Power Transformer Inrush Current Detection & Harmonic Sharing In Differential Relay Protection

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Abstract- *Differential relays protection is one of the most widely used methods for protecting power transformer against internal faults. The technique is based on the measurement and comparison of currents at both sides of transformer primary and secondary lines.*

Security of transformer differential protection schemes is dependent on detecting the magnetizing inrush currents of the protected transformer and associated differential operation due to inrush was maintained for faults during inrush conditions, as the fundamental current in the faulted phase easily override the sum of the second harmonic currents associated with energizing the un-faulted phases.

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. By implementing harmonic sharing, a single harmonic signal was created. Each phase element of the differential relay uses this summed signal to make its independent restrain decision. With harmonic sharing, the overall percent harmonic signal is significantly higher. It permits fast tripping for all internal faults with minimal delay when energizing a faulted transformer, and prevent differential relay operation during transformer over excitation.

Keywords: *MPBR, Differential Relay, Power Transformer, CTs, Inrush Current, Harmonic Sharing.*

I. INTRODUCTION

Differential relays protection is one of the most widely used methods for protecting power transformer against internal faults. The technique is based on the measurement and comparison of currents at both side of transformer: primary and secondary lines. The differential relay trips whenever the difference of the currents in both sides exceeds a predetermined threshold. This technique is accurate in most of the cases of transformer internal faults however mal-operation of differential relay is possible due to inrush currents, which result from transients in transformer magnetic flux. The transients in transformer magnetic flux may occur due to energization of transformer, voltage recovery after fault clearance or connection of parallel transformers (Manoj, 2012). Transformer differential protection generally has been recommended for transformers of 5MVA rating and above, but the economics of multifunction, microprocessor-based 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. Differential protection is a fast, selective and most reliable technique in power system protection against internal faults, short circuit and security against operation on large external faults in power transformers. Differential relay protection operates on the basic theory of Kirchhoff's current law which states that the sum of the currents entering the node should equal the sum of the currents leaving the node. In Differential protection, the currents entering and leaving the protected zone are compared by CTs. If the net sum of the currents entering and leaving a protection zone is zero, it is concluded that there is no fault in the protection zone. However, if the net sum is not zero, the differential protections conclude that a fault exists in the zone and takes steps to isolate the zone from the rest of the system. Merz and Price, 1904 developed the first approach for differential protection. The advantages of the scheme proposed by Merz and Price were soon recognized and the technique has been extensively applied since then (Perez, 2006).

II. GENERAL DESCRIPTION

Differential relays are often used as main protection for all important elements of the power system such as generators, transformers, buses, cables and short overhead lines. The protected zone is clearly defined by the positioning of the main current transformers to which the differential relay is connected. It is based on ampere-turn-balance of all windings mounted on the same magnetic core limb. In order to correctly apply transformer differential protection it is necessary to properly compensate for:

- current magnitude compensation;
- Phase angle shift compensation; and provide
- Zero sequence current compensation.

With electromechanical differential relays such compensations were performed with, the CTs on the delta transformer windings connected in star and the CTs on the star winding of the transformer connected in delta, or by using interposing CTs or special connection of main CTs (Guzman, et al., 2002).

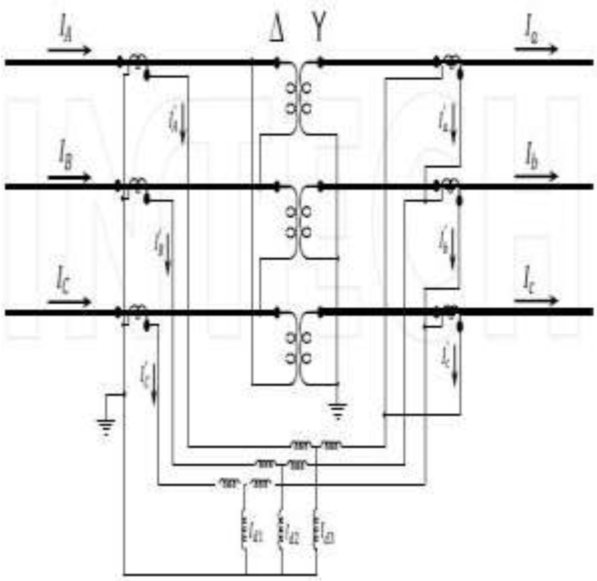


Figure 1: Differential protection of 3-phase Star/Delta Transformer

This is to ensure that the phase shifts created in the currents of the power transformer are compensated by the CTs, so that the secondary currents are once again in phase. This provides a zero sequence current circulating path within the current transformers connection so that it cannot flow in the relays. Figure 1 show the connections of a differential protection scheme with Star / Delta CTs.

a) Energization of Transformer

Energization of transformer is a typical event where magnetizing inrush currents are of concern. The excitation voltage on one winding is increased from 0 to full voltage. The transformer core typically saturates, with the amount of saturation determined by transformer design, system impedance, the remnant flux in the core, and the point on the voltage wave when the transformer is energized.
An external fault may significantly reduce the system voltage, and therefore reduce the excitation voltage of the transformer. When this fault is cleared, the excitation voltage returns to the normal system voltage level (Blackburn and Thomas, 2007). The return of voltage may force a dc offset on the flux linkages, resulting in magnetizing inrush current. This magnetizing inrush current will be less than that of energization, as there is no remnant flux in the core. The current measured by the differential relay will be fairly linear due to the presence of load current, and may result in low levels of second harmonic current.
Transformer energization creates a true unbalance, 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. The evaluation of harmonic content in the energization currents has been the primary means of inrush detection in transformer differential relays for many years. The transient generates a current known as inrush current. The magnitude of this inrush current can be several times the load current and flows only on one side of the differential relay, which tends to operate if some form of restraint is not provided. Figure 2 shows a typical curve of inrush current due to the energization of a power transformer. 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. Faults during energization are detected by supervising the restrained element with an unrestrained element, set above the largest expected energization magnitude.

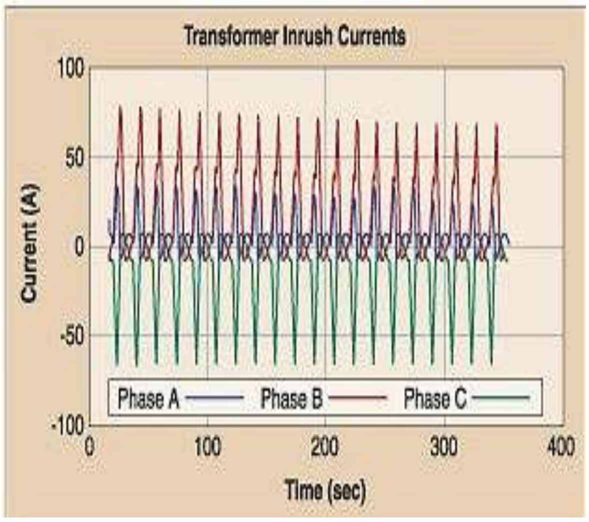


Figure 2: Typical magnetizing inrush current in a power transformer

Thresholds for defining energization generally have been fixed between 12% and 32%, depending on relay type. Undesired operations of differential relays during energization 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. 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.

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.

i. Harmonic Restraint and Blocking Techniques

In the harmonic restraint element, the operating current, I_{OP}, must overcome the combined effects of the restraining current, I_{RT}, and the harmonics of the operating current for the element to assert a trip output. Any measurable harmonic content provides some benefit toward the goal of preventing differential relay operation during inrush conditions. On the other hand, in the harmonic blocking element, the operating current is independently compared with the restraint current and those selected harmonics when the harmonic content is above a specified threshold. When the harmonic content is below the specified threshold, the harmonic blocking has no effect. The selection of harmonics, and the variables used to compare harmonics with the operate current in either a harmonic blocking or harmonic restraint relay, are crucial to the successful operation of either type of scheme. Generally, harmonic blocking or harmonic restraint elements are successful if they fulfill all of the following requirements:

- Permit fast tripping for all internal transformer faults with minimal delay when energizing a faulted transformer
- Prevent transformer differential relay operation during transformer over excitation
- Prevent differential element operation during transformer energization and during voltage recovery following a power system fault

The magnetizing inrush currents have high component of even and odd harmonics (Guzman et al., 2002).

ii. Advantages of Microprocessor-Based Differential Relay Protection

- High stability against CT saturation provided by integrated saturation detector and add-on stabilization.
- Highly stabilize against inrush currents due to advanced filter technology (Fourier analysis) and optional cross-blocking function.
- High stability against over-excitation (5th harmonic blocking).
- Short tripping time - typically 1.5 cycles
- High set differential current (Iop) fast tripping < 1 cycle

Microprocessor-Based Relays offer many other features that electromechanical relays do not offer such as fault locating, event reporting, advanced metering functions and control capability. The event record provides data on the internal relay element operation and the currents and voltage waveforms at the time of operation. This is similar to having a fault recorder on every breaker where a microprocessor-based relay is installed. The event data is an invaluable tool in evaluating relay and system performance. All of the waveforms presented in this paper are derived from relay data recording.

III. Material and Methods

Microprocessor-based differential relays incorporate second harmonic restraint feature (magnetizing inrush currents). Harmonics restrain is based on the fact that the inrush current has a large second-harmonic component of the differential current which is much larger in the case of inrush than for a fault. The over-excitation current also contained fifth-harmonic component. Therefore, these harmonics are used to restrain the relay from tripping during these conditions. Modern relays use second and fifth harmonics for restraint so that the relay is prevented from tripping for inrush and over-excitation, but is not blocked from tripping for internal faults with CT saturation.

In harmonic sharing technique, the incoming currents are filtered to extract the fundamental signals (for faults and load) and the second harmonic signal (for inrush). The overall inrush signals (2nd harmonic) are then summed to create a single harmonic signal, representing the overall inrush currents as shown in figure 3.

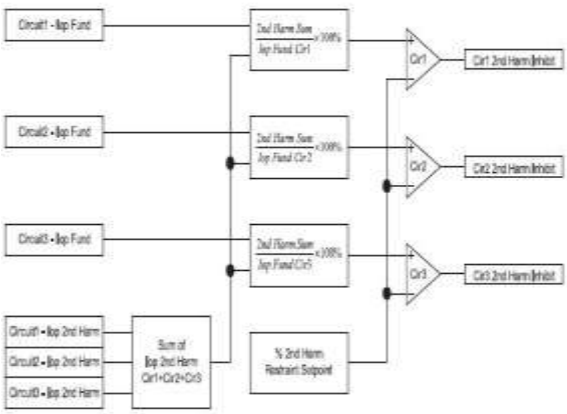


Figure 3: Circuit Diagram of Harmonic (blocking) Inhibit

The inhibit threshold is adjusted to accommodate the larger overall signal resulting from the summing. Rather than using 12% independent harmonic, 18% summed harmonic was used. 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 was maintained for faults during inrush conditions, as the fundamental current in the faulted phase (unbalance) easily override the sum of the second harmonic currents associated with energizing the unfaulted phases.

Two case studies are presented to clarify these points. Each was taken from data records from microprocessor-based relay systems, with the data exported from COMTRADE format, and imported into Excel spreadsheets.

IV. ANALYSIS AND RESULTS

Case study #1: Transformer Energization:

The waveform in figure 4 shows an energization of a three phase 33/11kV, 15MVA D-Y connected transformer with internally compensated recorded by a digital relay. The transformer was energized from the high voltage side, with the secondary side open. The secondary circuit currents (LV side) are zero, so the primary circuit currents will reflect as the differential current.

Load current $I_L = \frac{MVA}{\sqrt{3}\,V_L} = \frac{15*10^3}{\sqrt{3}*33} = 262$ A

Select CT ratio of 300/5 and differential relay currents

$$= \frac{I_L}{CTR} = 4.367A.$$

Energization peak is 328A. It contained more harmonic content of minimum ~40% without sharing, but C phase is lower than A&B.

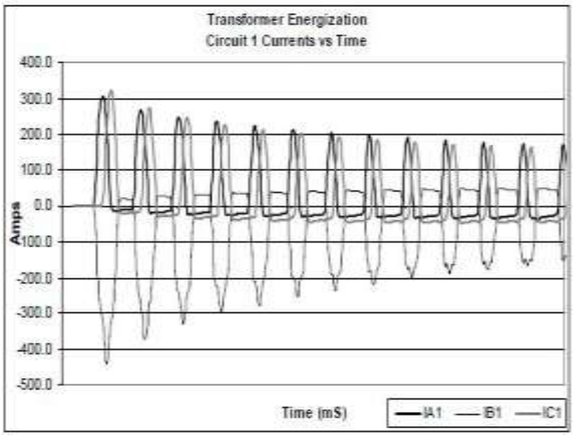


Figure 4: Transformer Inrush Current

The A and C phase inrush currents are close in magnitude (within 3% at first peak); while the B phase peak is significantly less than 27%. 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 secondary circuit signals are not shown. They are accounted for in the spreadsheet calculations and the associated charts.

Figures 5(a &b) show the signals developed internal to microprocessor-based differential 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. 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.

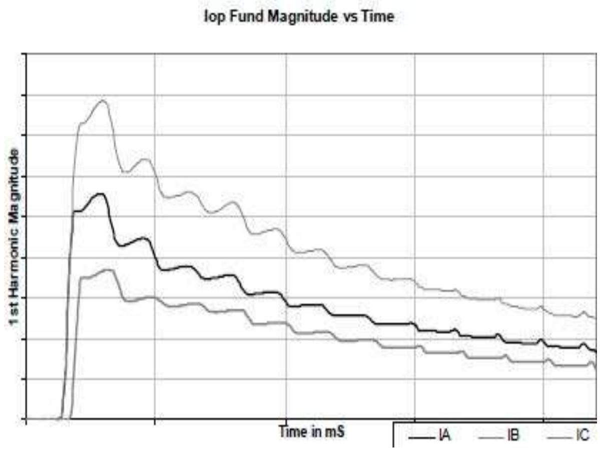


Figure 5 (a): Fundamental Unbalance Current

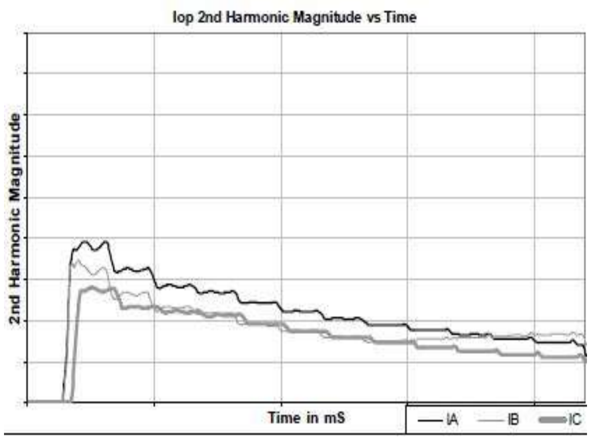
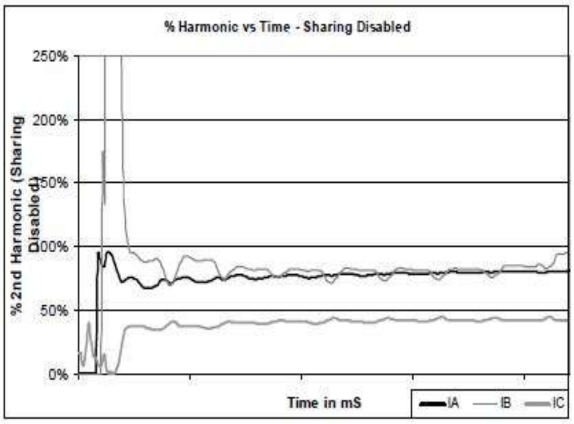


Figure 5 (b): 2nd Harmonic Unbalance Current

Figure 5 (c) shows the percent 2nd harmonic signal associated with the first energization, without harmonic summing. After the initial noise associated with the DFT signal processing, each of the phases was well above the typical thresholds of around 12% second harmonic. C phase, the lowest, has a second harmonic signal that was 35-40% of the fundamental signal. A and B phase have more second harmonic signals greater than 75% of the associated fundamental.



(c): Second Harmonic Content without Sharing

Case Study #2
Energization with Low Harmonics:

The data used for the analysis were obtained directly from the station power transformer as presented**.** The waveform in figure 6 shows an energization of a three phase, 60MVA, D/Y 132/33KV, 50Hz 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 digital relay specifically for data recording to analyze their situation.

Analysis

Load current $I_L = \frac{MVA}{\sqrt{3}\,V_L} = \frac{60*10^3}{\sqrt{3}*132}$ = 262.44 A

Select CT ratio of 300/5 and differential relay currents

$$= \frac{I_L}{CTR} = 4.374A.$$

Simulated energization peak was 440A. It shows that very low 2nd harmonic of less than 10% on B phase without sharing; and greater than 50% with sharing enabled. Figures 6 (a and b) shows an inrush condition, with both circuits primary winding (HV) and secondary winding (LV) included.

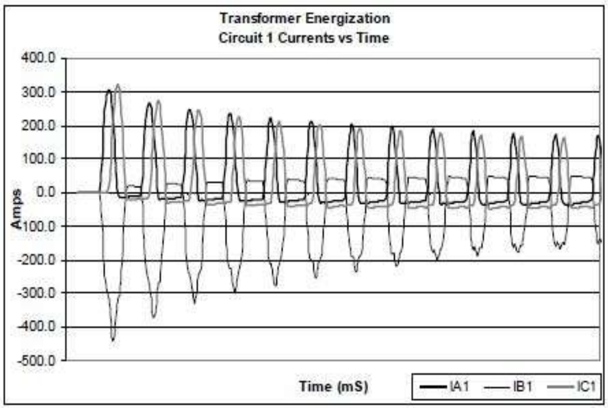


Figure 6: (a) Transformer Inrush Current, High Voltage Side

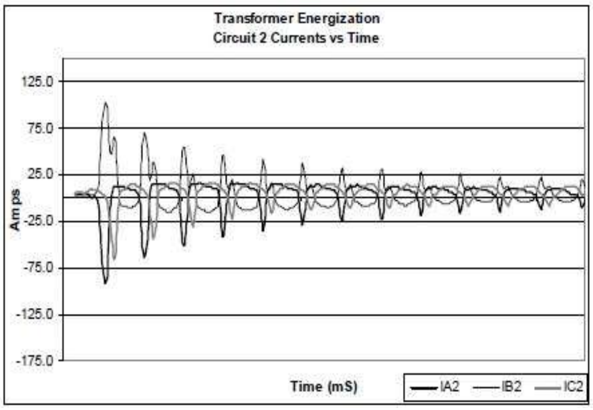
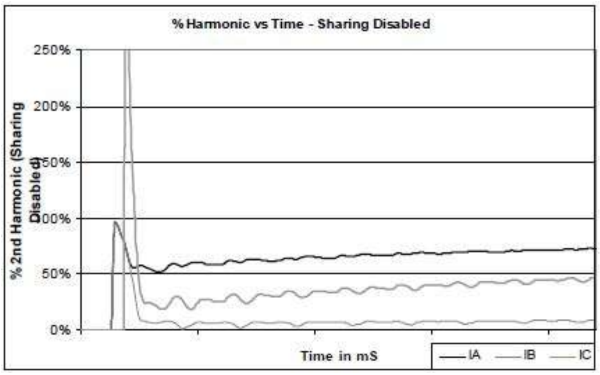


Fig 6: (b) Low Voltage Side

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. As a result, the B phase elements percent harmonic, without sharing, is well below normal thresholds, around 7- 10% as shown in Figure 7 (a). This is the cause of the insecurity. The C phase signal is lower than 20-25%, but still comfortably above the threshold.

By implementing harmonic sharing, a single harmonic signal was created. Each phase element of the differential relay uses this summed signal to make its independent restrain decision. With harmonic sharing, the overall percent harmonic signal is significantly higher. The faulted B phase rises from under 10% second harmonic to over 50% second harmonic as shown in Figure 7 (b).

Even with the higher threshold of 18 %, the safety margin exceeds 2:1, compared with being insecure with sharing disabled.



(a) Second Harmonic Content without Sharing

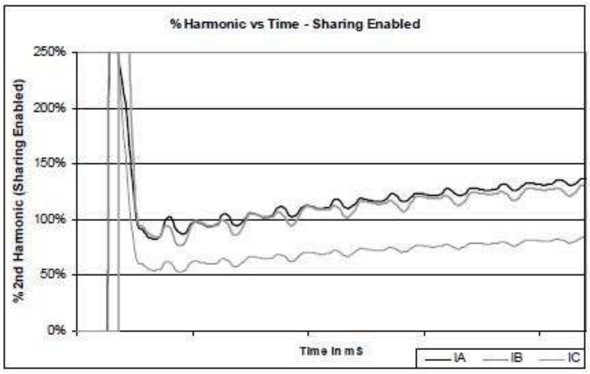


Figure 7 (b) Second Harmonic Content with Sharing Enabled

V. CONCLUSIONS

The availability of data event recording in microprocessor-based relay systems has provided a whole new level of data for analysing relay operations, and evaluating system conditions. The additional features which include fault locating, self-monitoring, control, and communication capabilities of relay systems allowed improve protection capabilities. The use of harmonic sharing in transformer differential protection gives the ability to improve security for some inrush conditions, while maintaining sensitivity.

Generally, harmonic blocking or harmonic restraint elements were successful as they permit fast tripping for all internal transformer faults with minimal delay when energizing a faulted transformer, Prevent transformer differential relay operation during transformer over excitation, Prevent differential element operation during transformer energization and during voltage recovery following a power system fault.

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