Stabilizing the Differential Protection of Transformers Supplied with High Charging Circuit

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Abstract

False trips of the current differential protection of power transformers have become more frequent in Hydro One grid in recent years due to decreasingly low second harmonics in the magnetizing inrush current of power transformers. Protection engineers have made great effort to mitigate these misoperations by applying the cross-blocking scheme, the two-out-of-three logic etc. These schemes have significantly contributed to reducing the number of misoperations of transformer differential protections during magnetizing inrush.

In metropolitan areas, transformers are commonly supplied by underground cables. This is the case in downtown Toronto. It is well known that underground cables have a high distributed capacitive effect which causes a discharge transient. The characteristics of this transient are very different from those of conventional magnetizing inrush currents. The discharge often generates currents in all three phases that contain low-magnitude second harmonics. The reduced level of second harmonics will result the differential elements to lose restraint even if the cross-blocking scheme is adopted. Several misoperations of the transformer current differential protections due to low second harmonics in all three phases occurred in past over 10 years in the Hydro One grid.

Event data of several misoperations are analyzed and presented in this paper. Recent analysis on event data of misoperation with high capacitive charging circuit shows that adaptive scheme in an IED can excellently deal with this kind of inrush transient without causing misoperation. The scheme is an embedded feature in the existing IED platform. No hardware or firmware upgrading is necessary. The modification is implemented simply by changing relay logic and settings. With this scheme change the protection reliability is significantly improved with minimal cost and no capital investment.

1.0 INTRODUCTION

Current differential protections have been traditionally used as the primary protection for power transformers. Traditionally, second harmonic restraint is one of the most popular schemes to avoid unnecessary trips caused by inrush currents. The scheme is implemented in almost every modern digital transformer protection. The basis of the scheme is that the magnetizing inrush current contains high second harmonic component, as opposed to fault currents, which do not contain very low second harmonics.

The magnitude of the second harmonic component, however, is a function of the degree of saturation and also of other factors. The second harmonic content, which becomes significant as the transformer enters the saturation state, can assume very small values if the transformer core goes into deeper saturation due to high residual flux, and operates in the linear region well above the knee point of the B-H curve as shown in Figure 1. In this zone, the magnetizing current has a linear relationship with the magnetic flux in the core. For this reason, the level of the second harmonic in inrush currents is significantly decreased due to the improvement of the core steel of power transformers [1]-[5].

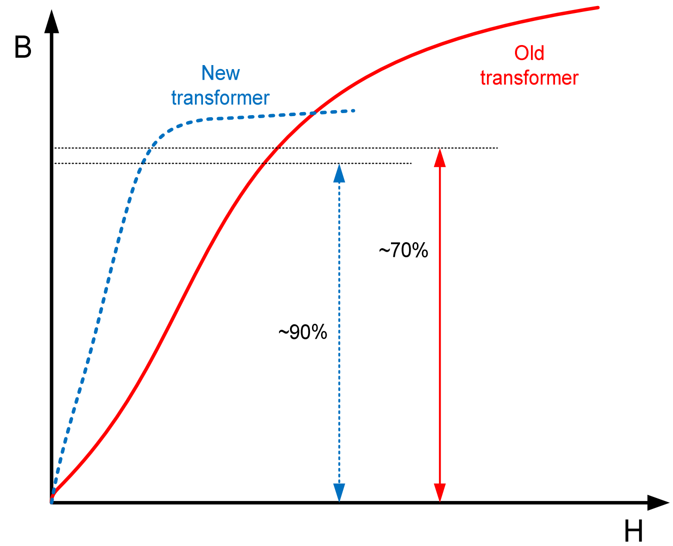


Figure 1 Magnetization characteristics of the new and old transformer cores

The reduced level of second harmonics in the magnetizing inrush current has been a major cause of false trips of power transformer current differential protections during energization and de-energization of power transformers in the Hydro One grid. As theoretically expected, in many cases the second harmonic component is not sufficient to restrain the relay adequately, and misoperation becomes unavoidable. Misoperation occurrences in Hydro One have escalated as the number of new transformers installed into the grid has increased, with total 41 times (IED only) from 2005 to 2010, distributed over the years as shown in Figure 2.

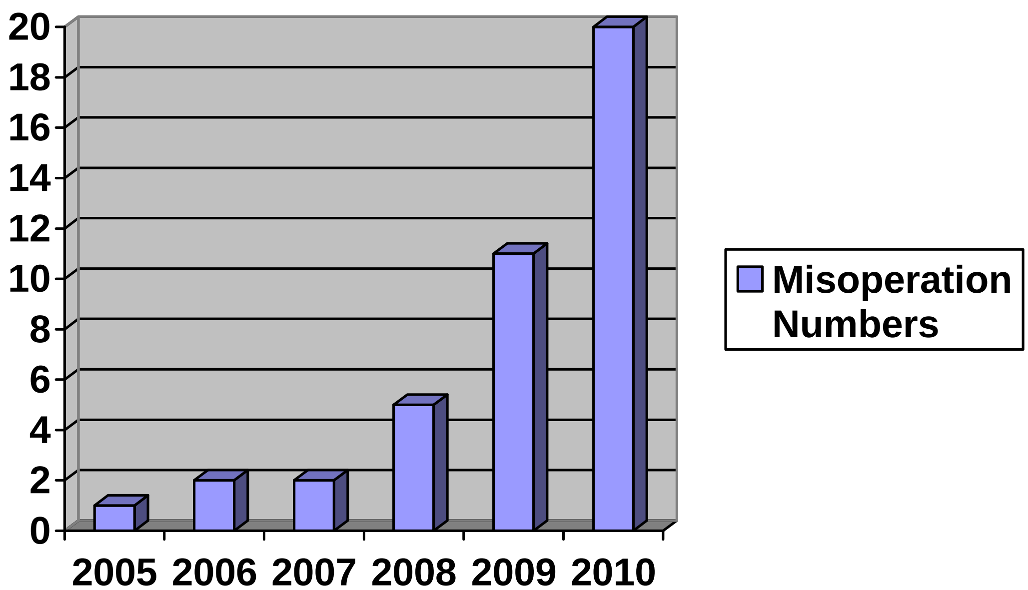


Figure 2 Misoperation Numbers in Years

Protection engineers have strived to find methods to solve this problem. One popular solution known as the cross-blocking scheme can prevent misoperation of a current differential protection if high second harmonic is detected by the differential relay of any individual phase.

2.0 HARMONICS ANALYSIS AND PROTECTION SCHEMES

Many utilities worldwide have reported increasing frequency of misoperations due to low levels of second harmonics in magnetizing inrush currents of power transformers. Harmonic analysis of the transformer inrush currents provides a better understanding on the problem and its solutions.

2.1 Magnetizing Inrush Analysis

Magnetizing inrush current is typically of much higher magnitude than the normal exciting and load currents. This is because the energization operation brings the transient process to the saturation region of the flux-current curve (B-H curve), due to a high DC component in the magnetizing current. The magnitude of the DC component is determined by the level of residual flux in the transformer core, the closing phase angle of the source voltage and other factors. Traditionally, the second harmonic component in the inrush current has been used to distinguish magnetizing inrush from actual fault currents. For most of the energization operations, the ratio of the second harmonic to the fundamental component should be at least 17-20%. However, as newer transformers have been adopted in the past two decades, many utilities have experienced an increased frequency of false trips due to the lower second harmonic inrush current of these transformers. As more transformers built with new core materials and improved material orientation are put in service, misoperations related to low second harmonics will become even more frequent [[1]-[11].

A key characteristic of the second harmonic in core saturation is that its magnitude will gradually increase as the core recovers from deep saturation as the transient process progresses because of the resistive impedance and the hysteresis characteristics of the B-H curve. Conversely, the fundamental component will decrease, causing the ratio of the second harmonic to the fundamental component to increase. As explained in many academic papers and observed from actual field data recorded by IED relays and DFRs, it will take up to 4-5 cycles for the second harmonic to grow to about 20% of the fundamental if the second harmonics is low at the initial moment of energization [3].

Figure 3 shows an event of the variation of actual inrush currents measured in the field. These oscillography waveforms show that the current differential protection senses low second harmonics in phase B with a duration of up to 5 cycles (XFMR PCNT 2ND B element). It results in the differential protection operates (XFMR PCNT DIFF OP).

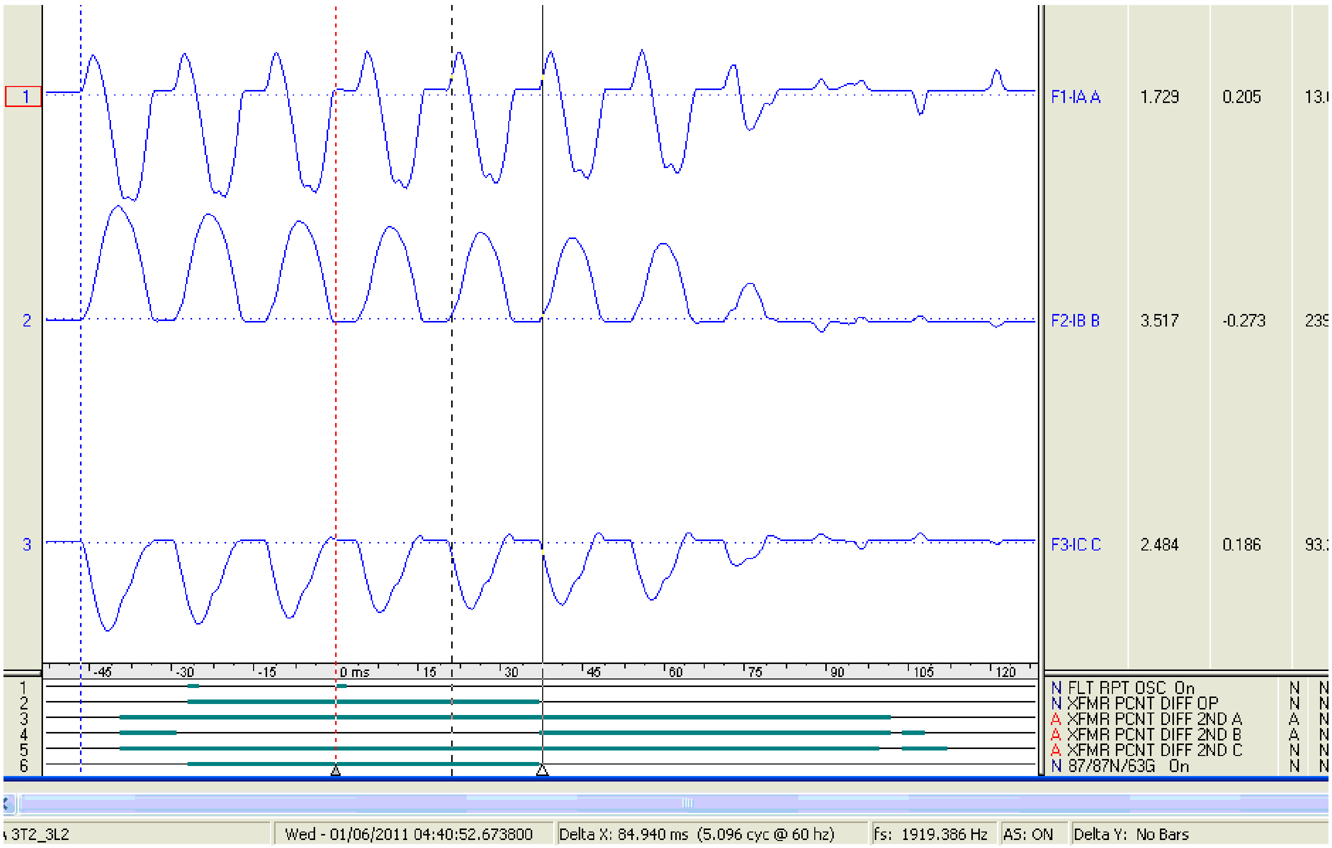


Figure 3 Magnetizing Inrush Current in Differential Relays

Figure 3 also shows the protection elements operation due to sensing second harmonic components (lines 3-5 in the lower part), which represent the ratios of the second harmonics to the fundamental components in the differential current in each phase. In phase B, It can be shown that the ratio is lower than the setting value, i.e., 15%, at the initial moment of energization. However, the ratio exceeds the setting threshold after 5 cycles from the inception of the energization. Therefore, loss of second harmonic restraint only occurs during the first few cycles. Experience acquired through extensive field measurements by many utilities worldwide reveals that the absence of harmonic restraint can last for up to 4-5 cycles [1].

The characteristics of magnetizing inrush current of transformers can be summarized as follows:

1) During most of the energization duration, the second harmonic content in the magnetizing inrush current is normally high enough to restrain the current differential protection.

2) Low second harmonic content typically appears during the first few cycles of energization. The maximum duration may be 4-5 cycles.

3) During energization, low second harmonic is experienced in only one phase of the differential current. The second harmonic contents in the other two phases are typically high enough to stabilize the current differential protection.

4) Different relay algorithms have different effect on operation behavior of the relays [1], that is, two relays from different manufacturers may have different operation behaviors.

Hydro One has significantly mitigated misoperations by applying cross-blocking and two-out-of-three blocking logic schemes. Therefore, this paper will not further discuss this topic.

2.2 <u>Magnetizing Inrush Current with Underground Cables</u>

However, in misoperation events listed Figure 2, it is found that some events can't be avoided by applying cross-blocking scheme or two-out-of-three logic since inrush current in these event have different patterns.

In downtown Toronto and other metropolitan areas, there are some 115 kV or 230kV transformers connected at the end of long underground cables as shown in Figure 4. In order to save cost of the HV circuit breakers, no circuit breaker is normally installed at HV side of a transformer in Hydro One. One disconnect switch is used to isolate the transmission line from the transformer instead.

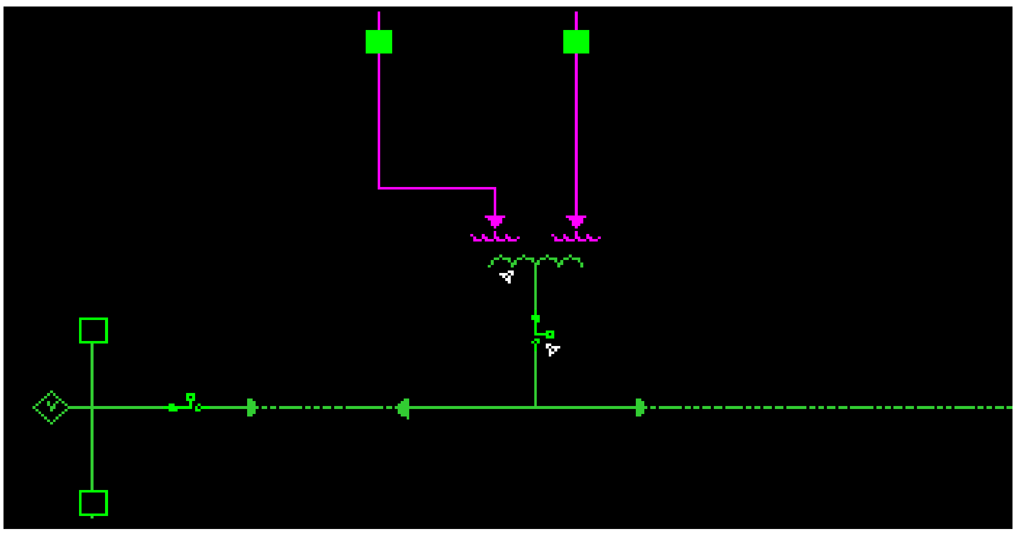


Figure 4 One Transformer Supplied with Long Underground Cable

It is well known that interrupting a current with a high inductance generates a high voltage across the open pole. Therefore, for some old transformer stations in downtown Toronto area, energizing or de-energizing a transformer is normally done by closing or opening a line breaker at a remote station as shown in Figure 4. The switching operation of the remote breaker will cause a transient between the distributed capacitance and transformer magnetizing impedance. The distributed capacitance of the long underground cables has caused many misoperations during transformer de-energization by opening the remote breaker at the terminal stations. Figure 5 shows an event waveforms recorded by an IED when the transformer shown in Figure 4 was de-energized. The IED operated during the transient current.

The inrush current in Figure 3 has a pattern that the current is offset to one side of time axis, but the inrush current in Figure 5 has both positive and negative value for all three phases, which is kind of symmetrical with respect to the time axis. According to Fourier frequency analysis, this symmetrical pattern of waveforms has lower even harmonic contents but with high odd harmonics.

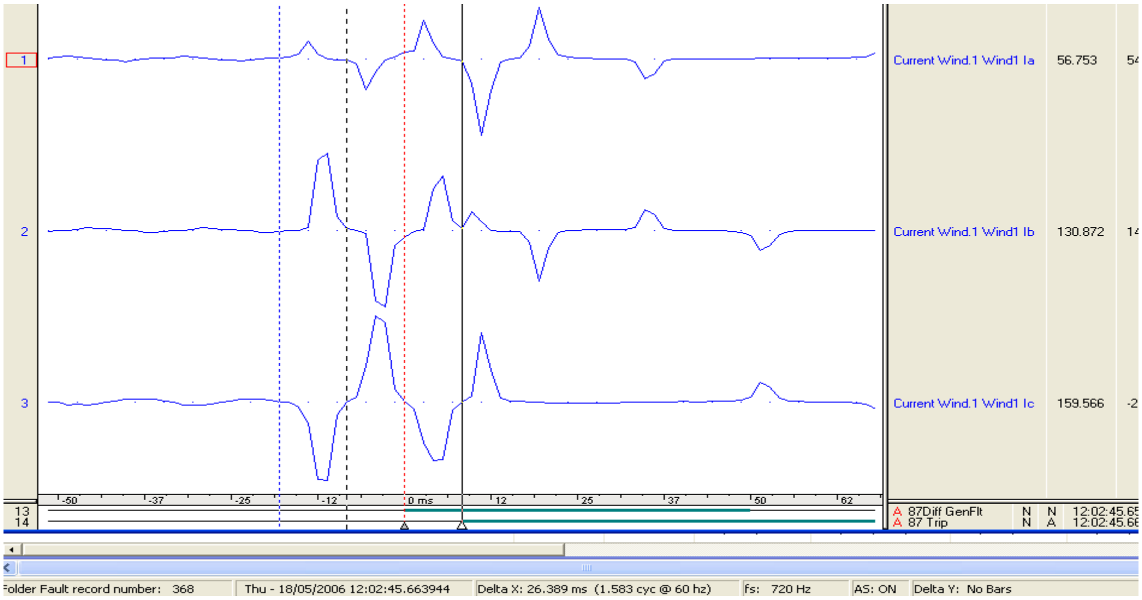


Figure 5 Transient Current during De-Energization

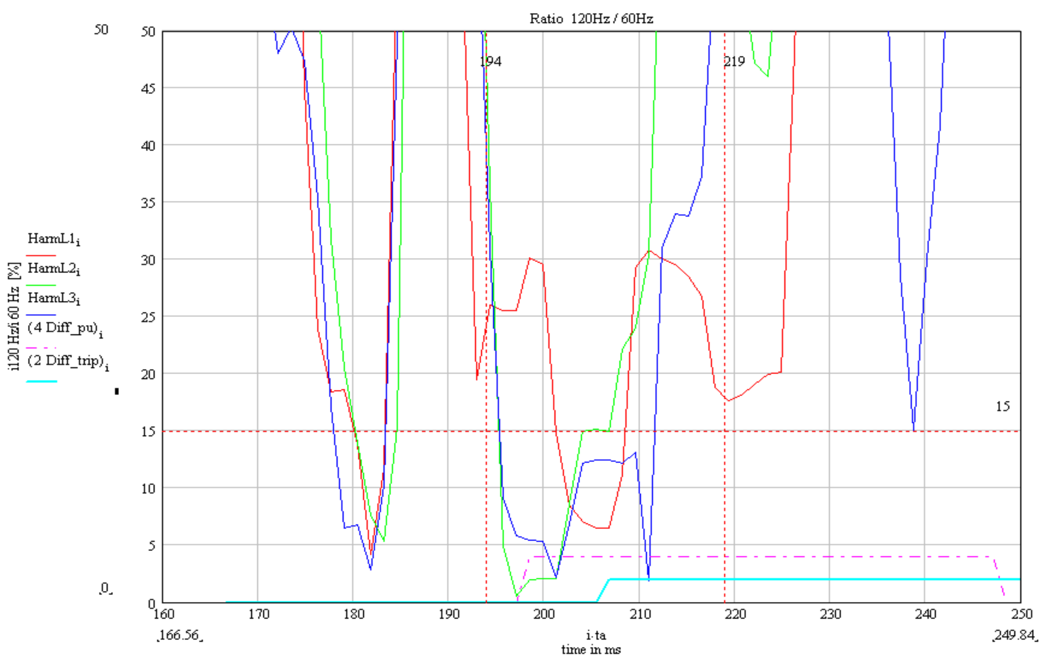


Figure 6 the Second Harmonics in Three Phase Transient Currents

The spectrum analysis on the data recorded by the relays for different circuits reveals that second harmonic currents at the three phases may have very low magnitudes at the same time even though not for a very long period as shown in Figure 6. During the period between 200ms and 210ms, there is short duration that all three phases of differential elements experience low second harmonics.

This paper will focuses on how to avoid misoperation of transformer current differential protection during inrush due to high capacitive charging effect.

2.3 Application of Adaptive Scheme

The adaptive scheme [3, 6] is proposed to distinguish actual fault from inrush current in some types of transformer protections. The method was intended to provide high security under low second harmonic inrush conditions. The adaptive scheme operates on the basis of individual phases. It compares both the magnitude and the phase angle between the fundamental and second harmonic in the inrush current. If the differential relay of any phase operates, a trip signal will be issued.

One of the main obstacles to use the adaptive scheme is that users must make a very difficult choice between the adaptive scheme and other traditional schemes. Protection Engineers in Hydro One also are not confident on the adaptive scheme in that it doesn't need a setting like other traditional scheme. Therefore, the adaptive scheme has not been used in Hydro One grid for transformer protection.

However, during the investigation of a misoperation event, it was found incidentally that adaptive scheme had been applied in a turnkey project by a contractor. In this event, the IED with adaptive scheme did not misoperate, but, another IED with traditional method operated on same inrush due to high capacitive charging.

After the event, Matlab simulation tests were done with historic event data of misoperation under similar conditions. The simulation tests verified that the adaptive scheme can effectively avoid misoperation under the inrush with high capacitive charging. Since the adaptive scheme is a feature embedded in the existing IED platform, no hardware, firmware and external wiring changes will be required for applying the adaptive logic. It is a cost effective solution to avoid misoperation of transformer protection. In addition, the problem is solved without sacrificing dependability of the protection.

2.3.1 Adaptive Inhibit Method

Traditional differential protection scheme distinguishes fault from inrush by comparing second harmonic level. It uses only magnitudes of second harmonic content and fundamental component. The Adaptive Inhibit method uses both magnitude and phase angle relation between the second harmonic and fundament component in the differential current.

The ratio between the second harmonic and the fundamental frequency component is defined as:

$$I_{21} = \frac{I_2}{I_1 \cdot e^{j\omega t}} = \frac{|I_2|}{|I_1|}(\text{angle}(I_2) - 2 \cdot \text{angle}(I_1)) \qquad (1)$$

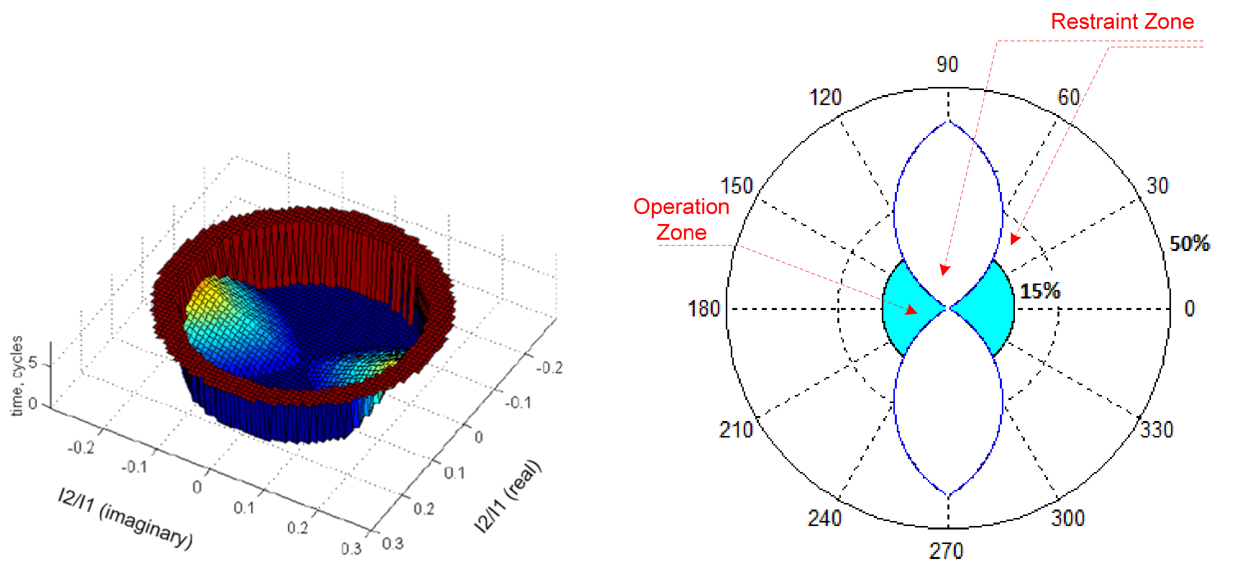
$$I_{21\_MAG} = \frac{|I_2|}{|I_1|} \qquad (2)$$

$$I_{21\_ANG} = \text{angle}(I_2) - 2 \cdot \text{angle}(I_1) \qquad (3)$$

where $e^{j\omega t}$ in equation (1) is to account for the fact that the second harmonic rotates twice as fast as the fundamental frequency.

Traditional 2nd harmonic inhibit method uses I_{21_MAG} alone. In adaptive inhibit method, besides I_{21_MAG}, I_{21_ANG} is also used to cope with low magnitude of 2nd harmonics inrush current applications to prevent differential elements from false tripping during inrush.

Through analysis and simulation testing, it's concluded that I_{21_ANG} is close to ±90 degrees region during inrush, and close to 0 and 180 degrees region with I_{21_MAG} less than preset ratio (e.g., 15%) of the second harmonic to fundament component for internal faults, and as such, two lenticular shape zones along ±90 are established on the I2/I1 complex plane to block differential elements from tripping. These two lenticular shape zones dynamically shrink with time as shown in the figure below, in which the time is counted from when the differential/restraint trajectory first time enters into the differential protection characteristic.



a) 2nd Harmonic Ratio Baries as Time [3]

(b) Operation Zone Vs Restraint Zone

Figure 7 Adaptive Inhibit Method

With the adaptive inhibit method, it can be concluded that [3]

- If the angle of I_{21} is close to 0 or 180 degrees, the inrush restraint is removed immediately for lower magnitude of the second harmonic, and as a result, there will be no additional delay for most internal faults.
- If the angle is close to ±90 degrees the delay before removing the restraint depends on the amount of the second harmonic: for low ratios of the second harmonic (I_{21} trajectories on some internal faults may transiently enter into this region), the delay is very short; while for ratios close to 20% is rises to 5-6 cycles; this is enough to prevent misoperation due to the second harmonic dropping below some 15-20% during inrush conditions.

2.3.2 Simulation Test Results

In order to validate adaptive scheme, numerous digital simulations were done with event data from Hydro One grid. Three cases were shown in this paper. The first two cases were shown in applying adaptive scheme to secure the current differential protection during inrush due to high capacitive charging, and the third case was shown that applying adaptive scheme would not cause dependability issues on differential elements during internal fault.

Case 1: 115kV transformer with long underground Cables

The inrush currents have similar pattern as Figure 5 but different from Figure 3. Frequency spectrum analysis shows that differential current experiences low second harmonic level (lower than 15%) during period 196ms-202ms (6ms) for three phases. The cross blocking can't properly secure the differential protection.

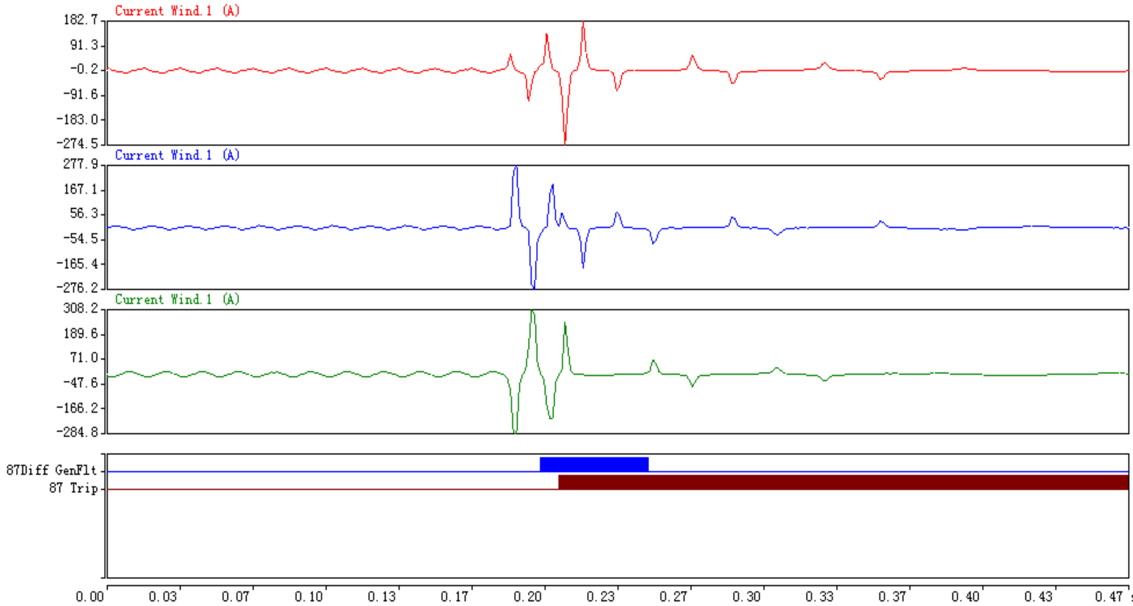


Figure 8 Case 1: Inrush Currents

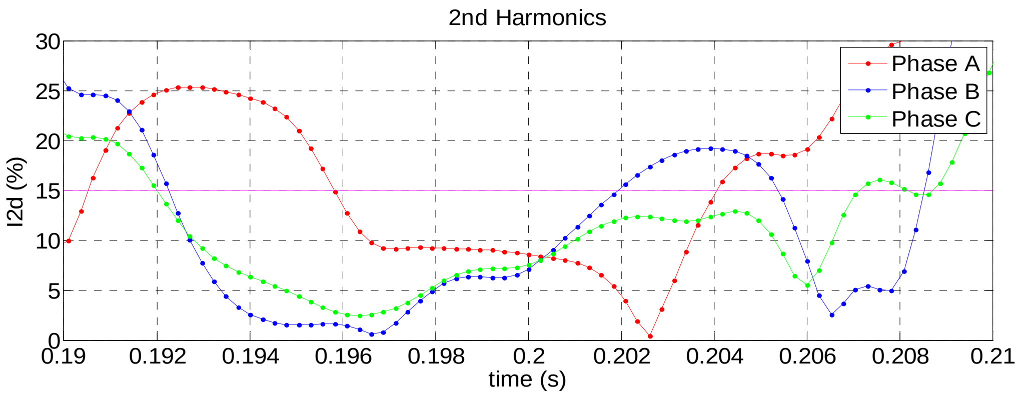
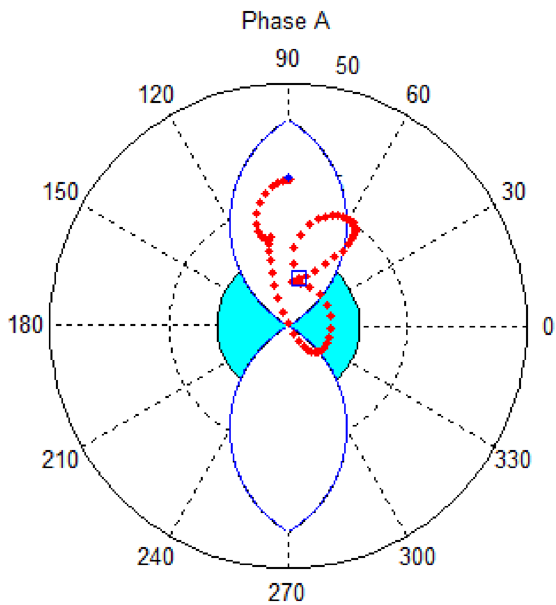


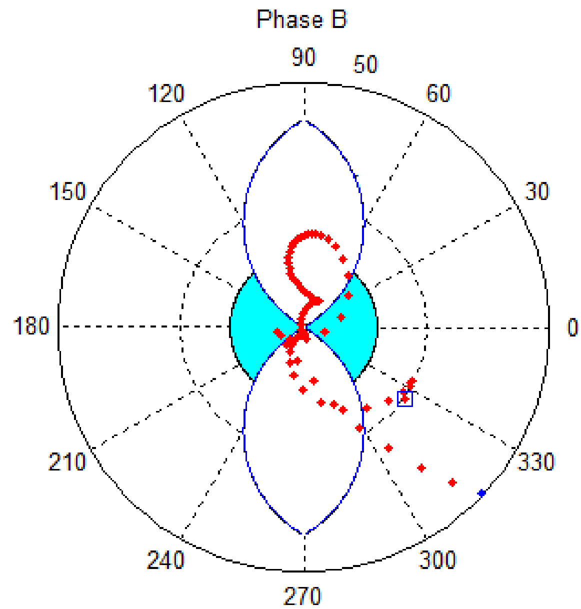
Figure 9 Case 2: Second Harmonics Ratios

By applying adaptive scheme and two-out-of-three-blocking, the misoperation is avoided as shown in Figure.

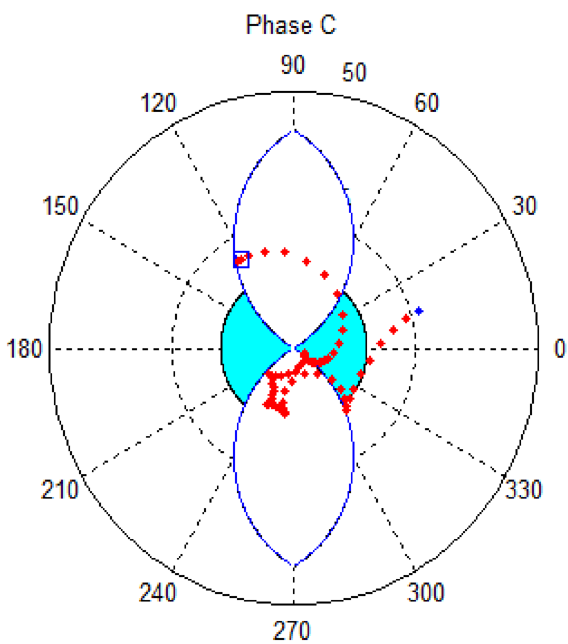
In Figure 10.a, 10.b and 10.c, the blue area represents operation zone, other area for non-operation zone. It is found that each phase of element based on adaptive scheme still has chances to enter the blue zone to operate. It stands for that adaptive can't avoid misoperation if per-phase scheme is used. However, if two-out-of-three blocking scheme is utilized, the misoperation shall be avoided as shown in Figure 10.d, all calculated phasors will be in non-operation zone.



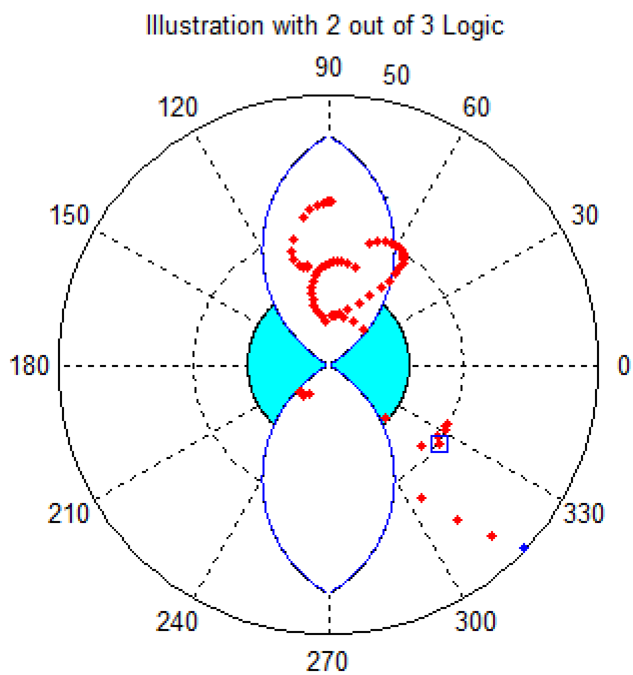
a) Adaptive Scheme for Phase A



b) Adaptive Scheme for Phase B



c) Adaptive Scheme for Phase C



d) Adaptive Scheme with 2-out-of-3 Logic

Figure 10 Case 1:Inrush Currents Adaptive Scheme Operational Behiviour

Case 2: 115kV transformer with long underground cables

The phase currents in Figure 11 have similar pattern as Figure 5 but different from Figure 3. Frequency spectrum analysis shows that differential current of phase B and C experiences low second harmonic level (lower than 15%) during period 197ms-206ms (9ms). Phase A's second harmonics is higher than 15% but lower than 20%. The two-out-of-three logic fails to secure the differential protection.

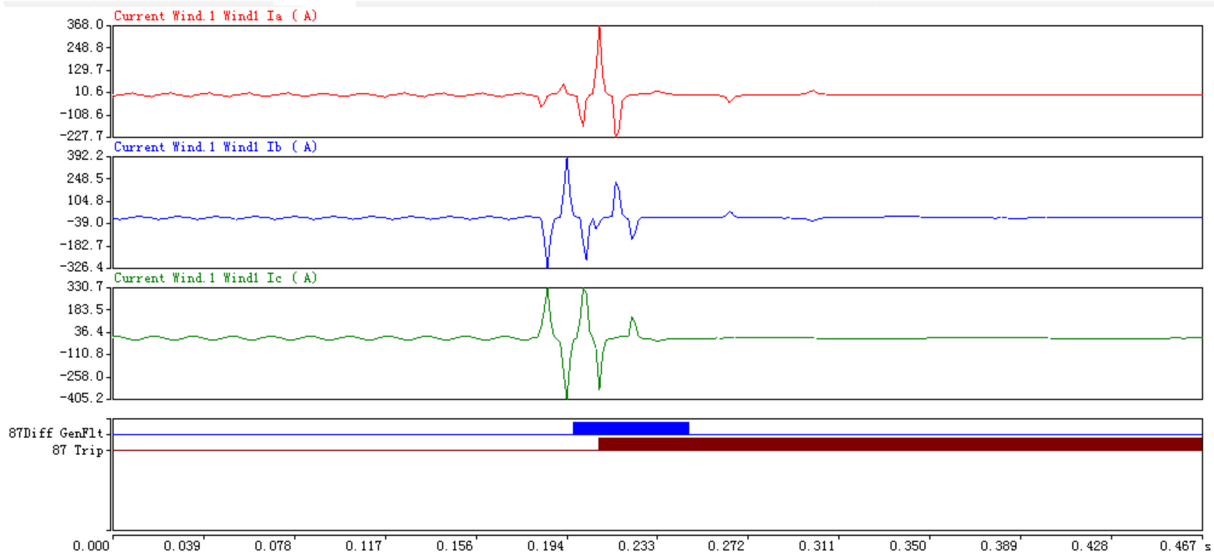


Figure 11 Case 2: Inrush Currents

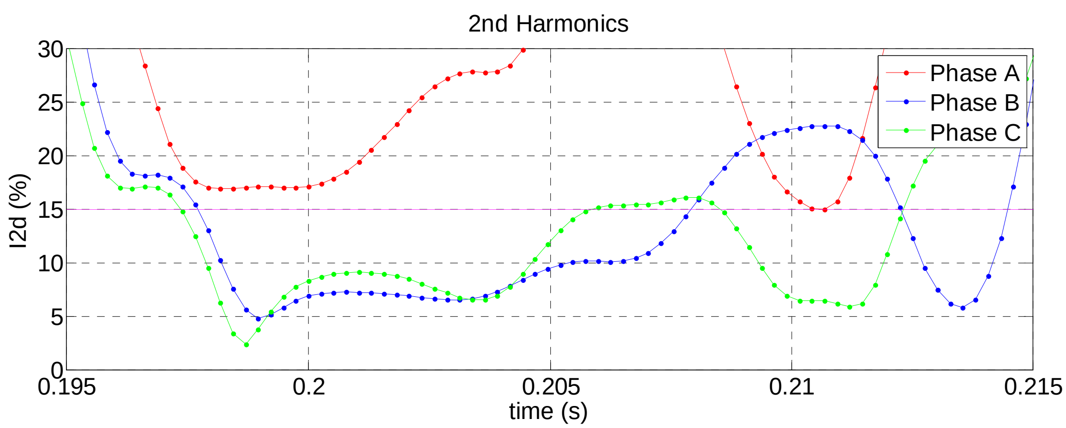
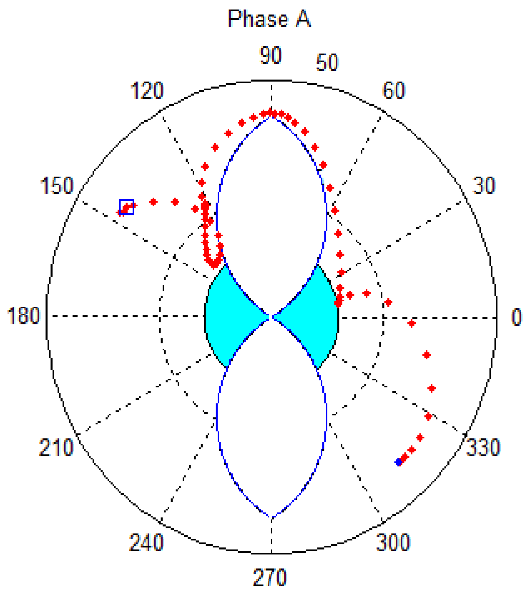


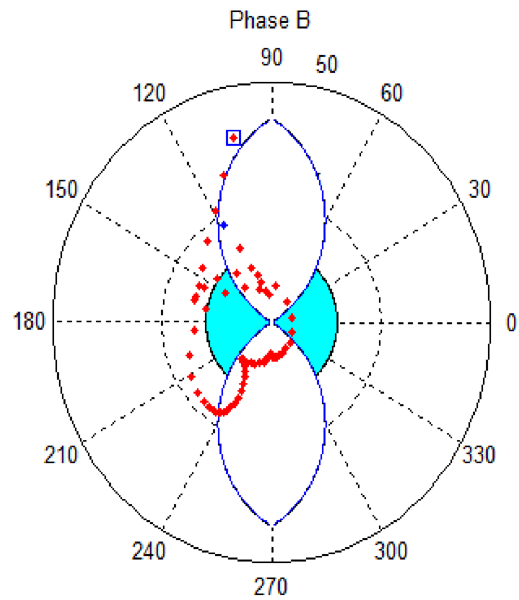
Figure 12 Case 2:Second Harmonics Ratios

By applying adaptive scheme and two-out-of-three logic, the misoperation is avoided as shown in Figure 13.

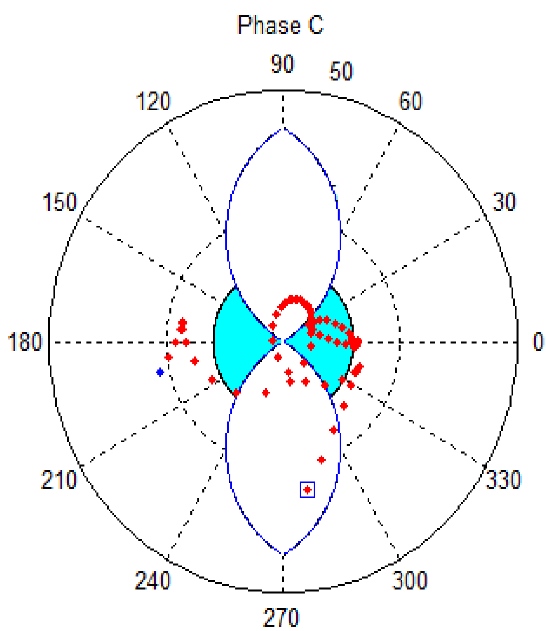
In Figure 13.a, Phase A element doesn't enter operation zone (blue area) because its second harmonic ratio is higher than 15% but close to the border of the operation zone. For phase B and C elements as shown in Figure 13.b and 13.c, each phase has chance to enter its operation zone. It stands for that adaptive can't avoid misoperation if per-phase scheme is used. However, if two-out-of-three logic is used, the misoperation shall be avoided as shown in Figure 13.d, all calculated phasors will be in non-operation zone.



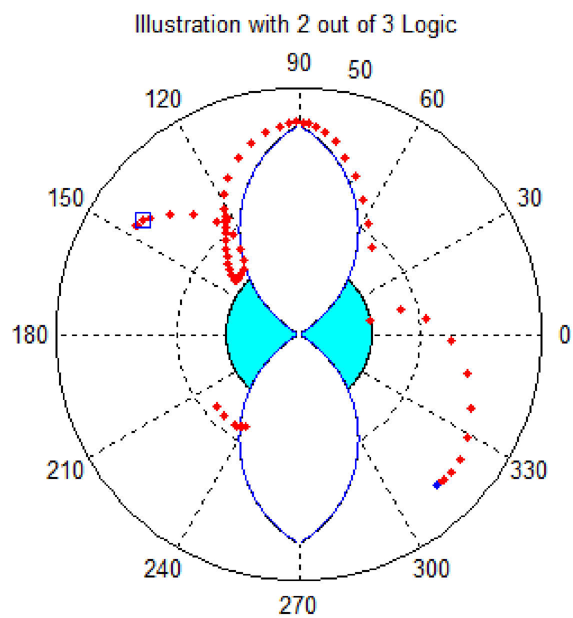
a) Adaptive Scheme for Phase A



b) Adaptive Scheme for Phase B



c) Adaptive Scheme for Phase C



d) Adaptive Scheme with 2-out-of-3 Logic

Figure 13 Case 2:Inrush Currents Adaptive Scheme Operational Behiviour

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Case 3: 230kV transformer internal fault

Case 3 shows an internal fault at 44KV bushing of a 230KV transformer with delta/wye winding connection configuration. 44Kv side of the transformer is grounded through a neutral reactor. Figure 14 shows 230KV and 44Kv three phases of currents.

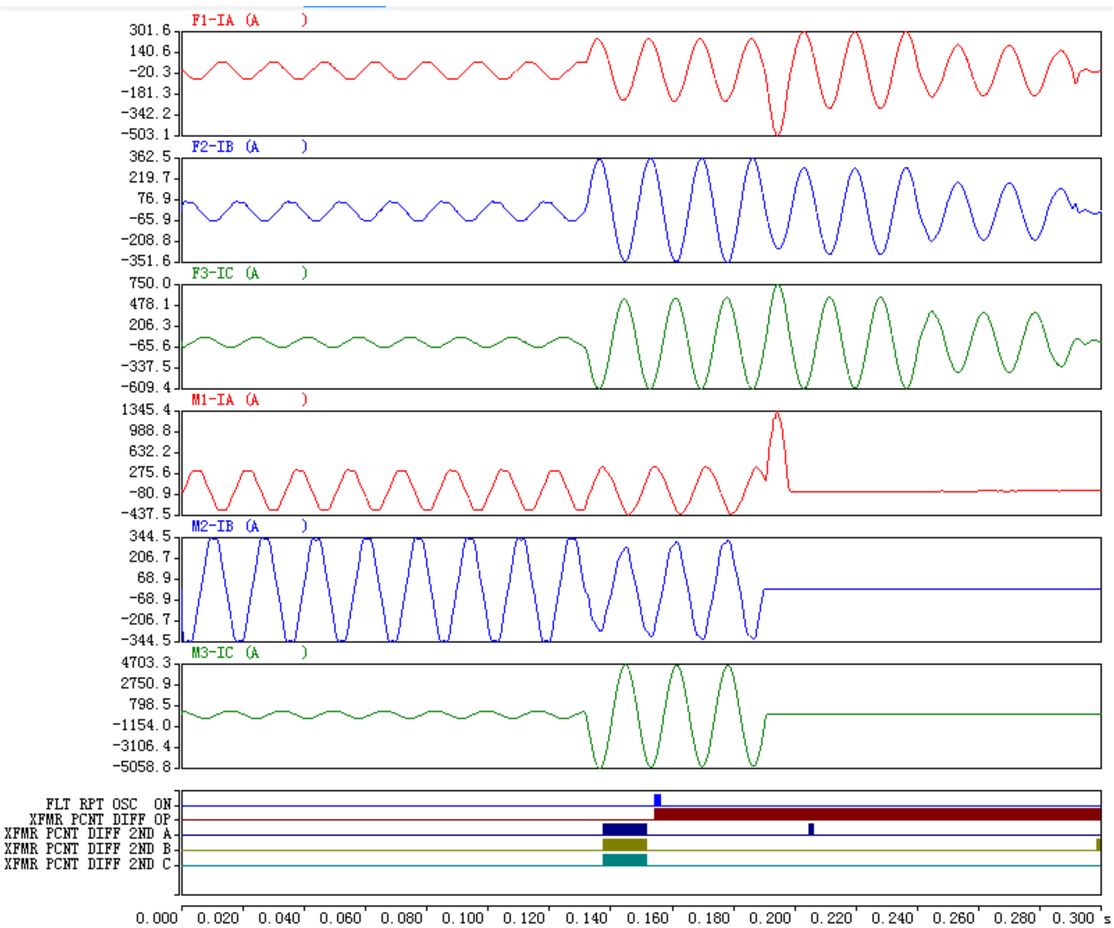


Figure 14 Case 3: Phase C to Ground Internal Fault

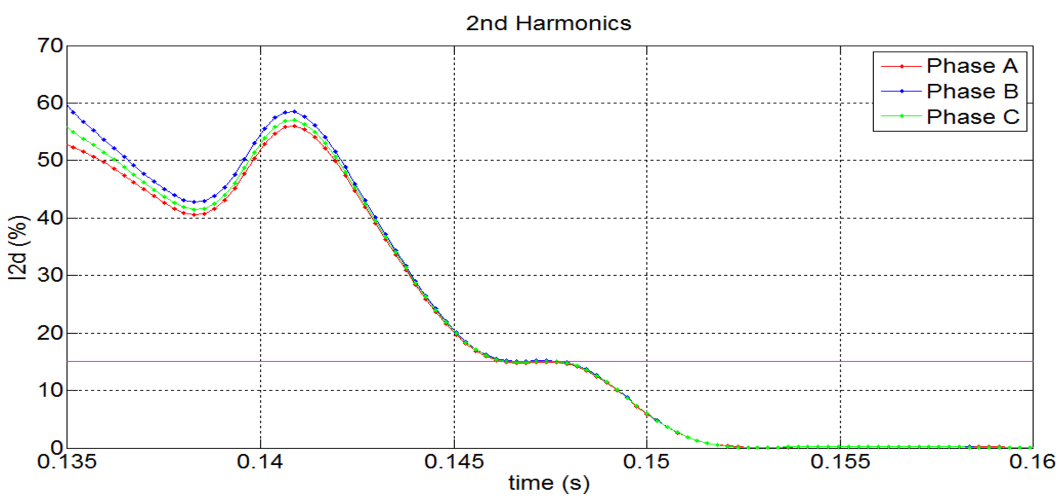
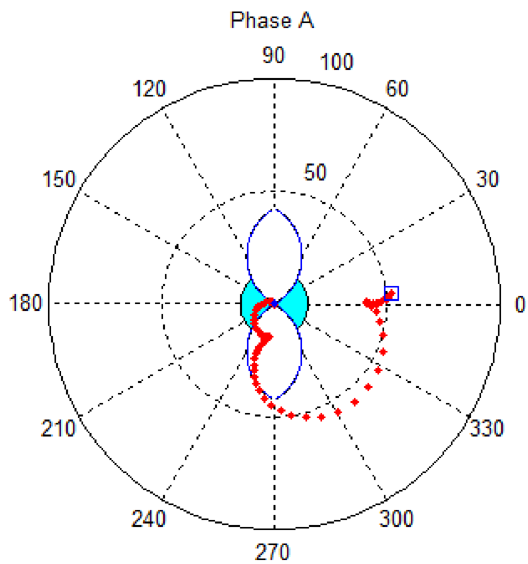


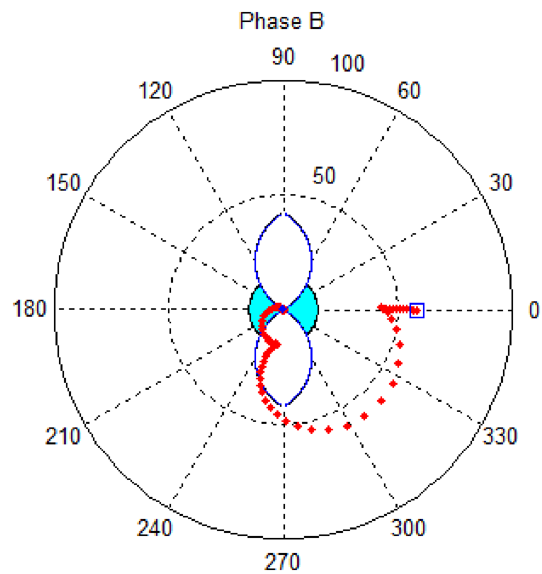
Figure 15 Case 3: Second Harmonics Ratios

It can be seen from figure 14 that the fault incepted at t=130 ms, the differential protection was blocked for almost 1 cycle after the fault inception due to the high 2nd harmonic component caused from the transition output of IED digital filters from pre-fault to fault condition.

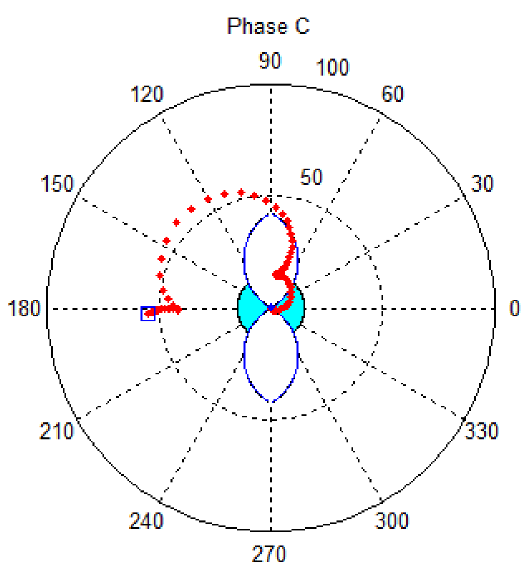
Figure 15 shows the second harmonics ratios. It drops to below 15% at t=147ms, and then stays very low (almost 0%) after t=155 ms.



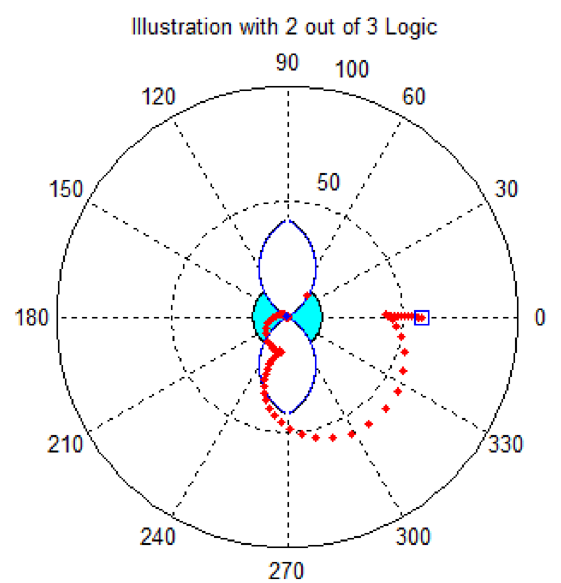
a) Adaptive Scheme for Phase A



b) Adaptive Scheme for Phase B



c) Adaptive Scheme for Phase C



d) Adaptive Scheme with 2-out-of-3 Logic

Figure 16 Case 3:Internal Fault Adaptive Scheme Operational Behiviour

From Figure 16.a, 16.b and 16.c, it can be seen that after fault inception, the I_{21} trajectories travel from blocking zone (2nd harmonic over 15%) to the origin (0%) through the operation zone either from 0 degree line or 180 degree line for all 3 phases, and this indicates that there is no additional delay to the differential protection element. After the I_{21} trajectories stay at the origin (fault transition has ended), there is also no impact to the differential protection element because the lenticular shape zones dynamically shrink with time as described earlier, as a result, the origin will be quickly excluded from the blocking zone and be included in the operation zone. Therefore, adaptive scheme can reliably operate on an internal fault.

3.0 CONCLUSIONS

That all three phases of differential elements experience low second harmonics due to discharging from long capacitive charging circuits has been a difficult issue for some Hydro One transformer protection applications. An occasional event revealed that adaptive method could avoid misoperation of transformer current differential protection. It is validated with numerous simulations testing on actual event data collected from Hydro One grid.

1) Adaptive method is a practice solution for 115kv and 230kV transformers supplied with long capacitive charging circuits. The solution to avoid misoperation is implemented by choosing adaptive scheme with 2-out-of-3 logic;

2) The adaptive method has high security under the magnetizing inrush condition caused with high capacitive charging effect circuit without noticeable delay for actual internal fault within the transformer differential protection zone under both energization and normal load condition.

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5.0 BIOGRAPHIES

Fenghai Sui received his Bachelor's degree from Northeast Electric Power Engineering Institute in China in 1984 and M. Sc degree in from Xi'an JiaoTong University in China in 1987, both in electrical power engineering. Since then, he had worked in Nanjing Automation Research Institute (NARI) in China for 13 years on development and design of microprocessor-based protections. From 1996, he was a senior protection development engineer.

Fenghai Sui joined in Hydro One Networks Inc. in 2006. Currently, he is a senior network management engineer in Hydro One Networks Inc, Toronto, ON. He is a licensed professional engineer in Ontario. Mr. Sui is a senior IEEE member and a member of IEEE/PES.

Zhiying Zhang received his B.Sc. and M.Sc. degrees from the North China Institute of Electric Power (now North China Electric Power University-NCEPU) and a Ph.D. degree from the University of Manitoba, Canada, all in Electrical Engineering. He has over 25 years of working experience with electric utilities and with relay manufactures in various technical positions. Since 2007 he has been with General Electric, and currently holds the position of principal applications engineer at GE Grid Solutions in Markham, Ontario.

Zhiying is a registered professional engineer in the province of Ontario and a senior member of IEEE.