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Improvement of power transformer differential protection through detection and exploitation of the negative sequence currents

Introduction. *Power transformers are the most important and the most expensive equipment used in transport and distribution of electrical energy. Their failure results in huge economic losses. Despite the great advances in the design of power equipment in recent years, the feeble link in the chain remains the insulation weakness of coil turns of the power transformer.* ***The novelty*** *of the proposed research consists in the development of a new procedure for diagnosing and localizing the occurrence of turn to turn short-circuits in the windings of three-phase power transformer. The main problems of the current differential relay are short circuits of one or more turns of a transformer winding. Hence a new approach using' the amplitude comparison between the negative sequence currents' is developed and a digital discriminator internal / external fault is applied to discriminate turn to turn faults among the other ones. The proposed procedure is based on the exploitation of the negative sequence currents.* ***The purpose*** *of using this new procedure is to identify small faults inside power transformer coils and to distinguish inner faults from the outer faults by using an ameliorate circuit.* ***The method*** *used in this paper is a novel algorithm which based on the comparison between the negative sequence current amplitudes and to calculate the corresponding phase angle shifts. The performance of the proposed procedure has been confirmed by MATLAB/Simulink environment. The* ***results*** *of simulation reveal the efficiency of the suggested procedure, and indicate that this procedure can provide fast and sensitive approach for detecting low level turn-to-turn faults.* References 22, figures 21.

Key words: **power transformer, diagnosis, inter turn faults, symmetrical components, negative sequence currents**.

Вступ*. Силові трансформатори – найважливіше і найдорожче устаткування, яке використовується при передачі та розподілі електроенергії. Їх відмова призводить до величезних економічних втрат. Незважаючи на великі успіхи в проектуванні силового обладнання в останні роки, слабкою ланкою в ланцюзі залишається недостатня міцність ізоляції витків котушки силового трансформатора.* ***Новизна*** *запропонованого дослідження полягає в розробці нової методики діагностики та локалізації виникнення міжвиткових коротких замикань в обмотках трифазних силових трансформаторів. Основні проблеми диференціального реле струму – це коротке замикання одного або декількох витків обмотки трансформатора. Тому, розроблено новий підхід, який використовує порівняння амплітуд струмів зворотної послідовності, а також застосовується цифровий дискримінатор внутрішніх/зовнішніх несправностей для розрізнення міжвиткових короткого замкнень серед інших. Запропонована методика заснована на використанні струмів зворотній послідовності.* ***Мета*** *використання цієї нової методики – виявити невеликі несправності всередині котушок силового трансформатора і відрізнити внутрішні несправності від зовнішніх несправностей за допомогою поліпшеної схеми.* ***Метод****, який використовується в цій статті, це новий алгоритм, заснований на порівнянні амплітуд струму зворотної послідовності і обчисленні відповідних зміщень фазового кута. Еефективність запропонованої методики підтверджена у середовищі MATLAB/Simulink.* ***Результати*** *моделювання показують ефективність запропонованої методики і вказують на те, що цій метод може забезпечити швидкий і чутливий підхід для виявлення міжвиткових коротких замикань низького рівня.* Бібл. 22, рис. 21.

Ключові слова: **силовий трансформатор, діагностика, міжвиткові короткі замикання, симетричні складові, струми зворотної послідовності**.

1. Introduction. Protective relays constantly monitor the power system to assure maximum continuity of electrical service with minimum damage to life and property. Thus, they are on guard throughout – from the generation, through transmission into distribution and utilization. They are found in large and small systems, in the power companies and in the industrials. This wide usage, with high demands for reliable operation, has created a continuing desire for additional training. Such training is valuable not only to those directly implicated but also to the many others indirectly associated with relaying. For the latter group, a better understanding of the protective relaying can contribute considerably toward better system design and operation [1].

Power transformers are among the most important elements in electrical power systems. During their service they are exposed to various failures and abnormalities including dielectric, mechanical, or thermal failure. This means that the transformer cannot remain in service, and remedial actions are required before it can be returned to service [2].

Transformer abnormality means that the transformer operation is beyond the normal status, and this may adversely affect the performance or asset life of the transformer itself or other apparatus, or system reliability and operation. Power transformers can fail or be abnormal in a variety of factors and for a variety of reasons. The important factors and reasons are:

Electrical faults originated from internal faults, transient over voltages, over-currents, ageing, service loading, pre-existing faults, and timescales for fault development [3].

Winding faults are considered to be the most reason of transformer collapse. They involve a magnitude of fault current which is small relative to the power transformer nominal currents. This indicates that once a fault takes a place, a rapid, sensitive and reliable protection for its detection and location is necessary to prevent more retards in the network function.

Regarding to the IEEE recommendations [4], there is no unique standard way to protect all power transformers against small internal faults and at the same time to preserve basic protection recommendations such as sensitivity, selectivity, and rapidity. Turn to turn faults in transformer windings are considered to be among the difficult internal faults to detect because only IEEE Standard a few turns is initially implicated. The C37.91-2000 admits that about 10 % of the transformer coils may as well be short circuited to generate a noticeable variation in the ultimate current [5]. Therefore, when small numbers of turns are short-circuited, the resulting differential current won't be detectable due to its initially small value.

The winding inter turn fault detection, particularly at low current is critical. It has a negative effect on the transformer duration life. The cause of the coil inter turn fault is the insulation breakdown and short circuit of conductors with different voltages [6].

According to [7], the frequency response analysis (FRA) technique is a powerful technique for diagnosing transformer winding distortion or for detection of small turn-to-turn short-circuits faults and several other types of troubles that are caused during fabrication, transportation, installation and/or exploitation. Article [7] studied and simulated many types of short-circuits under different fault severities in various winding points within the high voltage and low voltage. It introduces a novel approach for FRA signature by incorporating both magnitude and phase angle plots in one graph, which facilitates and standardized the FRA interpretation process. The suggested approach is simple, sensitive, and convenient to apply within current frequency response analyzers to normalize the FRA signature process.

Generally, transformers are subject to failing due to internally or externally conditions, so the protected area is delimited by the area that incorporates equipment such as current transformers (CT), relays and power transformer. When a fault is within this area is called internal fault, and when it is outside is called external fault. It is essential that differential protection operates for internal faults only.

From [1, 2], the examples of abnormal conditions are overvoltage, over excitation, and overload. For these cases a transformer is protected with a set of different relays (in case of electro-mechanical relays) or a multiple choice of different elements in one relay (in case of a numerical relay). Although this one is the most commonly used protection, still not yet powerful enough to detect small inter winding faults in power transformers. Since the resulted differential current is too small in comparison to input and output currents, so it will not be sensed by the percentage differential protection. This means that it is not sufficient and reliable in detecting minor internal faults in transformer windings. For instance, if the restraint characteristic of the percentage differential relay is set to 25 % and a minor internal fault gives a differential current of 10 %, thus the internal fault cannot be detected until this differential current fault exceeds a pre-determined value or the setting threshold value of 25 %. For this reason, the traditional percentage differential protection is not sensitive enough to determine small turn-to-turn faults. Alternatively, the literature review shows that detecting small inter turn faults in power transformer winding is not an easy problem to solve [5, 6, 8].

Techniques and schemes, which have been proposed to ameliorate the differential relay towards diagnosis and location of internal faults within the power transformer, were emphasized by many research and studies.

A digital relaying algorithm for detecting transformer winding faults in reference [9] introduces a protection algorithm based on verifying the validity of differential equations of voltages, currents and mutual flux linkages, at the primary and secondary windings during normal conditions, in the presence of external faults and magnetizing inrush. According to the results presented in this paper, the exposed algorithm was valid for 5 % of short circuited coil turns. Their algorithm is faster, supersensitive than the restraint differential current algorithm and is qualified in fault finding while energizing the transformer.

The algorithm in [10] presents differential algorithm which uses the negative sequence currents to find turn-to-turn fault in transformers. Studies presented in this paper were limited and dealt with one particular configuration and system conditions. It uses 1 % of shorted turns throughout ordinary function of the transformer.

Primary and secondary negative sequence current magnitudes and their phase shifts are used to recognize internal faults and decline external faults. The results were also not convincing because of limited studies and no detailed investigations.

The paper [11] proposes a transformer protection using Relay Increment of Flux Linkage (RIFL) for three phases Y-Y transformer, the increments of the flux linkages are calculated for a three phase Y-Δ transformer, the differences between the two phases of the increments of the flux linkages are calculated to use the line current because the delta winding current is unavailable. The RIFL is compared against the turn's ratio, if there is a difference between them that means an internal fault exists.

The performance of the proposed relay was compared with the conventional current differential relay with the harmonic blocking. Test results indicate that the proposed relay has perfectly distinguished the coil faults from inrush currents. It also, reduces the operating time of the relay for internal faults. The digital signal processor of prototype relay is implemented and it was concluded that the prototype algorithm is faster when compared to conventional relay with harmonic blocking.

The work [12], by using the advanced digital technology, it becomes possible to protect power transformers with new differential protection principle. This new principle possesses higher sensitivity than the traditional transformer differential protection for minor turn to turn faults. It investigates the negative sequence currents. The new protection principle yields a higher sensitive protection for very small internal faults in the order of 1 % short-circuited turns. The new negative-sequence current-based sensitive protection is an excellent backup to the traditional power transformer differential protection, which based on the famous differential characteristic. A case study of the new principle protection concludes some limitation of this algorithm, that it operates when power transformer is loaded and it does not indicate faulty phase(s).

The authors of [13] present an advanced model of the frequency response analysis (FRA) to analyze the integrity of power transformer parameters which depend on windings and their material properties. Among a wide range of transformer failure modes, the authors focused on using FRA for detecting changes in FRA signatures caused by breakdown insulation and deformation of transformer winding. In practice, insulation breakdown occurs due to the circulation of high currents and voltages in the transformer. As they are too much superior at the nominal values, simultaneously to this, a flashover of winding turns begins and causes a winding short circuit which may lead to transformer failure.

In this work, the frequency of the input signal was varied over a certain range and resulting responses were profoundly studied and analyzed. This allows the detection of internal turn to turn faults and confirms the sensitivity of the FRA signature.

In the scheme of [14] the transient states are taken as models. These different models are recognized by neural network. Inputs to neural network are the harmonics of the positive sequence of differential current. These inputs are the 1st, 2nd, and 5th harmonic components of the positive sequence differential current. The application of neural networks has some limitations because it requires a lot of training models which are produced by simulation of many cases and applied just on some specific power transformers.

The work in [15] proposes to reduce the main losses of electricity which occur in distribution networks; transformers with power quantity up to 1000 kVA are used. The authors gave new technological proposals for improving the performance and effectiveness of transformers through structural-geometric transformations of active elements. Such transformers are mainly produced with rectangular section of rod and armored planar magnetic cores.

Methods of energy saving in transformer construction are based on new electrical materials high technologies able to produce composite conductors of windings with «high-temperature» superconductivity and amorphous electrical steel. This agrees with the previously known optimization and design data of transformers.

However, the cost increases significantly, and questions arise about the specifics of the design, operation and assembly of transformer and technological equipment. But a significant reduction in no-load losses is possible by performing all corner sections of the combined magnetic core from isotropic electrical steel and all rod and yoke sections from anisotropic electrical steel.

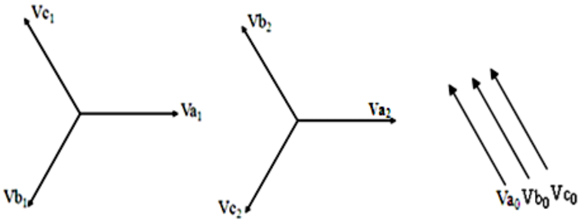
It is known that the presence of the negative sequence currents in the power transformer windings proves the existence of an internal turn-to-turn faults within this transformer [16]. Even though, sensing small power transformer coil faults is a difficult task to do, still the aim of our paper is to propose an algorithm based on the symmetrical components theory and the application of a procedure where comparison of the vector group amplitudes and phase angle shifts between negative sequence current components are realized.

The goal of the paper is to detect the internal faults for various operating conditions of the power transformer. And also, be sure that this proposed procedure is apt to accomplish its role significantly than any other classical relay.

2. The proposed procedure. Turn to turn winding fault are regarded as the main factor of the transformer deficiencies, and can lead to small changes on primary and secondary voltages and currents [17, 18].

This new algorithm is proposed to protect the power transformers against minor turn to turn faults through the exploitation of the negative sequence currents.

According to symmetrical components properties, the phase quantities are expressed in phasors notation using complex numbers, as shown in Fig. 1.



a *b* *c*

Fig. 1. Three phase voltage vector components: (*a*) positive sequence; (*b*) negative sequence; (*c*) zero sequence

The three voltage phasors are expressed by the following formulas:

$$V_{abc} = [V_a \; V_b \; V_c]. \tag{1}$$

This formula can be arranged as follows:

$$V_{012} = [V_0 \; V_1 \; V_2], \tag{2}$$

where 0, 1, and 2 subscripts are respectively referring to zero, positive, and negative sequence components.

A phase rotation operator «*a*» is defined in (3) to rotate forward by 120 degrees. The [*A*] matrix is applied to convert phasors into symmetrical components:

$$[A] = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}. \tag{3}$$

The phase voltage sequences are represented by the sequence equation

$$V_{abc} = [A] \cdot V_{012}. \tag{4}$$

Conversely, the sequence components are represented as:

$$V_{012} = [A]^{-1} \cdot V_{abc}, \tag{5}$$

where

$$[A]^{-1} = 1/3 \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}; \tag{6}$$

$$V_{012} = 1/3 \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \cdot [V_{abc}]; \tag{7}$$

$$I_{012} = 1/3 \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \cdot [I_{abc}]; \tag{8}$$

$$V_{abc} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \cdot [V_{012}]; \tag{9}$$

$$I_{abc} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \cdot [I_{012}]. \tag{10}$$

The symmetrical components must satisfy the constraint that their vector sum equals the original set of unbalanced phasors. The corresponding impedances are determined by using Ohm law as follows:

$$V_{abc} = [Z_{abc}] \cdot I_{abc}, \qquad (11)$$

or

$$I_{abc} = [Z_{abc}]^{-1} \cdot V_{abc} = [Y_{abc}] \cdot V_{abc}. \qquad (12)$$

It is known that, in faulty conditions the negative sequence currents in Fig. 1 are greater than the direct sequence currents [16–18]. The three symmetrical current components are described in this paper as:

- positive sequence current in the primary winding leads the positive sequence current in the secondary winding by an angle θ;
- negative sequence current in the primary winding lags the positive sequence current in the secondary winding by an angle θ;
- zero sequence current in the primary winding is in phase with the zero sequence current in the secondary winding.

It must be put in count that, when the turn to turn fault occurs inside the transformer, the negative-sequence current flows toward the fault point [19].

In this research, and in order to compare the negative sequence current amplitudes and the phase-angle shifts which separate them for both sides of the power transformer, three steps are to be followed.

First step. The measurement method of the negative sequence current amplitudes is applied to the previous electrical circuit of Fig. 2, 3, where the negative sequence currents in the primary and secondary sides are respectively written as: I_neg.seq_P and I_neg.seq_S, then compared with the preset value 2 % of the differential protection’s base current. If the result is greater than the pre-set value a vector-group compensation for current amplitudes is done by the differential relay itself without changing the interposing CTs on both primary and secondary windings. The measured difference of the negative current amplitudes must be as small as possible to avoid unnecessary trip during normal operation. Ones, vector compensation is done, the second step will take place.

Second step. An evaluation of phase angles shift difference between the two phasors of the negative sequence currents on both sides of the power transformer and the threshold is done. Generally, during no internal fault operation of the transformer this difference is equal to zero degrees. When internal turn to turn fault occurs a small phase angle shift due to high current in the shorted turns will happen, therefore, a trip command is issued.

Third step. It consists on the use of powerful algorithm, which should discriminate between normal and abnormal operating conditions that occur in power system related to transformer such as external faults, internal faults and magnetizing inrush currents. If a fault occurs, within the protected area, the current balance will no longer maintained and the relay will close and release a trip signal to cause a certain circuit breakers to activate in order to disconnect the faulty transformer from the grid [15, 20].

3. Principle of operation. Fig. 2 shows a typical differential relay connection operating diagram conditions, the fault is outside the protected transformer, the negative sequence currents will flow as illustrated in Fig. 2, where the I_neg.seq_P is flowing out of the protected area and the transformed I_neg.seq_P’ will flow in the faulty side externally to the power transformer and will get out from the other side of the transformer. So I_neg.seq_P and I_neg.seq_P’ will have the same direction This means that the phase shift between them is 0°, as it can be seen in the bellow electrical circuit of Fig.2. Meanwhile the current I_neg_P is getting from the external faulty secondary side towards the healthy primary side (it must be notice that I_neg.seq_P’ is a *transformed* I_neg.seq_P).

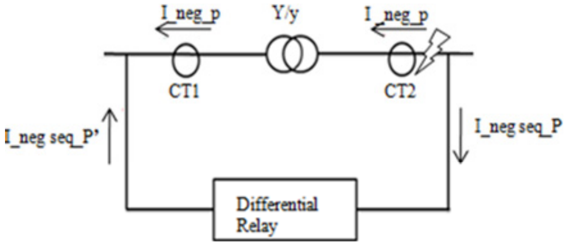


Fig. 2. Electrical circuit showing the negative sequence current directions during external fault

From Fig. 3 it can be seen that the fault is internal so, the negative currents I_neg.seq_P and I_neg.seq_S are flowing each from its own side towards the protected zone. But the negative sequence currents I_neg_P’ and I_neg_S will flow out of the primary and secondary sides respectively and will have the opposite directions, so, the phase shift between them will be equal to 180°.

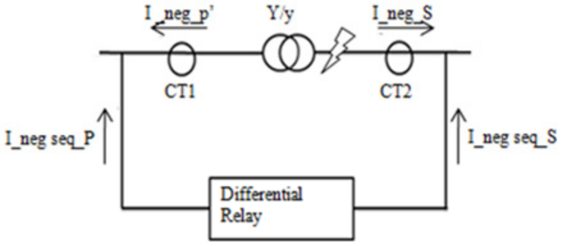


Fig. 3. Electrical circuit showing the negative sequence current directions during internal fault

In order to let the comparison of the negative sequence currents be relevant, the phase differences and turns ratio must be firstly compensated by the digital differential element which do this type of compensation automatically.

During external fault condition, the differential relay is well performing as long as the current transformers give primary currents correctly otherwise and in case of CTs saturation, a relay false operation is happened.

Modern logic differential relays are capable to accurately compute the negative sequence current quantities from actual measured current phases [21, 22]. So, internal/external fault discriminator algorithm can be developed on the basis of negative sequence current quantities and it can be reliable in detecting and locating external faults. It measures the amplitudes and their corresponding phase angle shifts of the negative sequence currents on both windings of the power transformer, and then detects the presence of the negative sequence currents which allows the fault location. It also uses the second harmonic to prevent false tripping during magnetizing inrush conditions and the 5th harmonic to restrain the differential relay during over excitation conditions.

4. Simulation results. The performances and effectiveness of the proposed algorithm are simulated under normal and abnormal transformer operating conditions. When the power transformer is under the condition of small turn to turn faults, it is preferred to use the negative-sequence currents for the detection of such type of faults. Since, the investigated power transformer is connected in Y-y mode, and is 20 MVA, 31.5 kV / 400 V; the detection of internal fault can be done directly due to the availability of the winding currents.

Performance of the proposed scheme during external faults. Figures 4, 5 show that the differential relay is stable for external faults and didn't trip because the fault was outside the protected transformer. This means that the relay has detected the external fault and the output of the negative-sequence current differential element did not trip during external fault and the 3 phase primary and secondary current wave forms did not alter. Also, it can be seen that the maximum and minimum current values of the primary side are respectively:

- phase A – $I_{A\mathrm{max}} = 4$ kA, $I_{A\mathrm{min}} = -2.2$ kA;
- phase B – $I_{B\mathrm{max}} = 2.3$ kA, $I_{B\mathrm{min}} = -3.2$ kA;
- phase C – $I_{C\mathrm{max}} = 2.3$ kA, $I_{C\mathrm{min}} = -3.2$ kA.

The external fault was detected within one cycle (0.96 s).

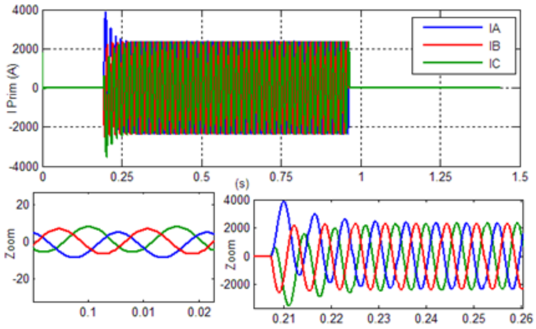


Fig. 4. Primary phase currents of the proposed scheme during external fault

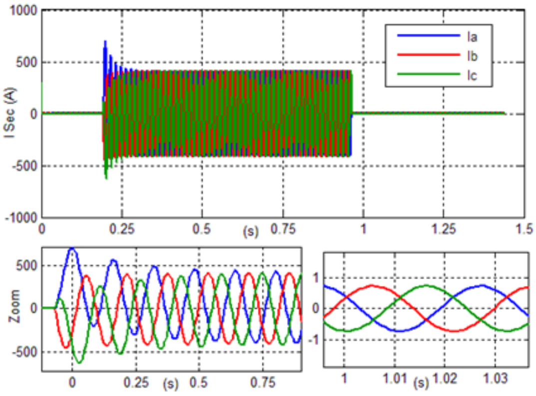


Fig. 5. Secondary phase currents of the proposed scheme during external fault

The maximum and minimum current phase values of the secondary side are respectively:

- phase A – $I_{a\mathrm{max}} = 700$ A, $I_{a\mathrm{min}} = -400$ A;
- phase B – $I_{b\mathrm{max}} = 400$ A, $I_{b\mathrm{min}} = -550$ A;
- phase C – $I_{c\mathrm{max}} = 700$ A, $I_{c\mathrm{min}} = -350$ A.

The differential relay did not issue the signal trip, because the fault was external.

In Fig. 5 the primary phase and secondary phase current wave forms did not alter, this means that, the relay signal trip didn't take place and no trip was executed, which confirms that the fault was external, as shown in Fig. 5.

Figure 6 shows the wave form of the three phase primary currents during internal turn to turn fault in the presence of inrush currents. It can be seen that the differential relay didn't send a trip signal because it considers the inrush currents as a transient phenomenon and will disappear quickly.

The primary phase currents values during turn to turn fault in the presence of inrush currents are:

- phase A – $I_{A\mathrm{max}} = 4$ kA, $I_{A\mathrm{min}} = -2.2$ kA;
- phase B – $I_{B\mathrm{max}} = 2.3$ kA, $I_{B\mathrm{min}} = -3.2$ kA;
- phase C – $I_{C\mathrm{max}} = 2.3$ kA, $I_{C\mathrm{min}} = -3.2$ kA.

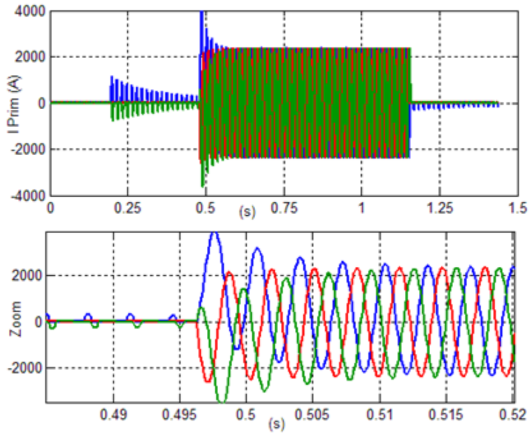


Fig. 6. Three phase primary currents during internal turn to turn fault in presence of inrush currents

In Fig. 7 it can be seen that the internal turn to turn fault has happened during an interval time of 0.645 s and the digital differential relay has ordered a signal trip, because the fault was internal and without the presence of inrush currents. The obtained data from the wave current forms is as bellow: The maximum and minimum values of the secondary phase currents from Fig. 7 are:

- phase A – $I_{a\mathrm{max}} = 0.6$ A, $I_{a\mathrm{min}} = -0.6$ A;
- phase B – $I_{b\mathrm{max}} = 0.6$ A, $I_{b\mathrm{min}} = -0.6$ A;
- phase C – $I_{c\mathrm{max}} = 0.6$ A, $I_{c\mathrm{min}} = -0.6$ A.

Fault duration interval was from 0.48 to 1.125 s.

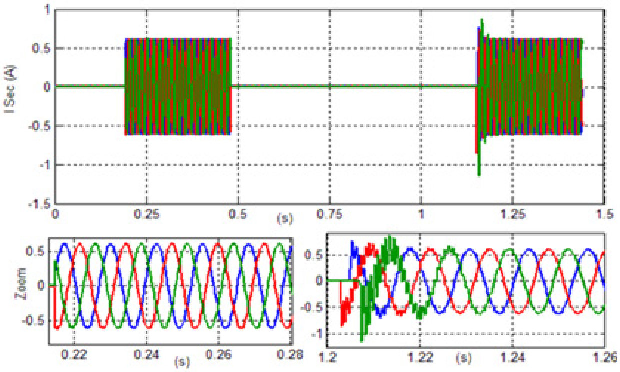


Fig. 7. Three phase secondary currents of the proposed scheme during internal turn to turn fault in the absence of the inrush currents

The inrush current phenomenon shown in Fig. 8 is obtained from simulation study using the MATLAB Simulink environment.

It can be noticed that the maximum value of the inrush current is higher many times than nominal current. The inrush currents may accidently push the protection relay to trip. In such conditions, the relay must be able to discriminate between the inrush currents and the internal turn to turn fault current and delay the trip signal until the inrush currents disappear, and then send a signal trip as illustrated in Fig. 9.

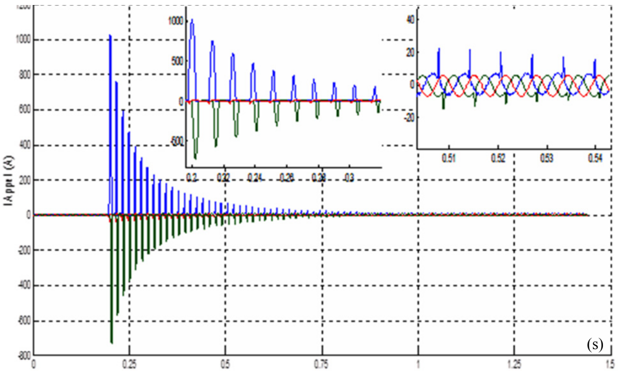


Fig. 8. Three phase inrush currents

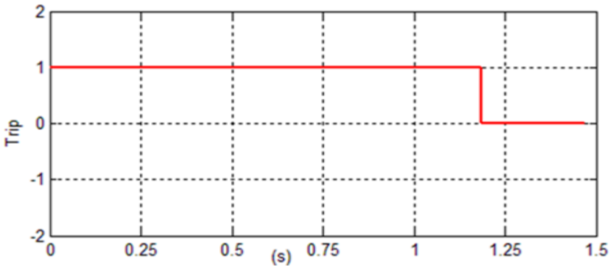


Fig. 9. Differential relay trip at 1.17 s

From Fig. 10–21 the primary, secondary and magnetization impedances are calculated in per unit (pu) system.

Performance of the proposed procedure during turn to turn faults. The performance of the proposed differential protection algorithm is profoundly studied and simulated by MATLAB/Simulink. Under turn to turn short-circuit conditions. Three sets of values for power transformer impedances are calculated in per unit system. Then, firstly, the negative sequence current amplitudes of primary and secondary sides are compared with the threshold 2 % of the winding. And secondly, the corresponding shift phase between these negative sequence currents are also compared to preset level which is from 0° to 3° to let the relay sensitivity higher for turn to turn faults recognition.

The simulation study is done for different per unit calculated values of primary impedance Z_1, secondary impedance Z_2 and magnetization impedance Z_M. These impedances values are equivalent to the percentage of short-circuited winding turns 10 %, 3 % and 0.5 %.

Case 1: Turn to turn fault on the secondary side. If the quantity of the negative current amplitudes is higher than the preset level, and the phase shift is zero, this means that an internal turn to turn fault has happened and a signal trip must be issued.

Figure 10 shows that a secondary internal turn to turn fault has happened in the calculated impedance values are: $Z_1 = Z_2 = 0.002$ pu, $Z_M = 0.5$ pu.

The corresponding negative sequence current amplitudes **(**I_neg.seq_P and I_neg.seq_P’**)** are compared with each other and with the preset level of 2 %. They are found to be equal and superior to the preset level as it can be seen on Fig. 10.

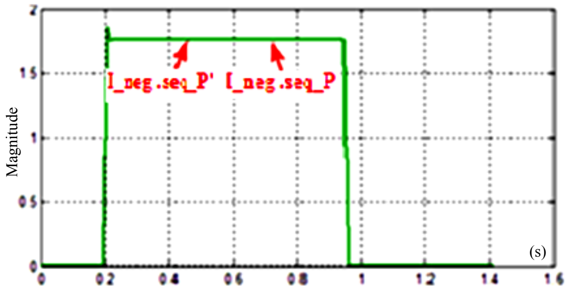


Fig. 10. Comparison of the negative sequence current amplitudes of I_neg.seq_P and I_neg.seq_P’ where calculated impedances are: $Z_1 = Z_2 = 0.002$ pu, $Z_M = 0.5$ pu

Figure 11 shows the phase shift comparison between the negative sequence currents (I_neg.seq_P and I_neg.seq_P’) during secondary turn to turn fault for calculated per unit impedances $Z_1 = Z_2 = 0.002$ pu, $Z_M = 0.5$ pu. It was found that the phase shift between them is 180°, which means that they are in opposite directions as it was expected.

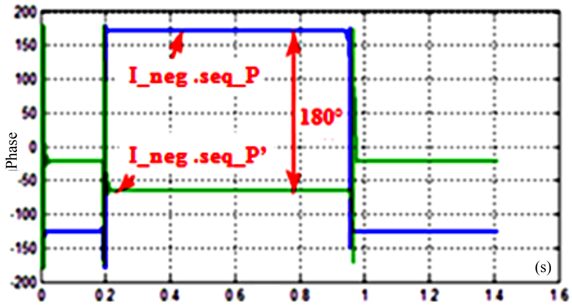


Fig. 11. Comparison of phase shift between I_neg.seq_P and I_neg.seq_P’ where impedances are: $Z_1 = Z_2 = 0.002$ pu, $Z_M = 0.5$ pu

Figure 12 shows an amplitudes comparison between I_neg.seq_P and I_neg.seq_P$^{'}$ during turn to turn fault for calculated impedances $Z_1 = Z_2 = 0.008$ pu, $Z_M = 0.5$ pu. It can be seen from Fig. 12 that the negative sequence current amplitudes of the faulted side I_neg.seq_P$^{'}$ is equal to the magnitude of the negative sequence current I_neg.seq_P on the healthy side and both of them are higher than the preset level as expected.

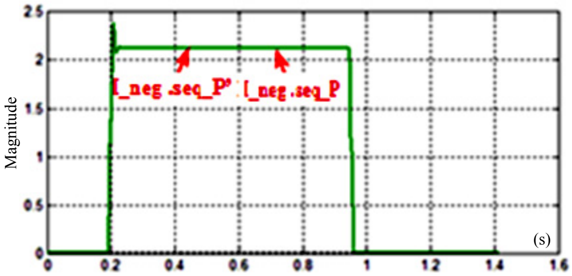


Fig. 12. Amplitude comparison between I_neg.seq_P, and I_neg.seq_P$^{'}$ where impedances are: $Z_1 = Z_2 = 0.008$ pu, $Z_M = 0.5$ pu

In Fig. 13 it can be seen that, the phase angle between the two negative sequence currents I_neg.seq_P, and I_neg.seq_P' during secondary turn to turn fault is 180°, this means that they are opposite in directions, which is already proven by the previous corresponding electrical circuit diagram (Fig. 2).

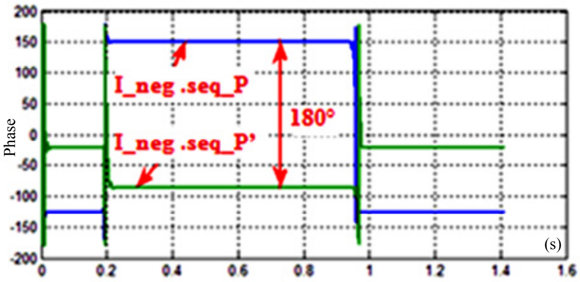


Fig. 13. Phase angle comparison between I_neg.seq_P and I_neg.seq_P' during secondary internal turn to turn fault for $Z_1 = Z_2 = 0.008$ pu, $Z_M = 0.5$ pu

Figure 14 shows equal amplitudes of the negative sequence currents on both sides of the power transformer. It can be seen in the previous electrical circuit (Fig. 2) which illustrating directions of the negative sequence currents during external fault. It can be noticed that I_neg.seq_P enters from the faulty side and leaves from the other side, after being transformed to become I_neg.seq_P' (Fig. 15).

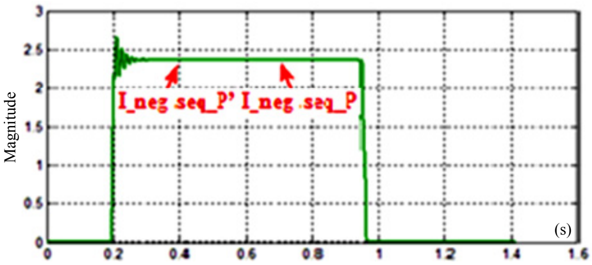


Fig. 14. Amplitudes comparison between I_neg.seq_P and I_neg.seq_P' during secondary external fault for calculated impedances: $Z_1 = Z_2 = 0.2$ pu, $Z_M = 0.5$ pu

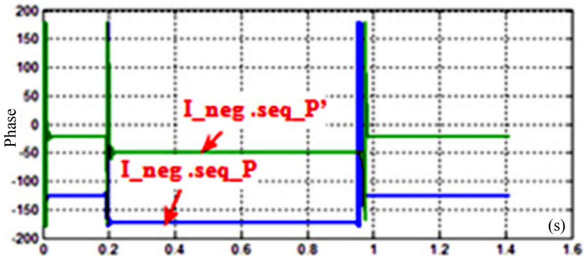


Fig. 15. Phase angle comparison between I_neg.seq_P and I_neg.seq_P' during secondary external fault side where calculated impedances are: $Z_1 = Z_2 = 0.2$ pu, $Z_M = 0.5$ pu

Case 2: Turn to turn fault at the primary side. Figures 16, 17 show that during internal turn to turn fault in the primary side, the negative current amplitudes of (I_neg.seq_S) are much higher than the amplitude of (I_neg.seq_P), due to the fault presence in the primary winding «very high resistance very low current Kirchhoff's second law» and the phase shift between them is moderate.

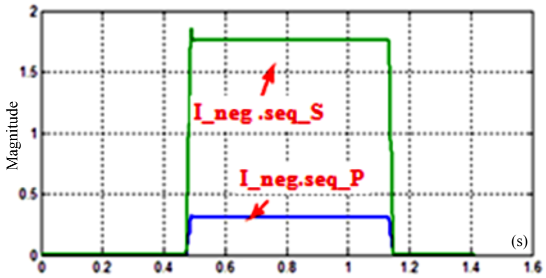


Fig. 16. Amplitudes comparison between I_neg.seq_P and I_neg.seq_S, during internal turn to turn fault, where calculated impedances are: $Z_1 = Z_2 = 0.002$ pu, $Z_M = 0.5$ pu

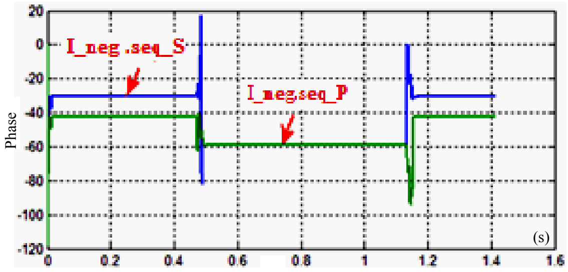


Fig. 17. Phase angle comparison between I_neg.seq_P and I_neg.seq_S during internal turn to turn fault, where calculated impedances are: $Z_1 = Z_2 = 0.002$ pu, $Z_M = 0.5$ pu

Figure 18 is illustrating the magnitudes of the negative sequence current in the primary and secondary sides respectively I_neg.seq_P and I_neg.seq_S during internal turn to turn fault for the corresponding impedances calculated in per unit system: $Z_1 = Z_2 = 0.008$ pu, $Z_M = 0.5$ pu. It can be seen on Fig. 18 that the amplitude of the secondary negative sequence current (I_neg.seq_S) is almost 3 times higher than the primary negative sequence current.

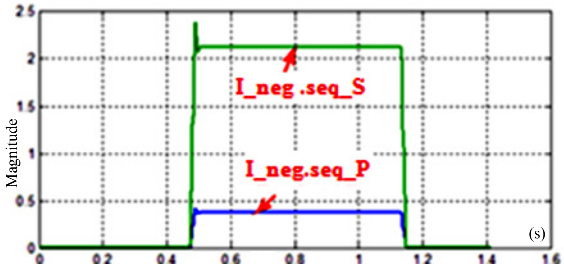


Fig. 18. Amplitude comparison between I_neg.seq_P and I_neg.seq_S during internal turn to turn fault, where impedances are: $Z_1 = Z_2 = 0.008$ pu, $Z_M = 0.5$ pu

Figure 19 shows the phase angle shift between the negative sequence currents (I_neg.Seq_P) and (I_neg.seq_S) where it can be remarked that its value is about 3° because the impedance values are very small.

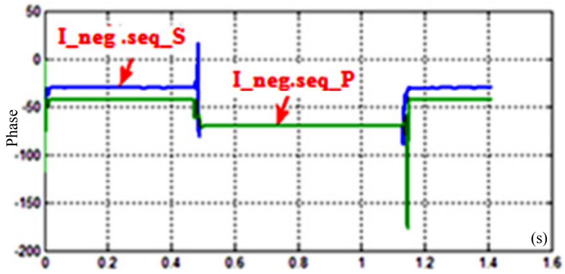


Fig. 19. Phase angle comparison between I_neg.Seq_P and I_neg.seq_S during internal turn to turn fault, where calculated impedances are: $Z_1 = Z_2 = 0.008$ pu, $Z_M = 0.5$ pu

In Fig. 20, 21 it can be seen that amplitude of I_neg.seq_S is higher than of I_neg.Seq_P, and the phase angle between the two corresponding negative sequence currents during internal turn to turn fault for primary winding, is almost 0°.

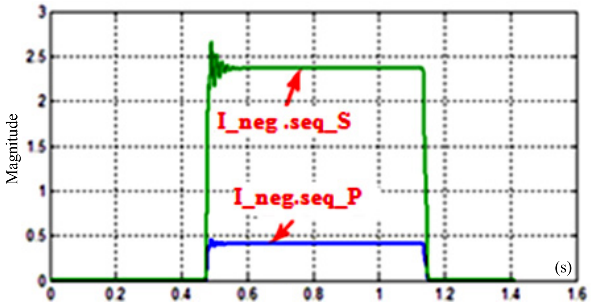


Fig. 20. Amplitude comparison between I_neg.seq_P and I_neg.seq_S during internal turn to turn fault, where impedances are: $Z_1 = Z_2 = 0.2$ pu, $Z_M = 0.5$ pu

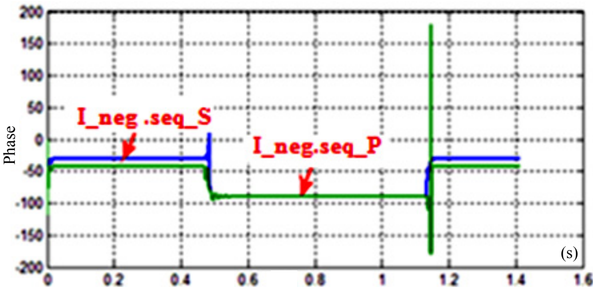


Fig. 21. Phase angle comparison between I_neg.Seq_P and I_neg.seq_S during internal turn to turn fault, where impedances are: $Z_1 = Z_2 = 0.2$ pu, $Z_M = 0.5$ pu

5. Conclusions.

This paper describes a new negative sequence current based protection method for detecting and locating the inter-turn faults in transformer windings that overcomes the limitation of the traditional transformer protection schemes in determining low level inter-turn faults. The negative current values are very exploited in the domain of protection in general and especially in the field of power transformers. In spite of that, the problem of detecting and locating the small internal turn to turn faults is a hard task to accomplish. Overall, when it consists to the power transformer itself. Because the variation in power transformer amplitudes and phase shifts is very difficult thing to be reestablished. The proposed procedure is built on the contributions to total negative sequence currents from both sides HV and LV of the power transformer, it has proved to be reliable, efficient, and fast. It takes only few milliseconds to detect faults up to 0.5 %, and to characterize it as internal or external.

The evaluation of the proposed scheme has been done for different faults and operating conditions. It was found to be more sensitive than the classical differential relay. Hence, the scheme is very robust in such disturbance conditions which involves only few turns among primary or secondary windings of the power transformer.

Conflict of interest. The author declares that he has no conflicts of interest.

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