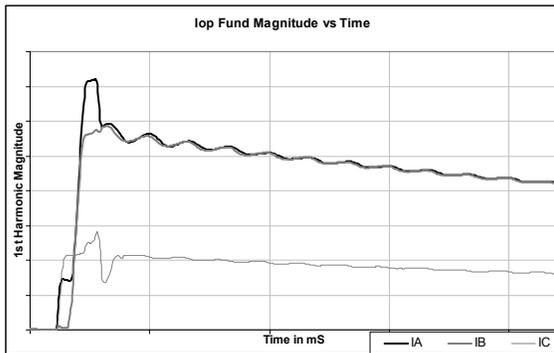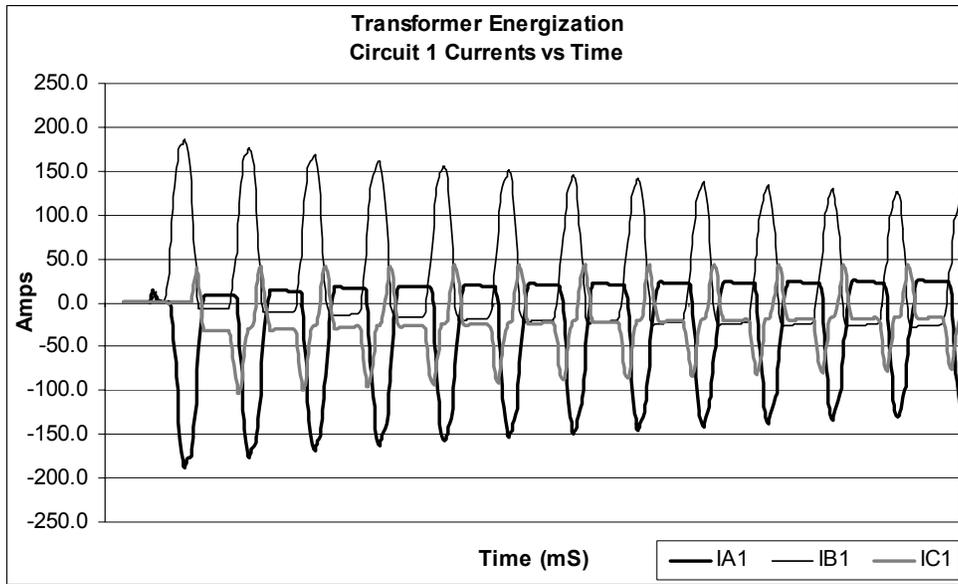
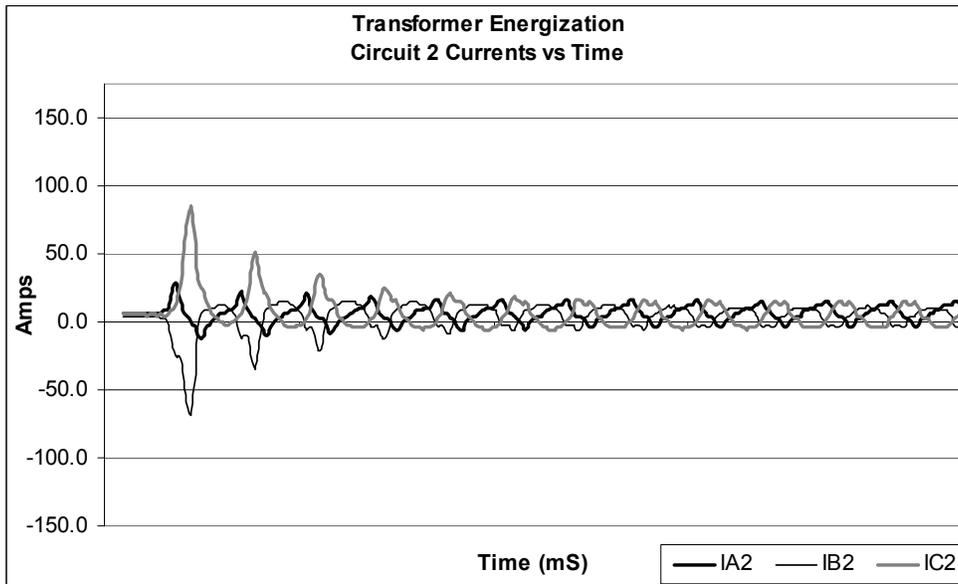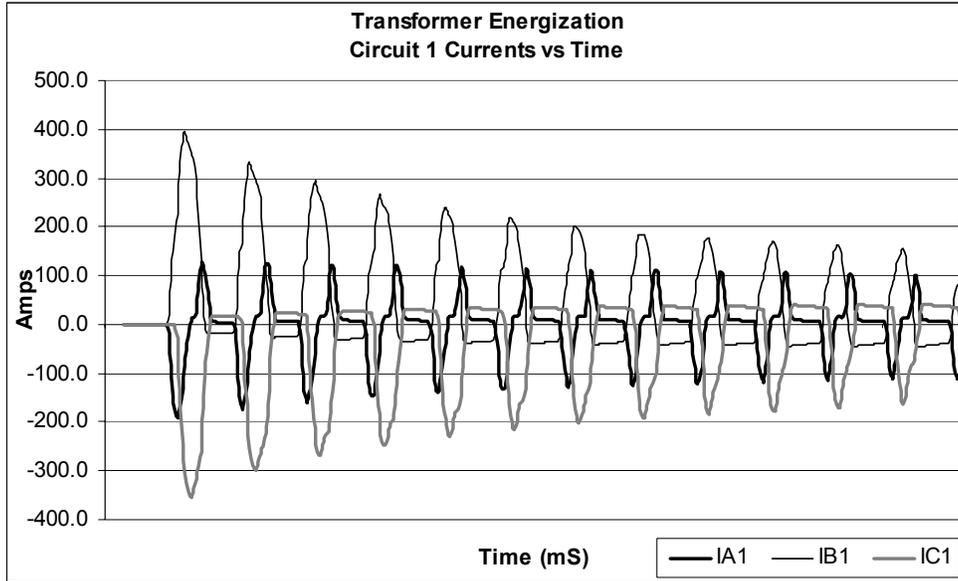**Case 4, file 0205200718.xls**

69//12.47kV 25MVA D-Y External compensation. 4.18A full load (250/5 CT) = 209A FL. Energization peak is 440A. Note: Very low 2nd harmonic %, w/o sharing (<10% on B phase). With sharing enabled, >50%.
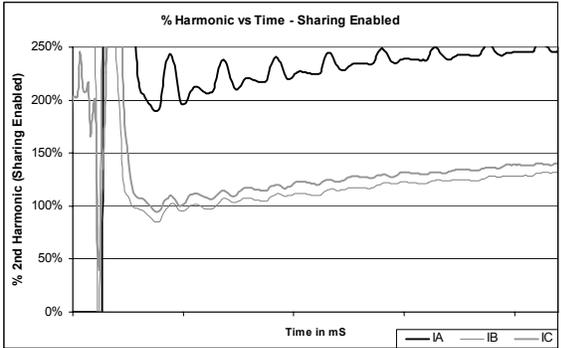
Iop Fund Magnitude vs Time

1st Harmonic Magnitude

Time in mS

IA   IB   IC

Iop 2nd Harmonic Magnitude vs Time

2nd Harmonic Magnitude

Time in mS

IA   IB   IC

% Harmonic vs Time - Sharing Disabled

% 2nd Harmonic (Sharing Disabled)

250%
200%
150%
100%
50%
0%

Time in mS

IA   IB   IC

% Harmonic vs Time - Sharing Enabled
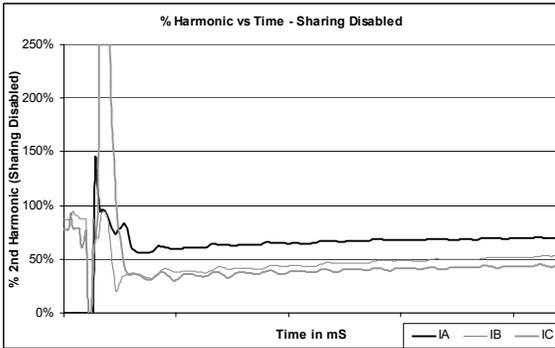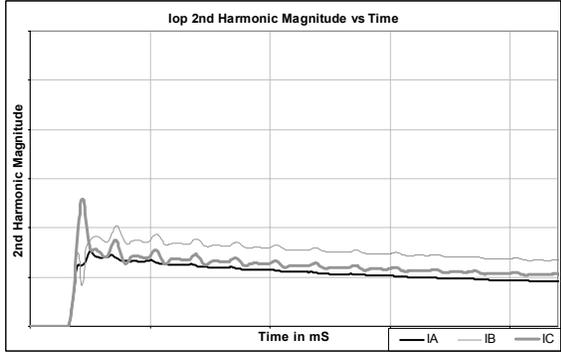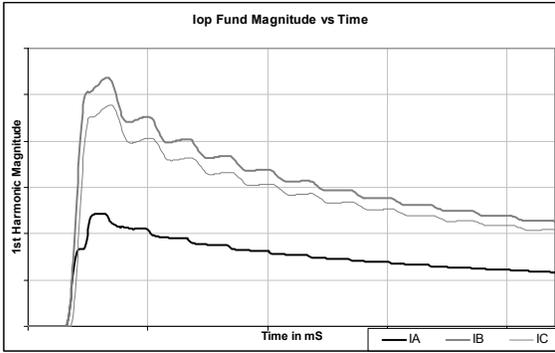
% 2nd Harmonic (Sharing Enabled)
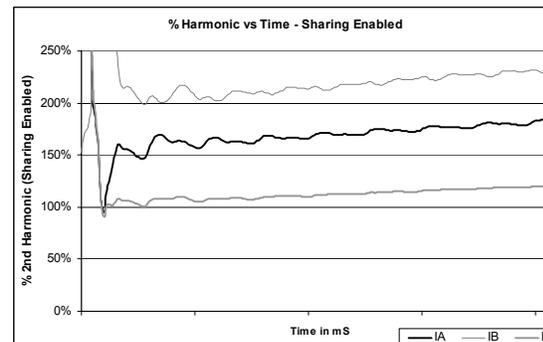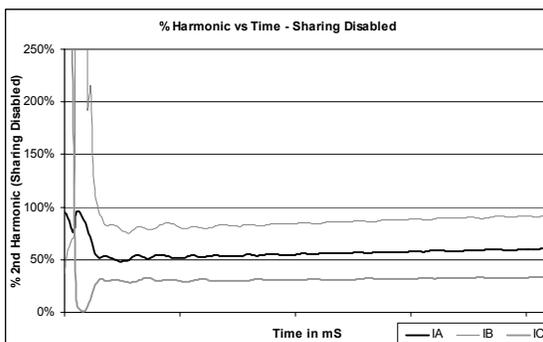
250%
200%
150%
100%
50%
0%

Time in mS

IA   IB   IC
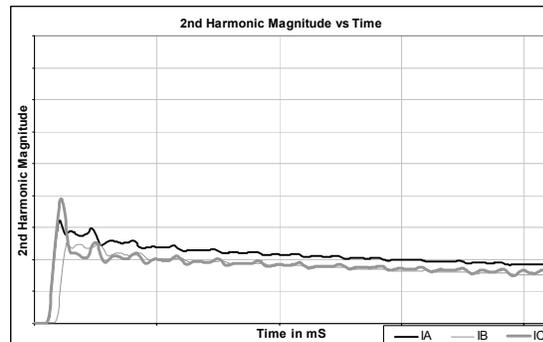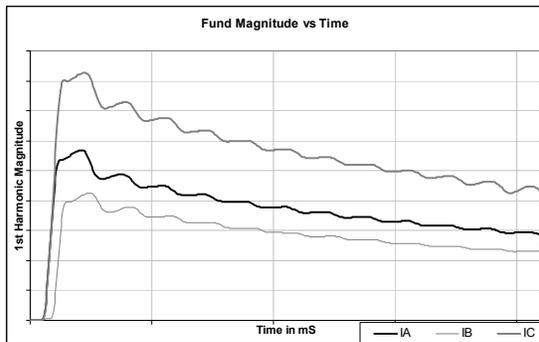
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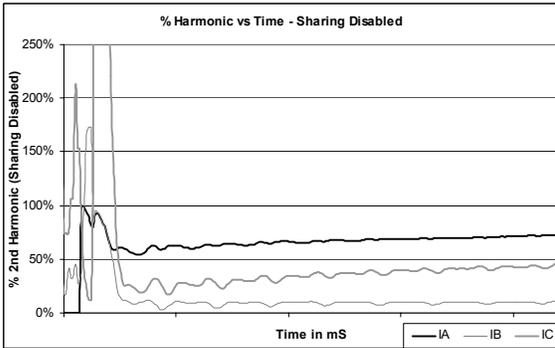
Case 5, file 0208121432.xls
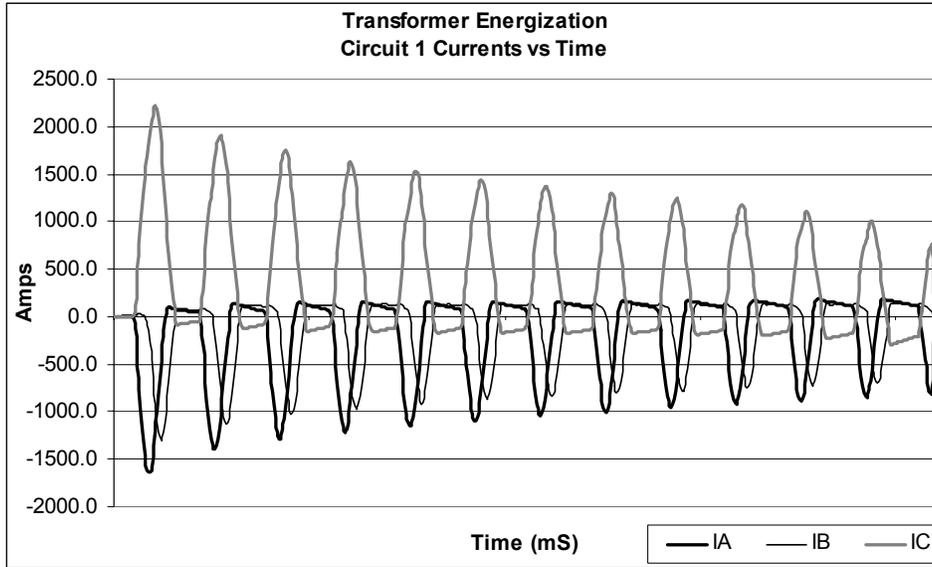
Same installation as case 4: 69/12.47kV 25MVA D-Y Internal compensation. 4.18A full load (250/5 CT) = 209A FL. Energization peak is 397A. Note: 2nd harmonic %, is reasonable. A phase energization very low (<50% of peak) and bipolar. B & C phase within 11%, opposite polarity

Transformer Energization
Circuit 1 Currents vs Time

Transformer Energization
Circuit 2 Currents vs Time

Iop Fund Magnitude vs Time

1st Harmonic Magnitude — *Time in mS* — IA — IB — IC

Iop 2nd Harmonic Magnitude vs Time

2nd Harmonic Magnitude — *Time in mS* — IA — IB — IC

% Harmonic vs Time - Sharing Disabled

% 2nd Harmonic (Sharing Disabled) — *Time in mS* — IA — IB — IC

% Harmonic vs Time - Sharing Enabled

% 2nd Harmonic (Sharing Enabled) — *Time in mS* — IA — IB — IC

21

Case 6, file 0003221427.xls

This is an example of an energization waveform captured by a basic numeric overcurrent relay connected to a transformer primary side. The inrush characteristics can be evaluated, sine the energization is with the secondary side open.

Transformer Energization
Circuit 1 Currents vs Time

Fund Magnitude vs Time

2nd Harmonic Magnitude vs Time

% Harmonic vs Time - Sharing Disabled

% Harmonic vs Time - Sharing Enabled

Case 7, file 0301221423.xls

66/11kV Delta-Wye transformer (50Hz). This is an example of a balanced 3 phase through fault just outside the transformer's zone of protection. The transformer was 66/11kV, connected Delta-Wye. There was significant unequal saturation on the sensing CTs, especially on the secondary side. Evaluation of the differential relay currents shows that there was significant second harmonic, but low enough compared to the fault current to not cause an undesirable inhibit, with or without sharing.
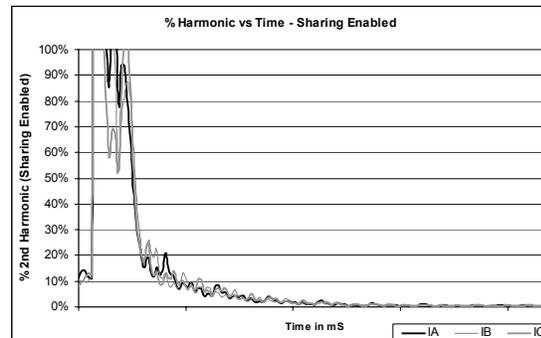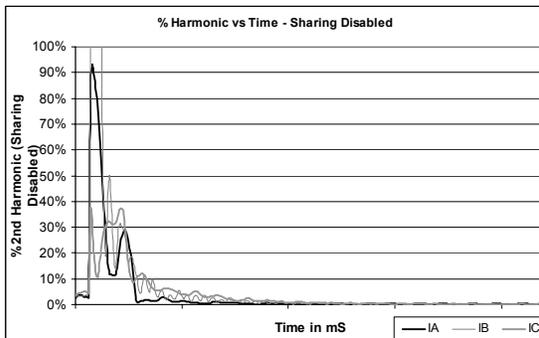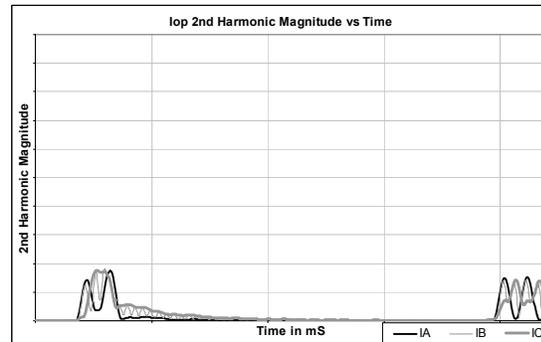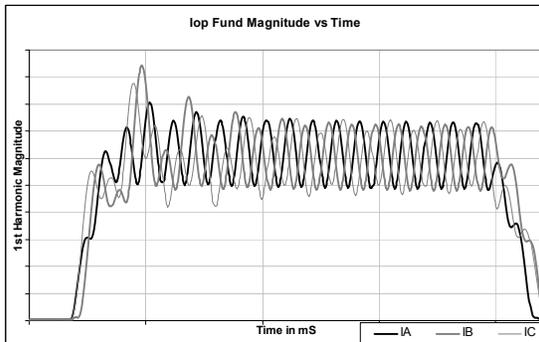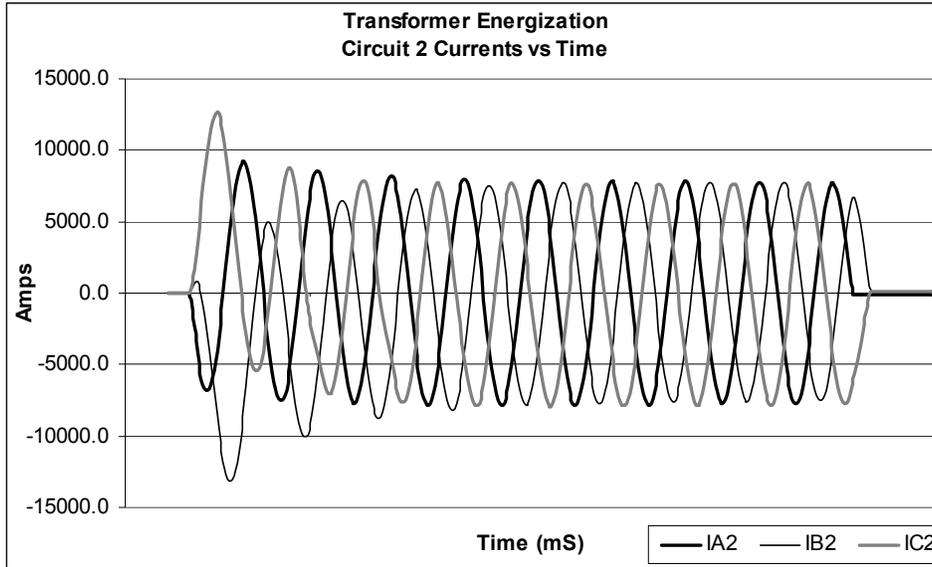
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