A New Method of Improving Transformer Restricted Earth Fault Protection

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***Abstract*—A new method of avoiding malfunctioning of the transformer restricted earth fault (REF) protection is presented. Application of the proposed method would eliminate unnecessary operation of REF protection in the cases of faults outside protected zone of a transformer or a magnetizing inrush accompanied by current transformer (CT) saturation. On the basis of laboratory measurements and simulations the paper presents a detailed performance assessment of the proposed method which is based on digital phase comparator. The obtained results show that the new method was stable and precise for all tested faults and that its application would allow making a clear and precise difference between an internal fault and: (i) external fault or (ii) magnetizing inrush. The proposed method would improve performance of REF protection and reduce probability of maloperation due to CT saturation. The new method is robust and characterized by high speed of operation and high reliability and security.**

***Index Terms*—power transformer, power system protection, fault discrimination, digital phase comparator, current transformer saturation.**

I. INTRODUCTION

At present, one of the most frequently met methods of protection of power transformers against internal faults is phase differential protection. In operation, in many cases it provides satisfactory level of reliability and safety. However, phase differential protection is not sufficiently sensitive for detecting an internal phase-to-ground fault if the fault is located near the neutral point of the transformer or if the ground-fault current is limited [1].

The restricted earth fault (REF) protection is used as an additional protection method in order to overcome the mentioned problem [2-5]. The REF relay operates for phase-to-ground faults of a grounded winding and also of the delta winding if a grounding transformer is installed between the delta winding and the current transformers (CTs) [6].

At an external fault or magnetizing inrush in the case of saturation of the current transformers a differential current may appear and cause unnecessary operation of the ground differential protection. Historically, because of equipment and technology limitations, only high-impedance REF relay was available. This relay has certain level of immunity to CT saturation during external faults. However, the use of this relay requires that: number of turns ratios of the phase and neutral CTs must be the same, saturation characteristics of the CTs should be the same, and also CTs should have closely similar and high knee-point voltage [6]. Today, numerical low-impedance REF relays are widely used. A very important advantage of low-impedance REF protection is the fact that the CTs characteristics and ratios for the phase and neutral CTs do not have to be the same. However, if saturation of the CT is present during external faults or during magnetizing inrush this relay is prone to unnecessary operation. Operation of this relay can be improved by using harmonic based methods [6], [7], directional supervision [6], [8], or adaptive restraint current method [9], [10].

This paper presents a new method founded on application of directional function which is based on a digital phase comparator [11], whose application could improve REF protection. For the purpose of testing and verification of the proposed method, a series of experiments and simulations has been carried out. In this way the signals suitable for testing operation of the proposed algorithm have been obtained.

It has been established in practice that a CT will not enter saturation immediately upon a fault has occurred [12], [13]. The new method can recognize external fault or magnetizing inrush within the first semi-period and thus prevent unnecessary operation of the protection. The new method is stable and reliable since it makes use of the parameters calculated within time interval equal to one half of the signal period. Also, the new algorithm is simple and offers significant improvements when applied in REF protection.

II. DIRECTIONAL FUNCTION BASED ON DIGITAL PHASE COMPARATOR

In this paper the method of integration of the product of two signals within one basic semi-period of the signals is used as a digital comparator. This method has been proposed and applied in [11], [14], [15]. In order to speed up the rate of convergence of the process of calculation of the value of normalized integral, the method of its calculation has been modified.

Digital phase comparison of the two signals (i_{s1}) and (i_{s2}) is carried out by using formula:

$$I_{s1-s2} = \frac{2}{T}\int_{t}^{t+T/2} i_{s1}(t)\cdot i_{s2}(t)dt . \quad (1)$$

Expression (1) represented in discrete form becomes:

$$I_{s1-s2} = \frac{2}{m}\sum_{n=1}^{m/2} i_{s1}(n)\cdot i_{s2}(n) , \quad (2)$$

where: m – even number of samples within signal period; $I_{s1\text{-}s2}$ – integral of the product of the two signals over one half period; $i_{s1}(n)$ – n-th sample of the signal i_{s1}; and $i_{s2}(n)$ – n-th sample of the signal i_{s2}.

Fig. 1(a) shows waveforms of two harmonic signals in phase, while Fig. 1(b) shows the case when they are phase

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shifted by 180°. In the first example integral $I_{s1\text{-}s2}$ is positive. When the signals are in counter phase, this integral $I_{s1\text{-}s2}$ is negative.

Sign of the integral of the product of two signals calculated over one half period is dependent upon phase shift between the signals. If the phase shift is in the range $-90^\circ < \varphi < 90^\circ$ integral of the product of the two signals is positive, whereas if it is in the range $90^\circ < \varphi < 270^\circ$ this integral is negative.

Numerical value of expression (2) is dependent upon both mutual phase shift and rms values of the signals. The integral has maximum value when the signals are in phase or counter phase. When talking about value of the integral of the product of two signals, one should bear in mind that it can be equal to zero if the phase shift between the signals being compared is 90° or -90°, or one of the signals is zero.

When currents i_{s1} and i_{s2} are harmonic, expression (2) divided by the rms values of these currents gives cosine of the angle which represents the mutual phase shift. For calculation of rms values of currents i_{s1} and i_{s2} it is suitable to use some of the methods which calculate the rms signal value over interval equal to half period of the signals. It has been observed that the results obtained by applying the expressions (3) and (4) are quite good. In favour of the application of these expressions are the speed of response and convergence of the indicators used for the phase comparison.

$$I_{s1\_ind} = \sqrt{\frac{2}{m}\sum_{n=1}^{m/2} i_{s1}(n)\cdot i_{s1}(n)}\ , \tag{3}$$

$$I_{s2\_ind} = \sqrt{\frac{2}{m}\sum_{n=1}^{m/2} i_{s2}(n)\cdot i_{s2}(n)}\ . \tag{4}$$

Index which will serve for the phase comparison represents normalized value of expression (2), i.e.

$$\text{Directional index} = I_{s1-s2}(p.u.) = \frac{I_{s1-s2}}{I_{s1\_ind}\cdot I_{s2\_ind}}. \tag{5}$$

Fig. 2 shows the indicators of rms values of the signals from Fig. 1 obtained by expressions (3) and (4) and normalized values of the integral obtained by expression (5).

III. The New Method Of Avoiding Malfunctioning Of REF Protection

Fig. 3 shows a typical scheme of the ground fault protection of an YNd-connected transformer. At a ground faults outside transformer (F1) and within transformer (F2) directions of the zero sequence currents through CT1 are the same, but directions of the sums of the phase currents through Fsum1 are opposite for the two mentioned faults. Therefore, directional function can distinguish fault within a transformer from faults outside the transformer. The same applies for faults F3 and F4 at the delta-connected side.

If we observe differential REF protection, at a ground fault outside transformer F1, at the side of wye-connected transformer winding, sum of the phase currents through filter Fsum1 is equal to the current through current transformer CT1, i.e. the differential current is small. At an external fault, in the case of saturation of the CT the differential current may cause unnecessary relay tripping.

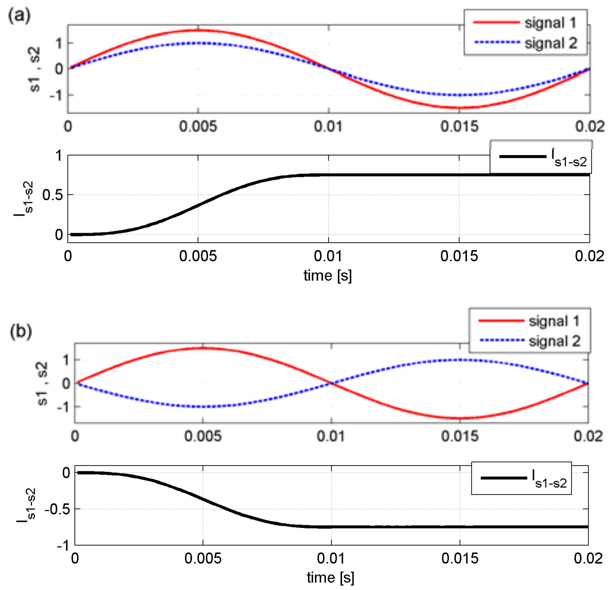

Figure 1. Waveforms of two harmonic signals and the integral of the product of these signals over time interval T/2: (a) in phase and b) phase shifted by 180°

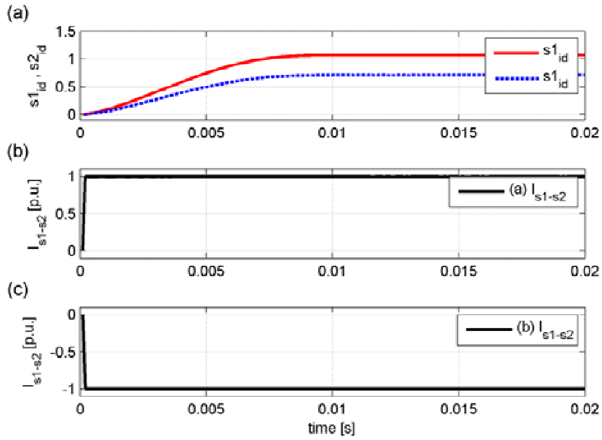

Figure 2 (a) Indicators of the rms signal values; and directional index when the signals are (b) in phase and (c) in counter phase

CT could saturate due to decaying dc component, high current magnitude, remanent flux or combinations thereof. The neutral CT is often underrated what additionally may complicate the problem [7].

Also malfunction of REF protection and unnecessary relay tripping may be caused by CT saturation during transformer energization. The waveshape, magnitude and duration of the transformer magnetizing inrush current are dependent on several factors, among them are the remanent flux and initial phase of the voltage at the instant of switch-on [13],[16]. Magnetizing inrush current contains a high

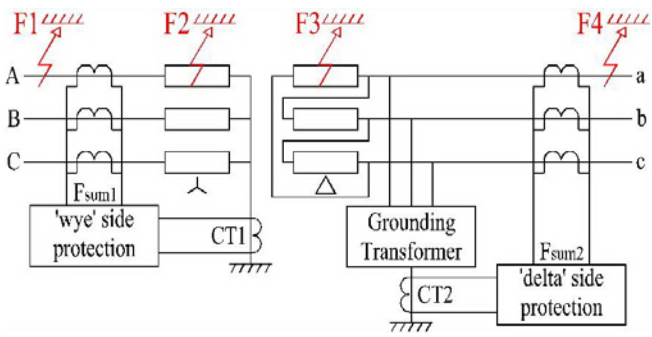

Figure 3. Ground fault protection of YNd-connected transformer

level of harmonics and a decaying dc component. Owing to a slowly decaying dc component, a CT may easily go into deep saturation.

In order to improve operation of REF protection during external faults or transformer energization accompanied by CT saturation, different directional supervision methods, combined with a blockade due to the presence of higher harmonics, are being in use [6], [8]. Security against unnecessary operation during transformer energization is provided by monitoring level of the second harmonic of the current in the transformer neutral and if it is above a pre-adjusted value, the REF element is disabled. However, the methods based on the second harmonic blocking have an undesired property in that they introduce a delay in operation of the protection, thus the protected element could be exposed to a fault for an unnecessarily long time. Also, in some transformer winding faults, level of the second harmonic may be high [17],[18], therefore in these cases the relay would be unnecessarily blocked. It has been noted that inrush currents of new generation transformers, having cores made of low-loss amorphous materials, contain considerably lower levels of the second harmonic, although inrush current amplitude could be quite high [18]. It is possible that during transformer switch-on, the relay will not be blocked owing to a lower level of the second harmonic, and due to a high level inrush current a CT would enter deep saturation causing REF protection to operate unnecessarily.

The method to be presented serves for avoiding unnecessary operation of REF relays. In all tests carried out on the basis of laboratory measurements and performed simulations, it was shown that the proposed method was robust and suitable for application in cases of CT saturation. The method is based on application of directional index calculated over one half period of the signal. From the point of view of safety and reliability it is suitable to use parameters calculated by using values taken from a data window whose length is one half of the signal period. In this way the influence of small or short disturbances on accuracy of the calculation is reduced. The new method does not make use of higher harmonics blockade which results in a high speed of making trip decision.

The information provided to the algorithm are sampled values of the phase currents and the ground currents. The new algorithm does not require amplitude conformity of the sum of phase currents and neutral current.

The method of the proposed algorithm for a transformer high voltage winding is as follows:

Step 1:

– A/D conversion of the signals with a preassigned sampling rate.

Step 2:

– Operation of the algorithm for one winding REF unit requires calculation of the following indicators.
– First, sum of the phase currents and neutral current are given by expressions:

$$i_{0-sum}(k) = i_A(k) + i_B(k) + i_C(k)\,, \tag{6}$$

$$i_{0-G}(k) = i_G(k)\,. \tag{7}$$

– Then, on the basis of expressions (3) - (5), calculation of the following indicators is carried out:
  - $I_{0\text{-sum}}$ - rms indicator for ($i_{0\text{-}sum}$),
  - $I_{0\text{-G}}$ - rms indicator for ($i_{0\text{-}G}$), and
  - I_{DI} (pu) -directional index.

Step 3:

– Checking whether the value of indicator ($I_{0\text{-G}}$) is greater than the threshold value. The next step is undertaken if the following condition is fulfilled:

$$I_{0\text{-G}} > I_{TH}\,. \tag{8}$$

Otherwise go to step 1.

– Condition (8) provides security as regards saturation of CT caused by external faults not involving contact with the ground, i. e. phase-to-phase and three-phase faults.
– It is known that current will flow through the transformer neutral in the case of a ground fault, therefore it is suitable to introduce a condition ensuring operation of REF protection only if current in the neutral conductor exceeds a threshold value.
– The threshold value is selected to be higher than the zero current due to the load, CT mismatch, or any other imbalance.

Step 4:

– Checking value of the directional index.
– For a ground fault F2 (Fig. 3) within a transformer, currents are mutually phase shifted by 180°, thus value of directional index is equal to -1 pu. For ground fault F1 outside the protected zone, currents $i_{0\text{-}sum}$ and $i_{0\text{-}G}$ are in phase, thus value of directional index is equal to 1 pu.
– Fig. 4 shows one example of the tripping characteristic. The operation area can be, as required, reduced or enlarged by choosing the value of directional index threshold (I_{DI_TH}). Directional index is equal to the cosine of the angle (φ) which represents the phase shift between currents $i_{0\text{-}sum}$ and $i_{0\text{-}G}$. Also, Fig. 4 shows one example of internal fault.
– Value of I_{DI_TH} should be chosen so that there will be no undesired tripping due to heavily saturated CT.
– In this step the tested algorithm value of I_{DI} is compared with the threshold value I_{DI_TH} and if the condition:

$$I_{DI} \le I_{DI\_TH} \tag{9}$$

is satisfied, it is considered that the present ground fault is within the protected zone.

Step 5:

– If conditions (8) and (9) are met, it is possible that an internal ground fault is present and the logical output is formed, otherwise the algorithm returns to the start.

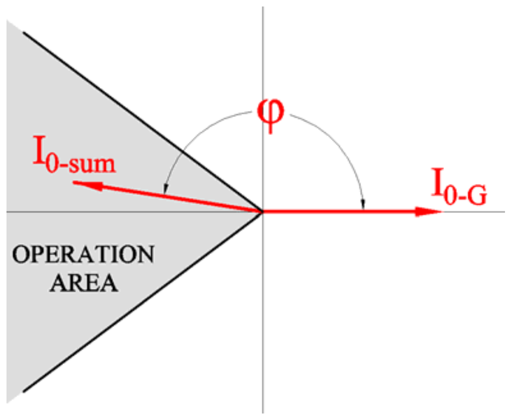

Figure 4. Tripping characteristic

The algorithm steps are described for the high voltage winding. Tripping decision is formed in the same way for the low voltage transformer winding. The complete flow chart of the algorithm is shown in Fig. 5.

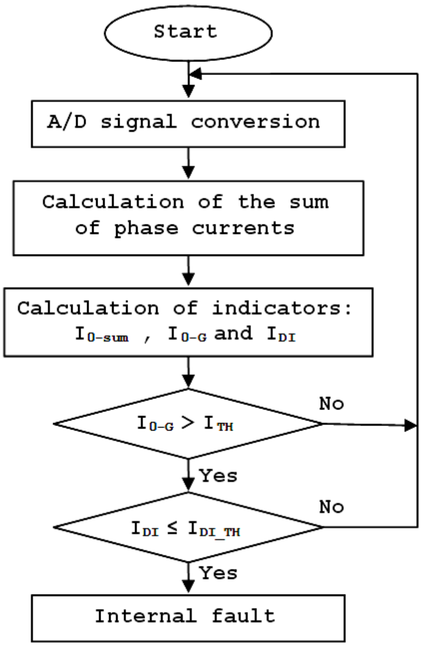

Figure 5. Flow chart of the algorithm

IV. Testing The Algorithm And The Results

Performance of the algorithm has been tested by using signals obtained by laboratory measurements and by the performed simulations.

A. Experimental measurements

Test studies have been carried out by using a custom-built transformer in the laboratory. The custom-built three-phase transformer has been equipped by taps placed in the 25%, 50% and 75% of high voltage winding so that internal faults could be generated. Transformer has three-limb core and YNyn connected windings.

Test procedures:

- A series of laboratory measurements has been carried out with the aim of obtaining signals suitable for testing the algorithm. Fig. 6 shows the circuit diagram used for these measurements.
- Recording and sampling of the currents have been performed by using data acquisition systems NI USB-6008 and NI USB-6009.
- By applying the recorded signal samples, operation of the algorithm has been tested. The algorithm testing by the laboratory recorded signals is presented though cases 1, 2, and 4.

B. Simulations

Signals for testing the algorithm for ground faults inside or outside protected zone of a three-phase YNd-connected transformer have been generated by simulations.

Test procedures:

- A series of simulations has been carried out by using the model corresponding to the equivalent scheme of Fig. 3.
- Signals at secondaries CT have been generated by PSCAD/EMTDC programing package.
- The obtained signals have been used for testing the algorithm. The results of these tests are presented through case 3.

C. The test cases and results

In all examples to be presented, calculated value of the directional index is compared with the threshold value $I_{DI\_TH} = -0{,}707$. If condition (9) is satisfied, phase shift (φ) is within the following limits: $\angle(i_{0-sum}, i_{0-G}) = \varphi,\ 135^{\circ} \leq \varphi \leq 225^{\circ}$. In this case it is considered that the present ground fault is within the protected zone.

The test cases are as follows. The first two examples present the results obtained for the cases when a phase-to-ground fault was outside and inside the protected zone of the transformer. Both examples are presented by two figures. Fig. 7 and Fig. 9 show measured values of the currents of CT in the transformer neutral and calculated sums of the phase currents. Fig. 8 and Fig. 10 show indices of the rms values for the HV and LV windings, directional index (eq.(5)), and tripping decision. Sampling frequency was 1,2 kHz. Input DAQ NI USB 6008 was fed by the following adapted signals recorded at the LV side of the transformer: 1) current of phase a (CT_{A1}), 2) current of phase b (CT_{B1}), 3) current of phase c (CT_{C1}); at the HV side: 4) current of phase A (CT_{A2}), 5) current of phase B (CT_{B2}), 6) current of phase C (CT_{C2}) and adapted currents of the neutral conductors: 7) CT_1 and 8) CT_2

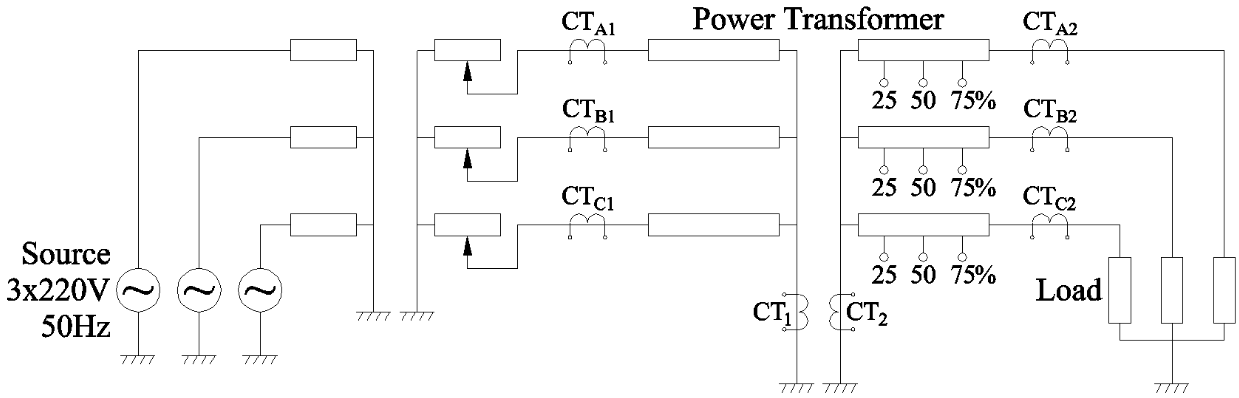

Figure 6. Circuit diagram for the experimental laboratory measurements

Case 1: *Ground fault outside transformer's protected zone.*

A fault occurred at the instant corresponding to 5552 sample (Fig. 7 and Fig. 8). During measurements, CTs have accurately reproduce currents to the secondary. It can be noted that all indicators converge monotonously and that convergence time of directional index towards a value approximately equal to 1 pu is only a couple of sampling periods (1-2 ms). As expected, in this case the condition for relay operation is not fulfilled.

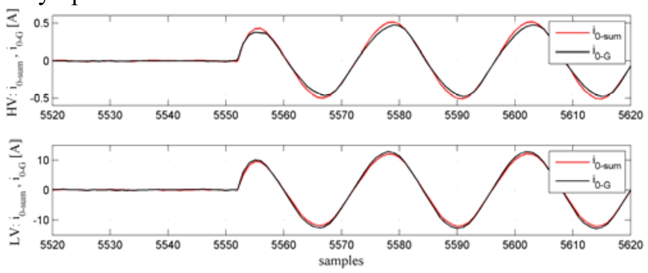

Figure 7. External fault: Experimental results –currents i_{0_sum} and i_{0_G} for HV and LV side

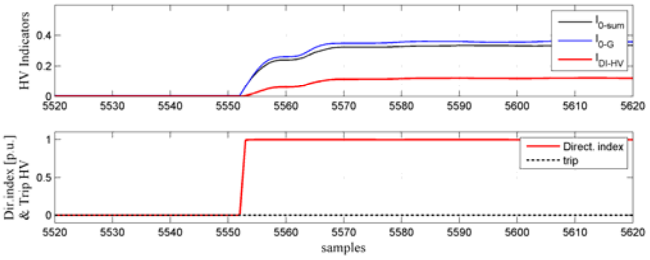

Figure 8(a). External fault: Directional indicators and trip decision for HV side

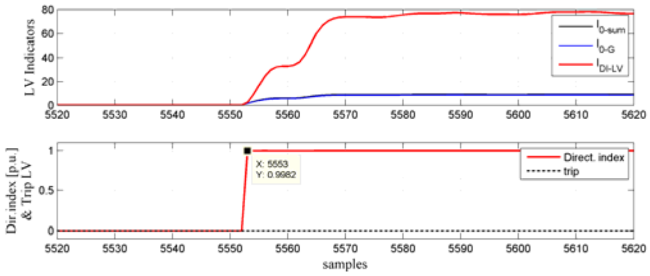

Figure 8(b). External fault: Directional indicators and trip decision for LV side

Case 2: *Ground fault at 50% of the winding of phase A.*

A fault occurred at instant corresponding to 5175 sample. During measurements, CTs did not go to saturation. It can be noted that all indicators monotonously converge and that directional index reaches value 0.98 pu after five sampling periods, i.e. it enters the operation area within first 5 ms after a fault has occurred. As expected, in this case the condition for operation is fulfilled and the relay would trip.

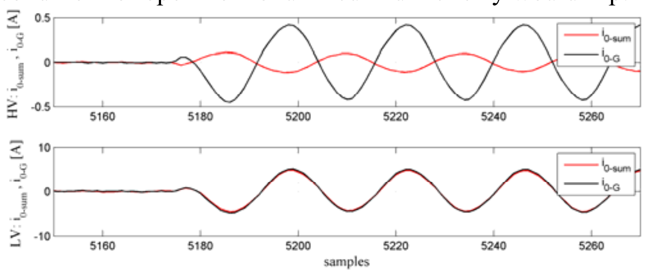

Figure 9. Internal fault: Experimental results - currents i_{0_sum} and i_{0_G} for HV and LV side

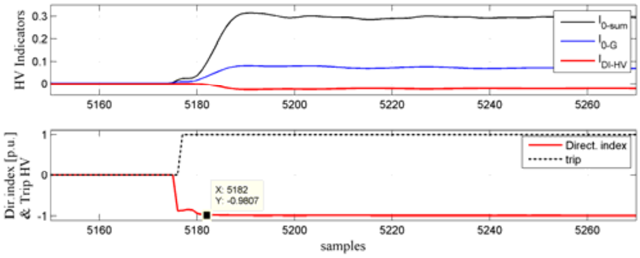

Figure 10(a). Internal fault: Directional indicators and trip decision for HV side

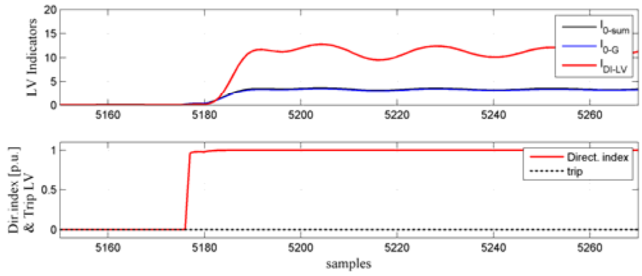

Figure 10(b). Internal fault: Directional indicators and trip decision for LV side

Case 3: *Ground fault outside protected zone accompanied by saturated neutral CT.*

In this simulation the sampling frequency was selected to be 2 kHz. From the figures which follow it can be noted that due to CT saturation a zero differential current arises, i.e. difference between the sum of phase currents and the current of the transformer neutral becomes significant (Fig. 12). Differential type of REF relay could unnecessarily trip in the case of such external fault. Also, it can be noted that value of the directional index throughout the first period of the signal is close to 1 pu and that minimum value of this index over the interval shown in Fig. 13 is 0.72 pu. All obtained index values are outside the operation area and in this case a relay based on the method presented in this paper would not operate.

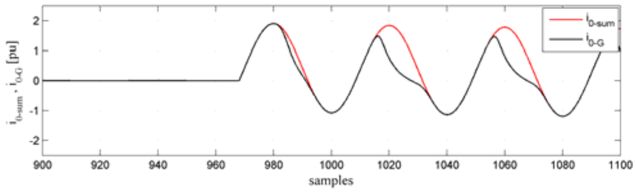

Figure 11. External fault: Simulation results – currents i_{0_sum} and i_{0_G}

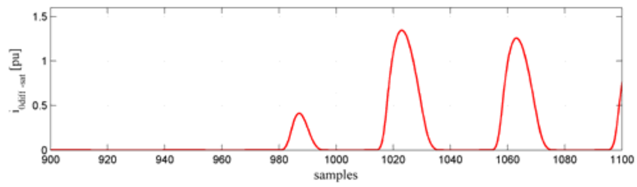

Figure 12. External fault: Simulation results – zero sequence differential current

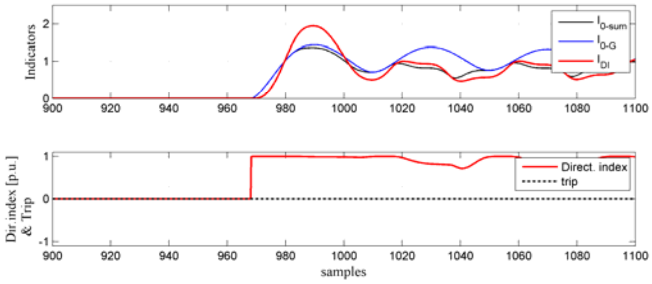

Figure 13. External fault: Directional indicators and trip decision

Case 4: *Magnetizing inrush accompanied by saturated current transformer of phase A.*

A three-phase transformer 5.8kV/220V, YNyn coupled, is switched-on to voltage 3x220 V at the low voltage side with open primary winding terminals. At the low voltage side in phase A two different CTs are connected in series, one of them has all the time been reproducing faithfully primary current to the secondary, while the other has entered saturation (Fig. 14). The sampling frequency was selected to be 5kHz. From the secondary, the following adapted signals are fed to input DAQ NI USB 6009: 1) current of phase A, 2) current of phase A of the saturated CT, 3) current of phase B, 4) current of phase C, and 5) current of the transformer neutral.

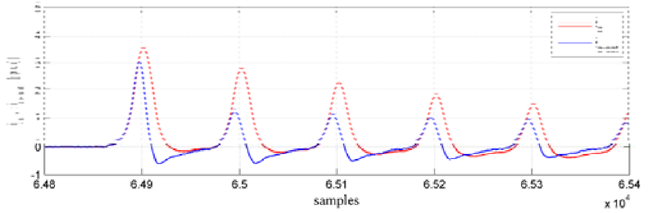

Figure 14. Inrush: Experimental results – phase A current with and without CT saturation

Fig. 15 shows measured currents of the transformer neutral of CT and calculated sums of the phase currents in the case when CT of phase A did not go to saturation and in the case when it did go to saturation. Then, from Fig. 16 it can be noted when CT entered saturation, a zero differential current appeared which may cause unnecessary operation of the differential REF relay. From Fig. 17(a) it can be noted that without CT saturation, directional index reaches values close to 1 pu within 5 ms. The case of CT saturation is accompanied by a significant value of differential current and the index would have positive values during first 20ms after the switch-on (Fig. 17(b)). All values of the index shown in the figure are outside the relay operation area, therefore the relay would not unnecessarily trip.

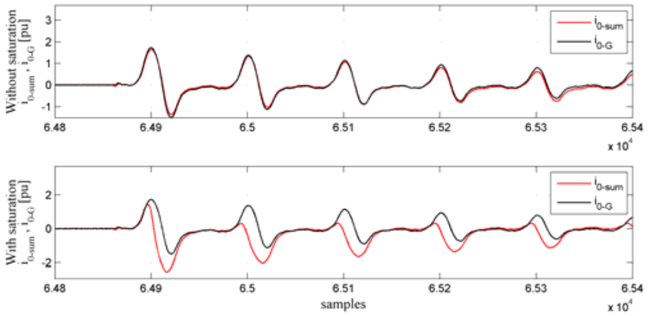

Figure 15. Inrush: Experimental results – currents i_{0_sum} and i_{0_G} (without and with CT saturation)

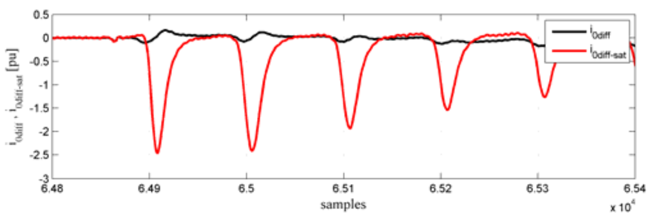

Figure 16. Inrush: Experimental results – zero sequence differential current

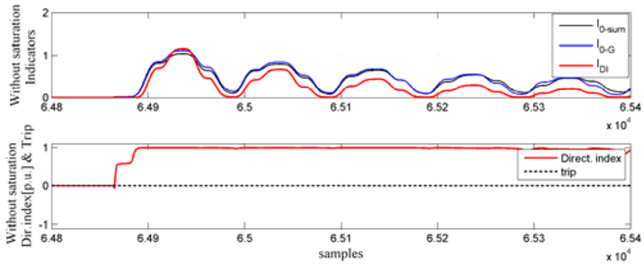

Figure 17(a). Inrush: directional indicators and trip decision

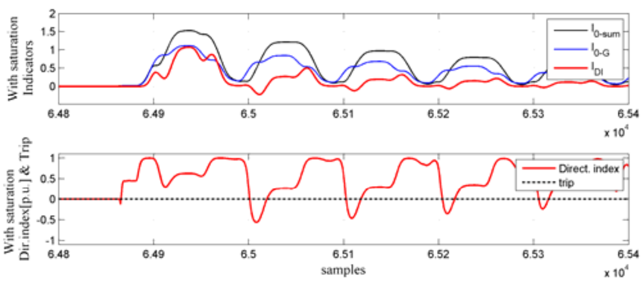

Figure 17(b). Inrush accompanied with phase CT saturation: directional indicators and trip decision

In all presented cases the algorithm made a clear difference between an external and an internal ground fault or magnetizing inrush. By the laboratory recorded signals it has been shown that in the regimes not accompanied by CT saturation the algorithm is capable of recognizing the states: external fault, internal fault or magnetizing inrush within a couple of the sampling periods. Then, by the laboratory recorded signals and signals generated by simulation, the algorithm was tested in these regimes when saturation has occurred. The tested cases showed that the algorithm was suitable for application under these conditions and that it could recognize the regime within 5ms.

V. Improvement Of The Presented Algorithm

The results presented in the preceding section show that application of the proposed algorithm could improve REF protection by avoiding its unnecessary operation caused by CT saturation. In this section, a method will be proposed to improve additionally the proposed algorithm with the aim of increasing its sensitivity.

From Fig. 17(b) it can be noted that value of directional index oscillates in the cases of magnetizing inrush accompanied by CT saturation. In order to improve sensitivity of the algorithm despite oscillations of the directional index, a method of averaging values of the directional index within certain time interval is proposed. The averaging process is aimed at reducing oscillations of the directional index. Having in mind that directional index for magnetizing inrush accompanied by CT saturation is predominantly positive, the averaging would eliminate or considerably reduce parts where the index takes negative values.

In section 3 it has been explained that the operation area along the tripping characteristic was defined by means of the threshold value of directional index. The threshold value of directional index should be selected so that no unnecessary operations are caused by CT saturation. Averaging would facilitate selection of a desired tripping characteristic, while extension of the operation area would increase the sensitivity without affecting the safety of relay operation.

If the last n values of index I_{DI} are used to define vector: $[I_{DI}(1) \quad I_{DI}(2) \quad I_{DI}(3) \quad \ldots \quad I_{DI}(n-1) \quad I_{DI}(n)]$, then the averaged value is obtained by:

$$I_{DI-avg}(k) = \frac{1}{n}\sum_{i=1}^{n} I_{DI}(i)\,, \tag{10}$$

where $n=m/2$ if averaging is performed over one half of the period, or $n=m$ if averaging is performed over one full period.

Fig. 18 shows operation of the algorithm when directional indexes from cases 1-5 are averaged over one half of the signal period. Also, the figure shows the averaged directional index value for simulated internal fault accompanied by CT saturation. Models for simulation of internal transformer faults can be found in the literature [19-22]. For the purpose of simulation of internal faults in this paper PSCAD/EMTDC model has been used, as in [23]. The faults and transformer switch-on occurred at instant corresponding to 0,04 s. It can be noted that the difference is obvious between an internal fault, with and without CT saturation, and:

1) external fault,
2) external fault accompanied by CT saturation,
3) magnetizing inrush, and
4) magnetizing inrush accompanied by CT saturation.

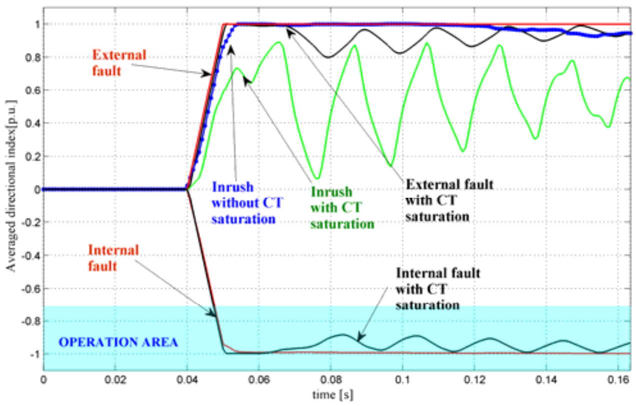

Figure 18. Averaged directional indexes over one half period of the signal

From Fig. 19 one can note that averaging over the full period of the signal resulted in a reasonably stable value of the directional index.

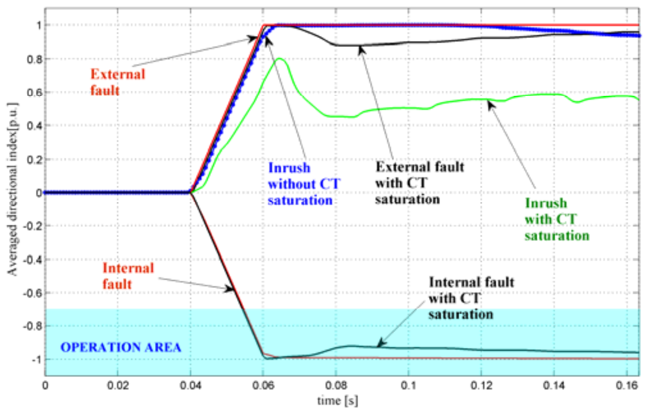

Figure 19. Averaged directional indexes over the full period of the signal

On the basis of the presented results, obtained by the improved new method, it is clear that by its application one can make clear difference between an internal and an external fault or magnetizing inrush.

Taking into account that within a couple of sampling periods the algorithm makes distinction between an internal fault and an external fault or magnetizing inrush, it has been shown that from the point of view of the speed of response, reliability and safety, it is most convenient to perform averaging over half period of the signal. By using this improved method, it is possible to make trip decision at one half of the signal period. Also sensitivity of the method has been improved by averaging.

VI. Conclusion

The presented algorithm is a new solution for realization of power transformer earth fault protection. By using directional index, the algorithm determines whether a ground fault is present within the protected zone of the transformer. Application of this algorithm would result in avoiding maloperations of REF protection due to CT saturation.

On the basis of the experimental results and simulations, it has been shown that the new method is stable and precise for all tested disturbances. It is shown that in the regimes accompanied by CT saturation, within 5ms upon a fault inception or magnetizing inrush started, a clear distinction is made by the algorithm between an internal fault and: (i) an external fault or (ii) magnetization inrush.

Tests of the algorithm show that its application could improve the performance of ground fault protection of power transformers. An advantage of this method is that for the purpose of phase comparison it makes use of data from one half of the signal period. This improves the reliability and safety of the relay operation. The additional averaging of the variable, serving for making the trip decision, improves immunity of the algorithm against small or short disturbances and reduces oscillations of the directional index values caused by CT saturation.

The presented results show that in all tests the reliability and speed of response of the algorithm are very good. Simplicity of the algorithm offers another advantage of the algorithm in its application in ground fault protection of power transformers. It can easily be implemented in the existing units for protection of power transformers. Differential protection usually consists of several units, among them are phase differential relays and differential REF relays. For operation of the mentioned units the phase currents at transformer terminals and transformer neutral are measured. Therefore the existing units for protection of power transformers provide signals required for operation of the new algorithm.

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