

Power transformer differential protection using current and voltage ratios



E. Ali^{a,*}, A. Helal^b, H. Desouki^b, K. Shebl^a, S. Abdelkader^a, O.P. Malik^c

^a Department of Electrical Engineering, Mansoura University, Mansoura, Egypt

^b Department of Electrical and Control Engineering, Arab Academy for Science, Technology & Maritime Transport, Alexandria, Egypt

^c Department of Electrical and Computer Engineering, University of Calgary, Calgary, Canada

ARTICLE INFO

Article history:

Received 15 May 2017

Received in revised form 12 July 2017

Accepted 21 August 2017

Keywords:

Differential relay

Current and voltage ratios

Inrush current

Internal fault

ABSTRACT

The main challenge in transformer protection is to find a fast and efficient differential relay algorithm that isolates the transformer from the system causing least damage. Algorithm should also avoid mal-operation while differentiating between the operating conditions. This paper presents an improved differential protection scheme for power transformer. The proposed scheme is based on the ratio of the absolute difference and absolute sum of the primary and secondary currents of each phase, supplemented by the ratio of the absolute difference and absolute sum of the primary and secondary terminal voltages of each phase. The proposed algorithm aims at avoiding mal-operation, possible with the conventional three-phase transformers differential protection scheme due to transient phenomena, including the magnetic inrush current, simultaneous inrush with internal fault, and faults with current transformer saturation. Investigation of the proposed differential protection scheme using both current and voltage ratios shows that it can provide fast, accurate, secure and dependable relay for power transformers.

© 2017 Elsevier B.V. All rights reserved.

1. Introduction

Power transformers, one of the most important equipment in power systems, are subject to faults, similar to any other component of the power system. About 10% of the faults take place inside the transformers and 70% of these faults are caused by short circuits in the windings [1]. Transformer protection is of vital significance to provide reliable operation of power systems.

The choice of protection depends on the criticality of the load, relative size of the transformer compared to the total system load and potential safety concerns. Percentage differential protection is the most widely used scheme for the protection of transformers rated 10MVA and above [2]. It is, however, recognized that the percentage differential relay can mal-operate due to various phenomena [2] related to the nonlinearities in the transformer core.

The major concern in power transformer protection is to avoid mal-operation of protective relays due to transient phenomena including magnetic inrush current, simultaneous inrush with internal fault, external faults with current transformer (ct) saturation.

* Corresponding author at: Department of Electrical and Computer Engineering, University of Calgary, Calgary, Canada.

E-mail addresses: elsaeed.ali@ucalgary.ca, eng.elsaeed2007@mans.edu.eg (E. Ali).

Many approaches to distinguish between inrush and internal fault currents have been proposed. Harmonic restraint is one of the simplest and most widely used approaches [3–7]. This approach has limitations with new low-loss amorphous core materials in modern transformers. These materials produce low harmonic content during magnetizing inrush current. Also, internal faults might contain sufficient amount of second and fifth harmonics like inrush current. So, it is hard to distinguish between internal fault and energization.

Other approaches have been developed to overcome the above limitations. These approaches include voltage and flux restraints [8–10] and inductance based methods [11–14]. These approaches have high dependence on transformer parameters. Digital signal processing approaches also have been proposed to avoid mal-operation of transformer differential protection. Among these approaches are pattern recognition based on neural networks [15–18] and fuzzy logic [19–24]. Their main drawbacks include the need for more training, complex computation, large memory and complex setup of experimental work [25].

Recently, wavelet transforms have been used with transformer differential protection [25–28]. Studies report that this approach has better ability of time-frequency location. Their shortcomings are that they need long data window and are also sensitive to noise and unpredicted disturbances, which limit their application in relaying [29]. The approaches mentioned above have limitations especially when the internal fault includes fault resistance and dur-

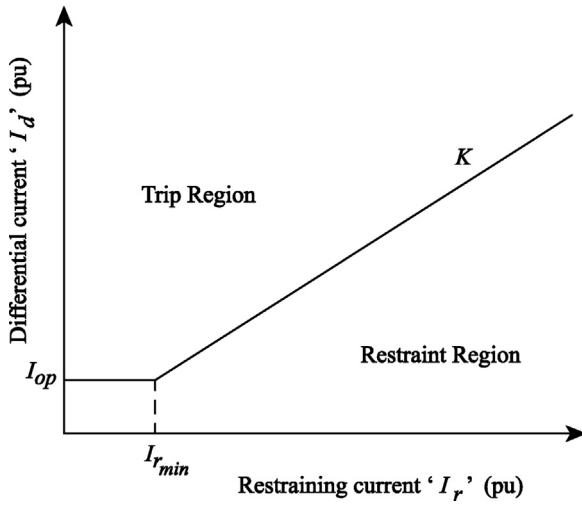


Fig. 1. Percentage differential relay characteristic.

ing transformer energization with internal fault that may affect their speed and security.

An approach using current and voltage ratios to address the challenges faced by the differential protection scheme for power three-phase transformers is proposed in this paper. The current ratio is used to discriminate between fault current and inrush current during no-load energization, and the voltage ratio is used to detect transformer energization on internal fault. Also, current direction criterion is used to discriminate between internal faults and external faults or loaded energization.

The proposed scheme is evaluated by studies such as inrush conditions, internal fault, external fault combined with ct saturation and simultaneous inrush with internal fault. The results demonstrate that the proposed discrimination scheme is fast, accurate, simple and robust to settings that improves the security and dependability of the power transformer protection.

2. Methodology of the proposed method

2.1. Percentage differential protection

Basis of the conventional percentage differential relay is that the differential current (I_d) is more than a predetermined percentage of the restraining current (I_r). Characteristic of the percentage relay is shown in Fig. 1. Magnitude of the fundamental component of the difference between the sampled values of the primary (i_1) and secondary (i_2) currents in per unit of each phase of the transformer, as measured by cts' secondary, is obtained using one cycle Discrete Fourier Transform (DFT). The differential current may be expressed as [30],

$$I_d = \text{Fundamental of } (|i_1(k) - i_2(k)|) \quad (1)$$

Likewise, the restraining current is calculated as [30]:

$$I_r = \text{Fundamental of } (|i_1(k) + i_2(k)|) / 2 \quad (2)$$

The operating characteristic of percentage differential relay is calculated as [31]:

$$\{I_d \geq I_{op}\} \& \{I_d \geq K(I_r - I_{r_{min}}) + I_{op}\} \quad (3)$$

where, I_{op} is the minimum operating current (0.2 pu), $I_{r_{min}}$ is the minimum restraining current (0.6 pu) and K is the restraint coefficient (20%). The relay is biased for tap-changing, ct saturation and ct mismatch during external fault.

2.2. Current and voltage ratios based scheme

To overcome the possibility of mal-operation using the operating criterion in Eq. (3), the following approach is proposed. On receipt of a positive (logic '1') signal based on the criterion in Eq. (3), check the current ratio, ε , calculated as:

$$\varepsilon = ||I_1| - |I_2|| / (|I_1| + |I_2|) \quad (4)$$

where, $|I_1|$ and $|I_2|$ are the magnitudes in per unit of the fundamental components of the primary and secondary currents obtained by DFT.

For normal operation the absolute values of I_1 and I_2 are almost equal and the value of current ratio, ε , is almost equal to zero. During energization, with the circuit breaker on the transformer secondary side open, inrush current flows on the primary side but no current flows on the secondary side. So, the value of the current ratio will be equal to one.

If an internal or external fault or loaded energization occurs, ε will be greater than zero and less than one depending on the value of I_1 and I_2 . To discriminate between internal, and external faults or loaded energization, the direction of instantaneous currents, i_1 and i_2 , is checked. Direction of one of these currents reverses for internal faults but not for an external fault or loaded energization. The magnitude of the fundamental component of $(i_1 - i_2)$ being less than the magnitude of the fundamental component of $(i_1 + i_2)$ indicates an external fault or loaded energization.

When an internal fault takes place simultaneously with transformer energization with secondary open, the current ratio will be also almost one. Moreover, if there exists an internal fault with loaded transformer energization, the current flow to the load will be a small value and the current ratio will be close to one. Therefore, current ratio scheme will mal-operate. So, it needs another discrimination criterion.

An internal fault not only affects the currents seen at the transformer terminals, but also the terminal voltages. Subject to the availability of the voltages on both sides of the transformer, it is proposed to use voltage ratio to detect the internal fault during transformer energization with or without load. Voltage ratio, λ , is the ratio between the absolute difference and absolute sum of primary and secondary voltages of the transformer and is calculated as:

$$\lambda = ||V_1| - |V_2|| / (|V_1| + |V_2|) \quad (5)$$

where, $|V_1|$ and $|V_2|$ are the magnitudes in per unit of the fundamental components of the primary and secondary voltages obtained by DFT.

During inrush current without fault this value is almost zero. When an internal fault exists during transformer energization, this value will be greater than zero.

The decision making logic is shown in Fig. 2. As indicated in the flowchart, the differential and restraining currents are calculated using Eqs. (1) and (2).

Magnitudes of the fundamental components of the currents I_1 and I_2 , and terminal voltages V_1 and V_2 of the power transformer are extracted using one cycle DFT. Subsequently, the percentage differential relay criterion in Eq. (3) is checked to ensure the operating conditions of the relay.

If the percentage criterion is satisfied, a condition of inrush and/or fault either internal or external exists. Otherwise, the condition is normal. Then, the current ratio is evaluated to discriminate between fault and inrush current. If the current ratio is greater than a threshold value (Th_i) and less than 0.9, a condition of loaded energization and/or fault, either internal or external, exists. The value of 0.9 is chosen to detect simultaneous fault with loaded energization. This value will avoid the error due to ct saturation. Then the direction of two currents is checked. If the direction of one current

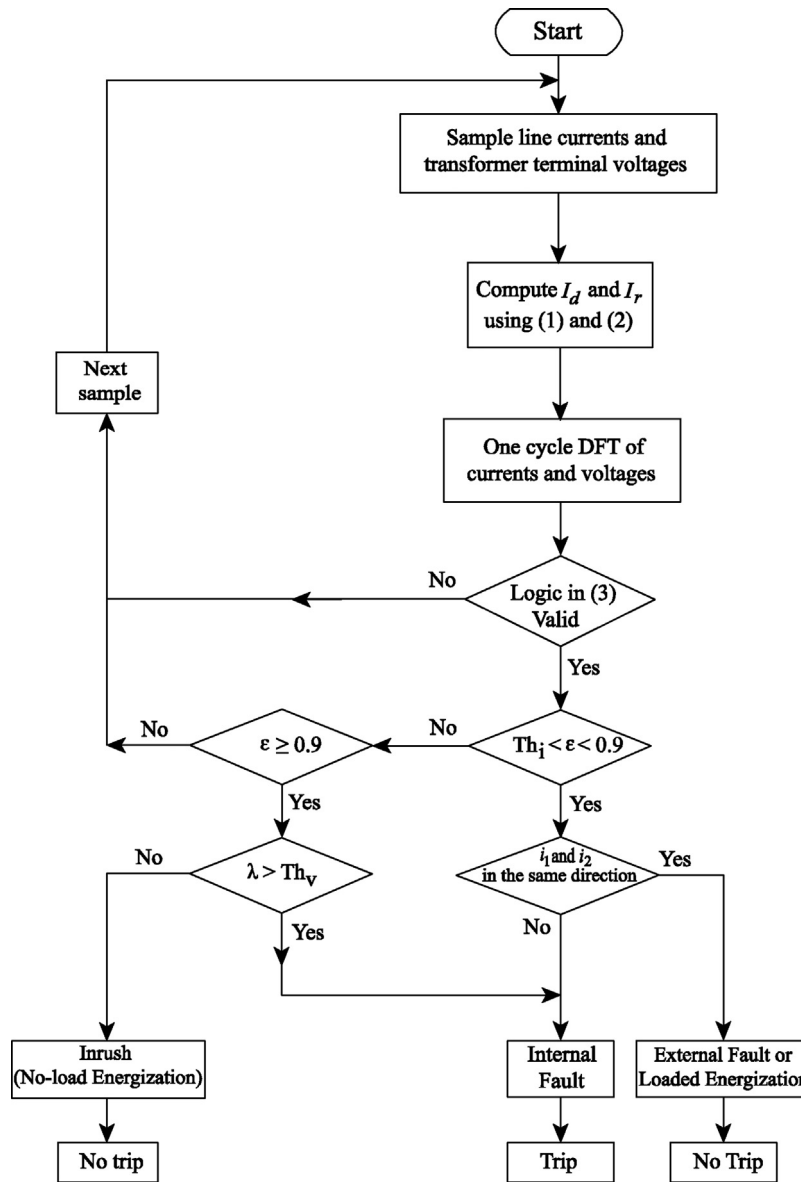


Fig. 2. Flowchart of the proposed scheme.

is reversed a trip signal is sent to the circuit breaker (CB) to isolate the faulted transformer. The value of Th_i chosen in this work is 0.05 based on normal operating conditions till 10% mismatch between the cts'. This leaves sufficient margin above zero for normal operation.

As long as the output of current ratio is equal to or higher than 0.9, the inrush condition and/or internal fault has taken place. After that, the voltage ratio is calculated to discriminate between the inrush and simultaneous inrush with internal fault. If the voltage ratio is greater than the voltage threshold (Th_v), the relay declares an internal fault and issues a trip signal to the CB. The inrush condition is assigned when voltage ratio is less than Th_v . Because of high current during energization there may be a voltage drop. So, the value of Th_v is selected equal to 0.025 taking the voltage drop into consideration. The classification trip logic of internal fault is shown in Fig. 3. Using four inputs, the output logic of ϵ , λ , current direction check and relay criterion in Eq. (3) for each phase, the relay can detect and classify the faulty phase, as shown in Fig. 3.

3. Simulated system

Single line diagram of the electrical power system used to evaluate the proposed differential protection scheme is shown in Fig. 4. It consists of a transmission grid with a 138 kV equivalent source, 25 MVA 138/13.8 kV 60 Hz star–star three-phase power transformer, 5 km transmission line connected to a 13.8 kV equivalent source. Parameters of the power system are given in the Appendix A [31].

The system is simulated using MATLAB/Simulink software. The sampling frequency is 2 kHz. The three-phase transformer has been modeled using MATLAB multi-winding transformer (see block diagram in Appendix A) where the low voltage (LV) winding is divided into sub-windings. The magnetizing characteristic of the power transformer is shown in Fig. 5. The current transformers, connected in each phase of the high voltage (HV) and LV sides as shown in Fig. 4, are 1200/5 and 100/5 for the LV and HV sides, respectively, and are modeled using saturated transformer model. Also, the magnetizing characteristics are taken into account to simulate the cts' saturation [32].

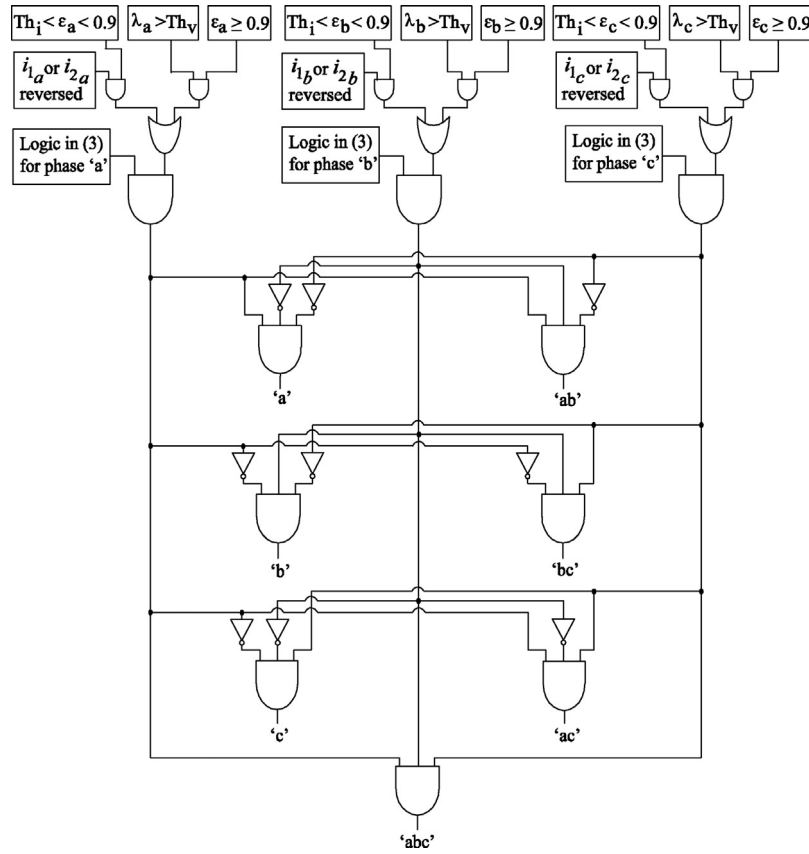


Fig. 3. Trip logic classification of internal fault.

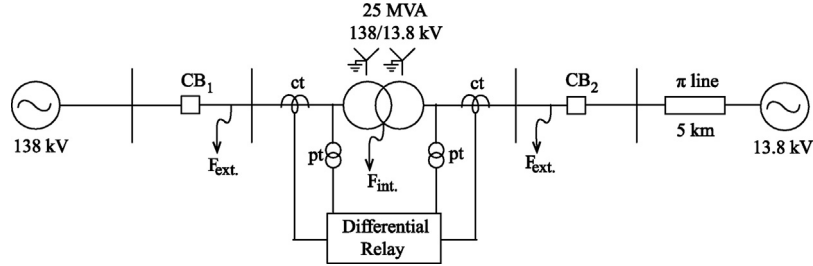


Fig. 4. Single line diagram of the simulated system.

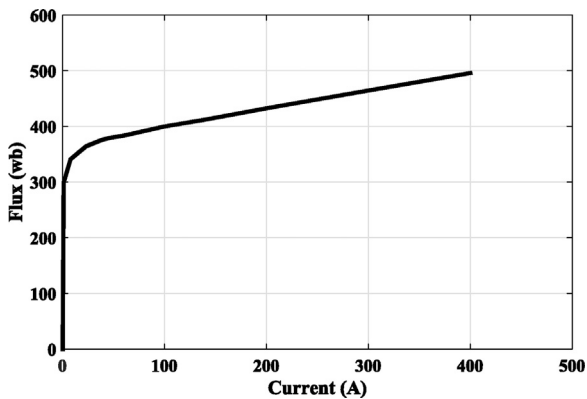


Fig. 5. Magnetizing characteristic of power transformer.

4. Results and discussion

A large number of studies have been performed on the simulated system for the normal conditions and the following fault cases at different switching angles (0° , 30° , 60° and 90°):

- Energization with and without load.
- External faults on both primary and secondary sides with fault resistance.
- External faults with ct saturation.
- Internal fault in both primary and secondary windings of the transformer simulated with different percentage winding and different fault resistance.
- Simultaneous energization with internal fault at different percentage winding and fault resistance.

To keep the paper length within limits, only a limited number of cases are described in detail and a summary of others is given in a table to illustrate the results and the performance of the proposed technique.

4.1. No-load energization

This test is carried out when CB₁ is closed at 50 ms and zero angle of phase 'a' voltage waveform with CB₂ open. Simulation results are shown in Fig. 6. Behavior of the three phase differential cur-

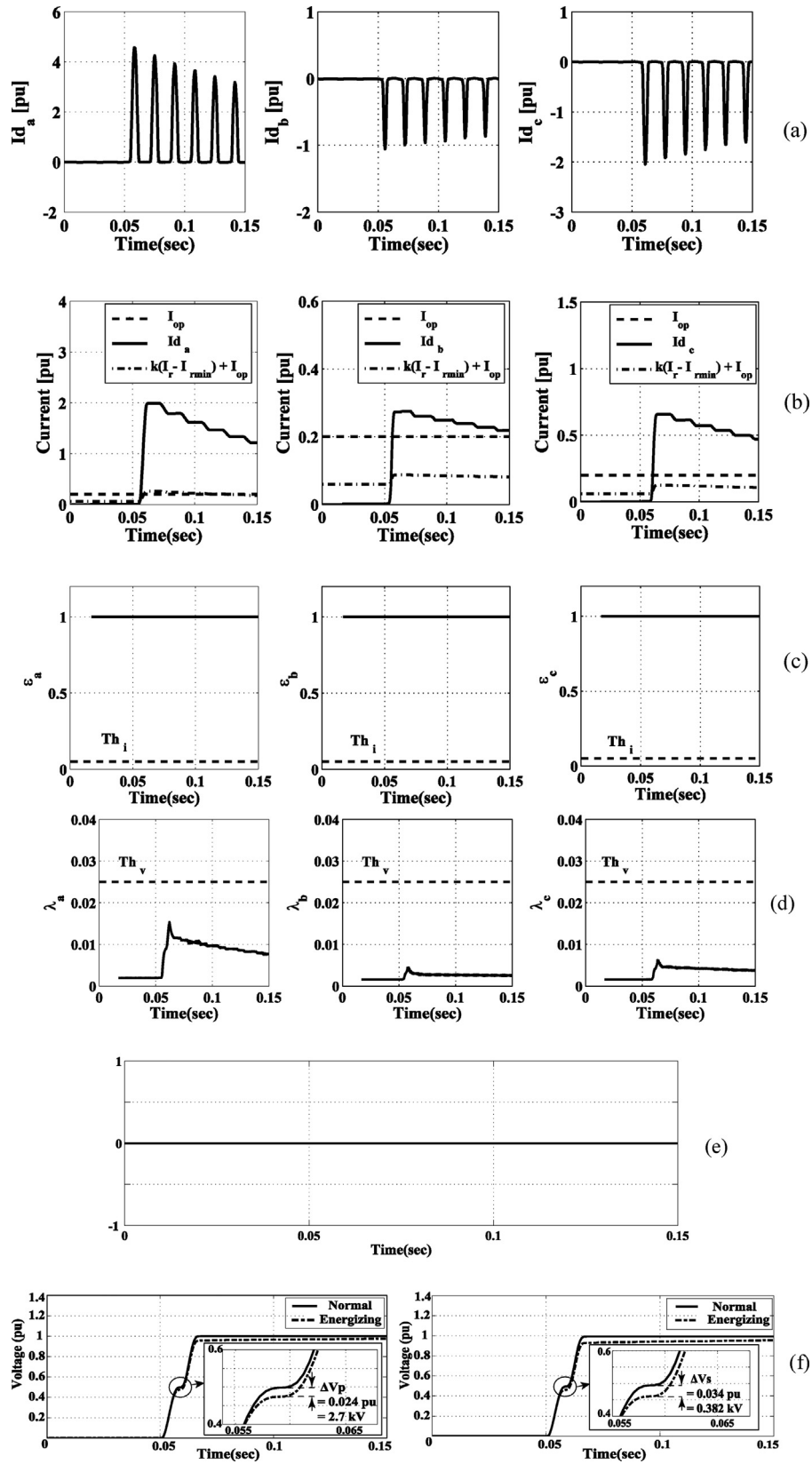


Fig. 6. Three differential currents and relay response during no-load transformer energization. (a) Three phase differential currents, (b) percentage differential operation, (c) current ratio, (d) voltage ratio, (e) output logic to CB, and (f) voltage behaviour during normal and energizing on primary (left) and secondary (right).

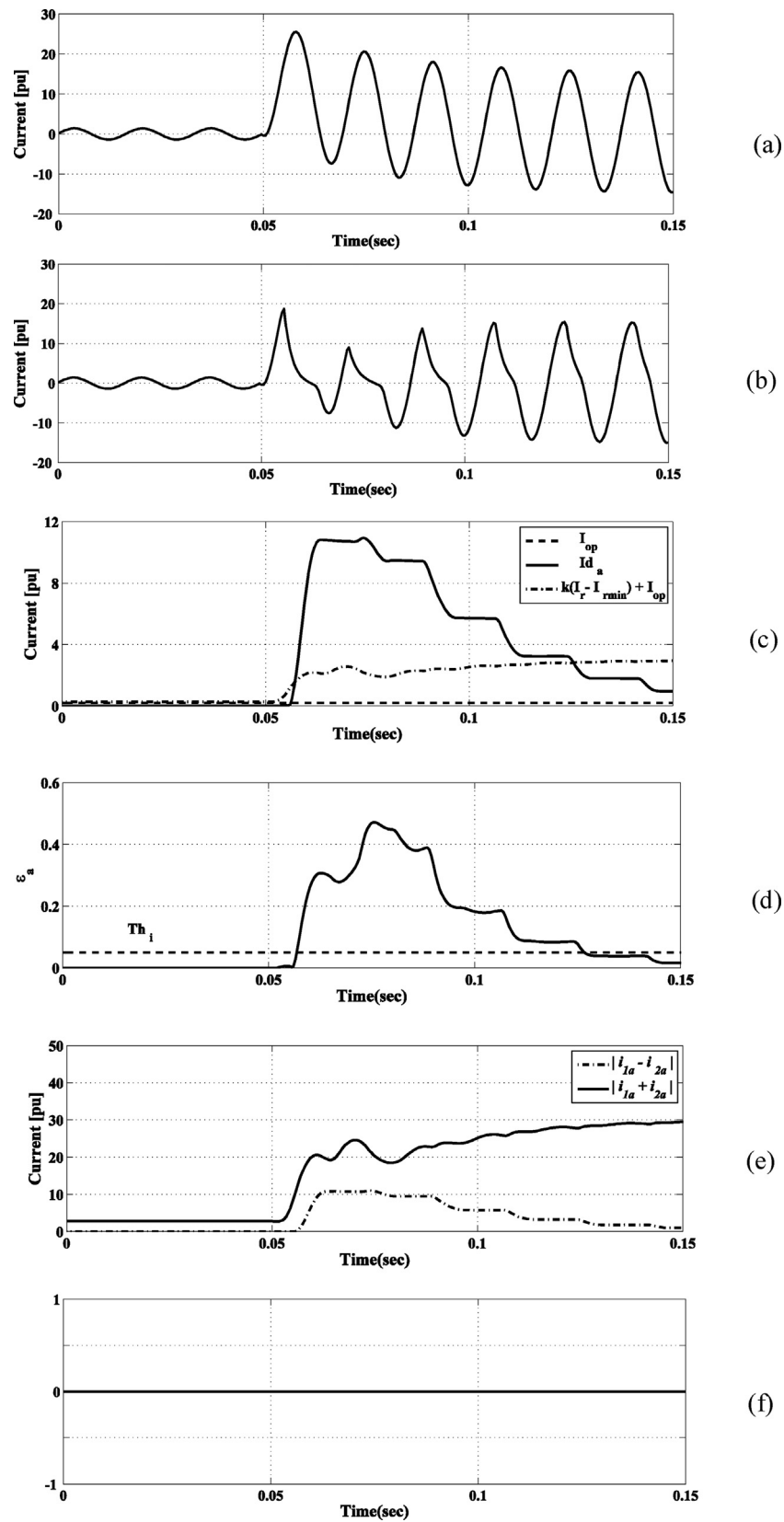


Fig. 7. Relay response during external fault on LV side. (a) Primary current, (b) secondary current, (c) percentage differential operation, (d) current ratio, (e) current direction check, and (f) output logic to CB.

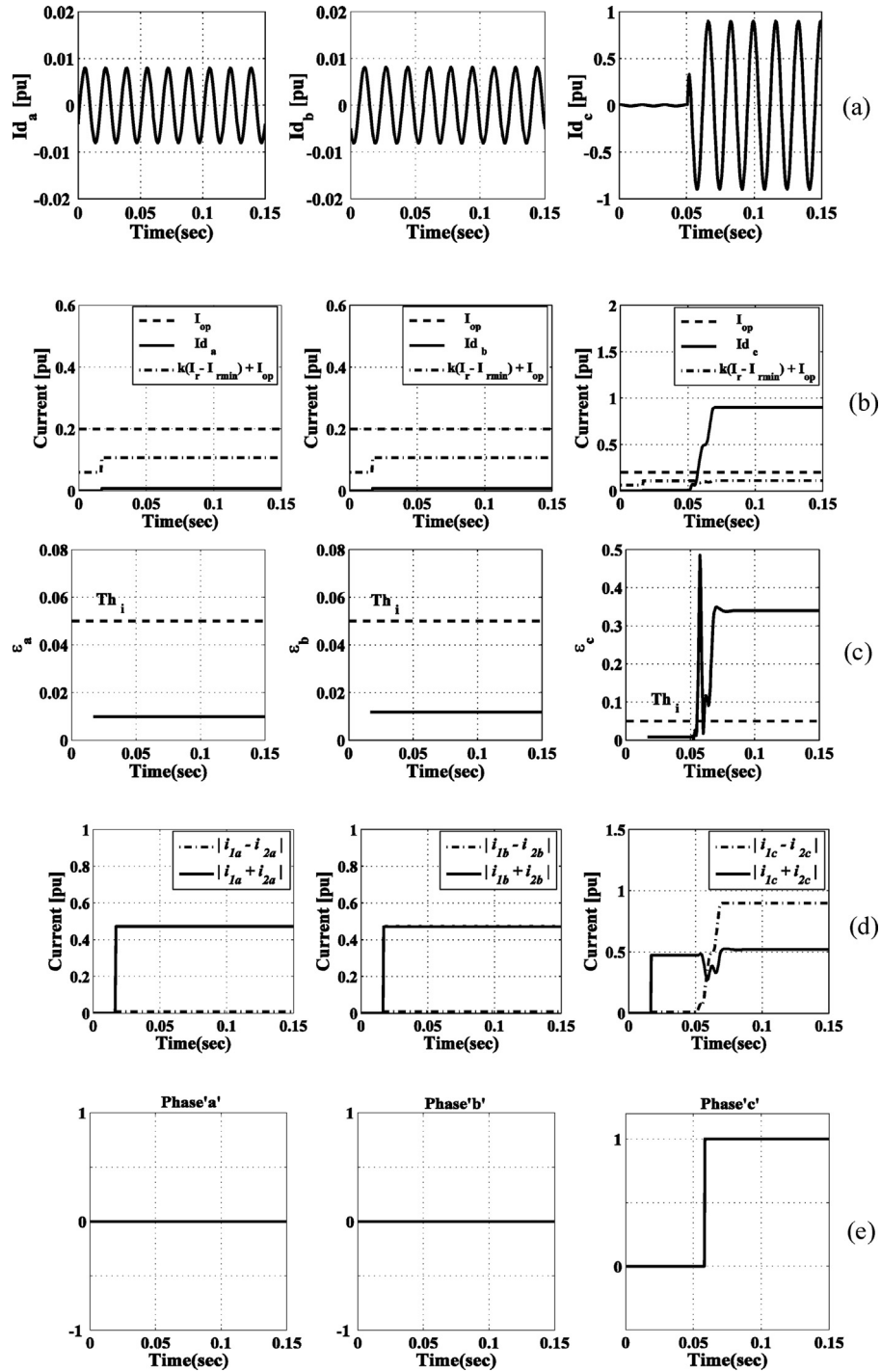


Fig. 8. Three differential currents and relay response on 3% turn to turn fault on LV winding of phase 'c'. (a) Three phase differential currents, (b) percentage differential operation, (c) current ratio, (d) current direction check, and (e) output logic to CB.

rents of three phases is shown in Fig. 6(a). The differential current is greater than the criterion logic in Eq. (3), Fig. 6(b). It means that the conventional percentage differential relay will mal-operate with transformer energization and send a trip signal.

With the proposed algorithm, although the current ratio value is one, Fig. 6(c), the voltage ratio in each phase is less than Th_v , Fig. 6(d), confirming that energization occurred and will restrain the relay. Subsequently, the trip logic output is zero which means normal operation and no trip signal is issued as shown in Fig. 6(e). Accordingly, the proposed scheme avoids the mal-operation of percentage differential relay with transformer energization. Voltage

differential between the normal and energizing operation on primary and secondary sides is seen in Fig. 6(f) left side and right side, respectively. It can be seen that on energization there is a voltage drop on both sides compared to the normal condition. Also, the voltage drop in V_1 and V_2 during energization is different. This voltage drop is taken into account when using the voltage ratio criterion.

4.2. External fault with ct saturation

In order to test the proposed scheme during ct saturation, a phase "a" to ground external fault at the beginning of the transmis-

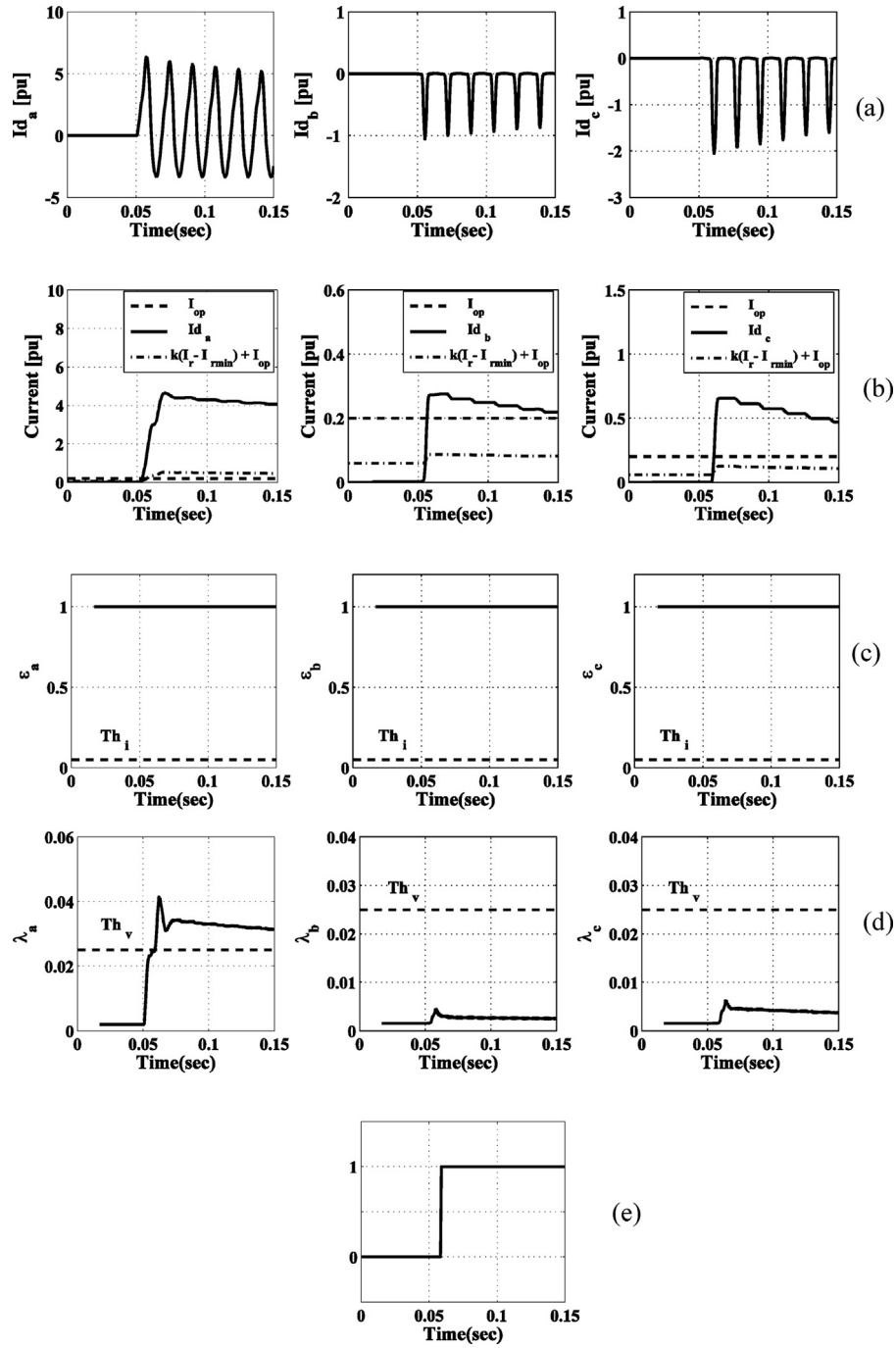


Fig. 9. Three differential currents and relay response for simultaneous Inrush with 5% T-T fault on phase 'a' at LV. (a) Three phase differential currents, (b) percentage differential operation, (c) current ratio, (d) voltage ratio, and (e) output logic to CB.

sion line with ct saturation is presented in Fig. 7. The simulation of this case is done using PSCAD software. As seen from Fig. 7(a) and (b), the direction of i_1 and i_2 is the same. Also, the differential current is greater than the criterion logic in Eq. (3) as seen in Fig. 7(c). So, the percentage differential relay will mal-operate during external fault with ct saturation. In Fig. 7(d), value of the current ratio is higher than Th_i . The direction check of the ct secondary currents for primary and secondary sides, Fig. 7(e), shows that the magnitude of fundamental component of $(i_1 - i_2)$ is less than the magnitude of fundamental component of $(i_1 + i_2)$ indicating an external fault. So, the final logic of the relay is no-trip, which indicates the security of the proposed scheme during external faults.

4.3. Internal fault

There are many cases of internal faults such as turn to turn faults, turn to ground faults and phase to phase faults. In these cases, the protection relay must detect and issue a trip signal to CB to isolate the faulted transformer. Indeed, during internal fault, direction of one of the terminal currents will be reversed. Response to a turn to turn fault across 3% of the phase 'c' winding on the low voltage side at 50 ms is shown in Fig. 8. As seen in Fig. 8(c), the value of current ratio in phase 'a' and phase 'b' is less than Th_i . However, this value is greater than Th_i in phase 'c'. Also, it is seen from Fig. 8(d) that the magnitude of fundamental component of $(i_1 - i_2)$ is higher than the magnitude of fundamental component of $(i_1 + i_2)$ in phase

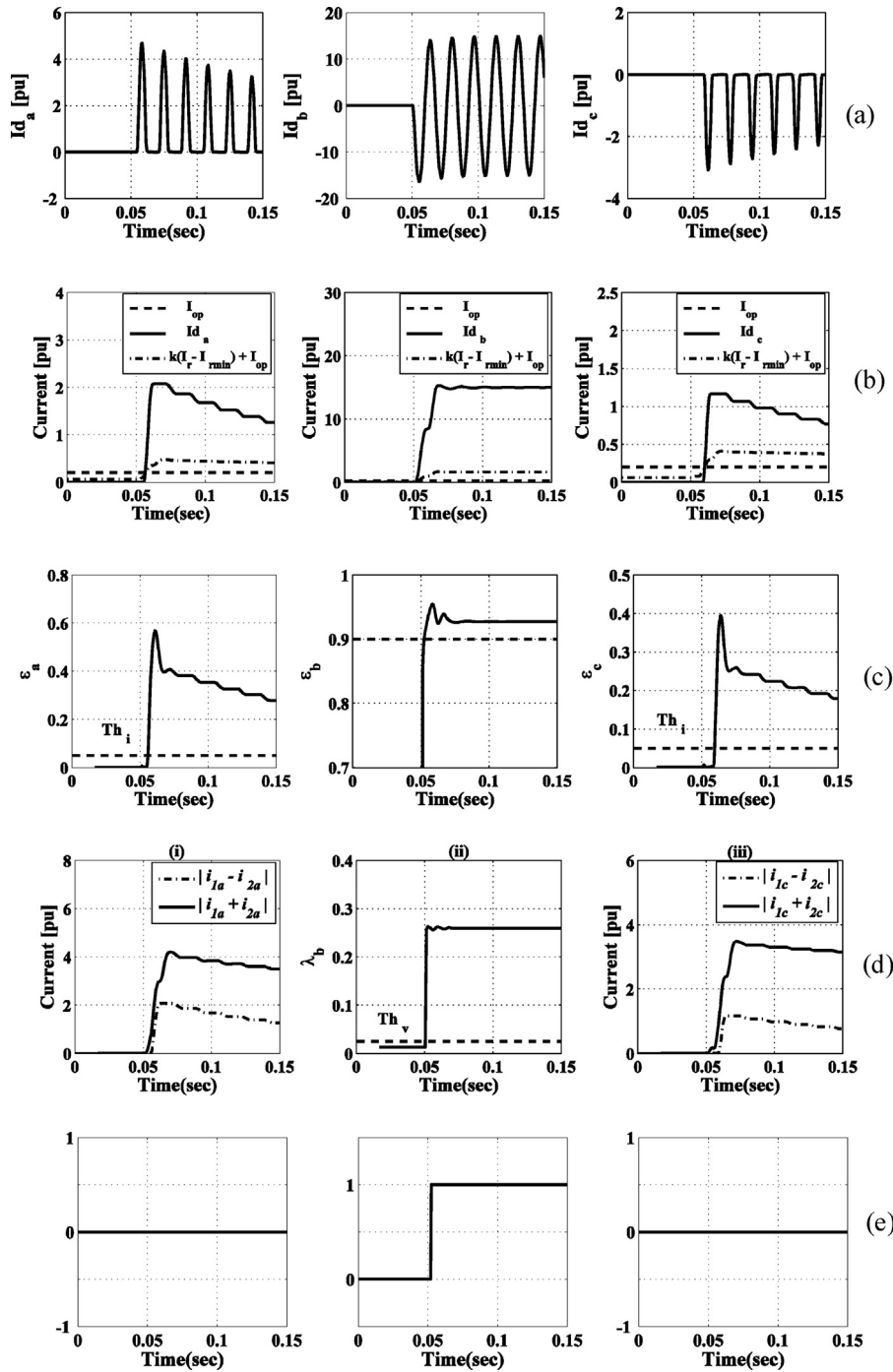


Fig. 10. Three differential currents and relay response for simultaneous 25% SLG fault with loaded energization on phase 'b' at LV winding. (a) Three phase differential currents, (b) percentage differential operation, (c) current ratio, (d) (i) phase 'a' current direction, (ii) phase 'b' voltage ratio, (iii) phase 'c' current direction, and (e) output logic to CB.

'c' indicating an internal fault has taken place. In order to classify the faulty phase a trip logic scheme is shown in Fig. 8(e). The relay issues a trip signal to CB at 58.5 ms, which indicates the detection in almost one half cycle based on 60 Hz. It can be seen that the proposed scheme succeeded in detecting the faulty phase (i.e. phase 'c') and then sent a trip signal to isolate the transformer.

4.4. Simultaneous no-load energization with internal fault

This situation takes place when the transformer is energized on a pre-existing internal fault. In this case, detection of the fault is more

difficult than any other case, especially when the fault is located close to the neutral point. As mentioned before, the current ratio will mal-operate during simultaneous inrush and internal fault current. So, this case is evaluated using the voltage ratio as proposed above. In this case, Fig. 9, the transformer is energized under 5% turn to turn fault across phase 'a' low voltage winding. As illustrated in Fig. 9(c), the current ratio value being one, current ratio cannot discriminate between inrush and inrush with internal fault. As shown in Fig. 9(d) the voltage ratio in phase 'a' is greater than Th_v . So, the proposed scheme succeeded in detecting the fault at 59 ms as depicted in Fig. 9(e).

Table 1
Performance of proposed relay at different transient phenomena.

Case	Switching angle (time)			
	0° (50 ms)	30° (51.388 ms)	60° (52.777 ms)	90° (54.166 ms)
3% turn–turn fault across phase 'b' at LV	Trip at 59.5 ms	Trip at 60.5 ms	Trip at 61 ms	Trip at 61 ms
10% SLG fault across phase 'b' at LV with $R_f = 0.2 \Omega$	Trip at 60 ms	Trip at 61.5 ms	Trip at 66 ms	Trip at 66.5 ms
7% turn–turn fault across phase 'a' at LV with $R_f = 0.1 \Omega$	Trip at 61.5 ms	Trip at 62 ms	Trip at 63 ms	Trip at 65 ms
20% turn–turn fault across phase 'b' at LV with $R_f = 1 \Omega$	Trip at 61.5 ms	Trip at 66 ms	Trip at 67.5 ms	Trip at 67.5 ms
30% SLG fault across phase 'c' at LV with $R_f = 2 \Omega$	Trip at 64 ms	Trip at 64 ms	Trip at 64 ms	Trip at 65 ms
No-load energization	No trip	No trip	No trip	No trip
Loaded energization	No trip	No trip	No trip	No trip
5% turn–turn fault across phase 'b' at LV during energizing	Trip at 57.5 ms	Trip at 57.5 ms	Trip at 58.5 ms	Trip at 65.5 ms
20% turn–turn fault across phase 'b' at LV with $R_f = 0.1 \Omega$ during energizing	Trip at 52.5 ms	Trip at 58 ms	No trip	No trip
20% SLG fault across phase 'c' at LV during loaded energization	Trip at 54.5 ms	Trip at 59.5 ms	Trip at 59.5 ms	Trip at 60 ms
25% turn–turn fault across phase 'c' at LV during loaded energization	Trip at 53 ms	Trip at 57 ms	Trip at 56.5 ms	Trip at 57.5 ms
a–G across LV terminals with $R_f = 25 \Omega$	Trip at 62 ms	Trip at 62.5 ms	Trip at 63.5 ms	Trip at 69 ms
ab–G across HV terminals with $R_f = 300 \Omega$	Trip at 52.5 ms	Trip at 53.5 ms	Trip at 55 ms	Trip at 56 ms
abc–G external fault at HV	No trip	No trip	No trip	No trip

4.5. Simultaneous loaded energization with internal fault

A transformer connected to a load (20 MW, 0.8 pf inductive) is energized on a pre-existing internal fault. A transformer is energized at 50 ms with a single line to ground (SLG) fault across 25% of phase 'b' on the LV winding. It can be seen from Fig. 10(c) that the current ratio in the faulted phase is higher than 0.9 and in the other two phases is less than 0.9. This means that the proposed algorithm will check the voltage ratio criteria for the faulted phase and check the current direction criterion for the other two phases. The voltage ratio of phase 'b' is higher than Th_v , as illustrated in Fig. 10(d(ii)). As seen from Fig. 10(d(i)) and (d(iii)), the current direction criterion of phases 'a' and 'c' is valid. So, the proposed algorithm issues a trip signal according to phase 'b', Fig. 10(e), at 52.5 ms.

4.6. Other faults

To test the performance of the proposed scheme thoroughly, many scenarios of inrush current, internal fault, external fault and simultaneous inrush with internal fault are analyzed at different switching inception angles as illustrated in Table 1. The inception angle is calculated according to the voltage waveform of phase 'a'.

It can be seen from Table 1 that the proposed relay succeeded in detecting the internal fault from 3% and above of the winding from the neutral end on the low voltage side. In addition, the proposed scheme can detect accurately the simultaneous inrush current and internal fault from 5% of the windings and above without load. Also, with load, it can detect ground fault from 20% and turn to turn fault from 25%.

All studies reported here are with the nominal tap ratio. Additional studies performed, however, showed that the algorithm performs correctly within a range of $\pm 5\%$ tap.

5. Conclusions

A transformer differential protection scheme based on current ratio and voltage ratio between difference and sum of fundamental components of line currents and power transformer terminal voltages, respectively, is proposed in this paper. The current ratio is used to discriminate between inrush and fault conditions. However, voltage ratio is used to detect transformer energization on internal fault. Also, the current direction criterion is used to restrain the proposed relay during external faults and loaded energization. Many scenarios of fault and non-fault conditions have been simulated. It is demonstrated in this paper that the proposed algorithm successfully differentiates between magnetizing inrush and fault conditions in almost one half power frequency cycle. Also, the pres-

ence of fault resistance and ct saturation are evaluated for many cases.

The results show that the proposed technique can detect and classify fault cases from 3% of windings and above from neutral end within a short time depending on the fault case. It is found that this technique is simple, dependable, secure and reliable in discriminating the inrush currents from the fault currents. It is simple to implement and is proposed to be tested on a physical transformer as the next step.

Acknowledgments

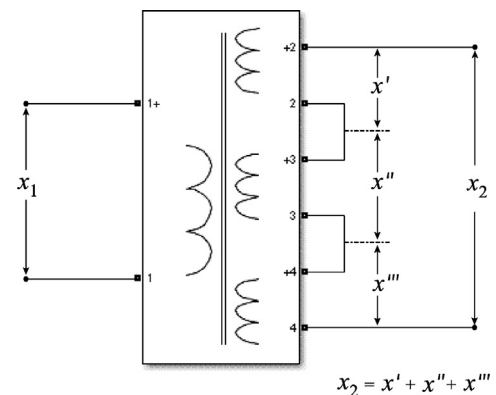
This work was supported by Egyptian Government-ministry of higher education (cultural affairs and missions sector) PhD scholarship.

Appendix A.

– Simulated power system parameters:-

138 kV source	$R_s = 7.1 \Omega$, $L_s = 53.99$ mH, $R_0 = 7.596 \Omega$, $L_0 = 115.45$ mH.
13.8 kV source	$R_s = 1.4 \Omega$, $L_s = 5.6$ mH, $R_0 = 1.498 \Omega$, $L_0 = 11.975$ mH.
Power transformer	$R_1 = 0.908 \Omega$, $L_1 = 78.51$ mH, $R_2 = 0.0091 \Omega$, $L_2 = 0.7851$ mH, $R_c = 1.19$ M Ω .
Transmission line	$R_1 = 0.3101 \Omega$, $L_1 = 2.41$ mH, $C_1 = 26.8$ nF, $R_0 = 0.1437 \Omega$, $L_0 = 11.45$ mH, $C_0 = 5.635$ nF.

– MATLAB multi-winding transformer block diagram:



References

- [1] J. Blackburn, T. Domin, *Protective Relaying: Principles and Applications*, third ed., Taylor & Francis, 2006.
- [2] S.H. Horowitz, *Power System Relaying*, third ed., John Wiley & Sons Ltd, 2008.
- [3] P. Liu, D. Chen, Y. Guo, O.P. Malik, G.S. Hope, Improved operation of differential protection of power transformers for internal faults, *IEEE Trans. Power Deliv.* 7 (1992) 1912–1919.
- [4] M. Sanaye-Pasand, M. Zangiabadi, A. Fereidunian, An extended magnetizing inrush restraint method applied to digital differential relays for transformer protection, *IEEE Power Eng. Soc. Gen. Meet.* 4 (2003) 2077–2082.
- [5] M.E.H. Golshan, M. Saghalian-Nejad, A. Saha, H. Samet, A new method for recognizing internal faults from inrush current conditions in digital differential protection of power transformers, *Electr. Power Syst. Res.* 71 (2004) 61–71.
- [6] A. Aktaibi, M.A. Rahman, A software design technique for differential protection of power transformers, *Proceedings of IEEE Int. Electr. Mach. Drives Conf.* (2011) 1456–1461.
- [7] S.R. Wagh, S. Kumar, V. Sreeram, Extraction of DC component and harmonic analysis for protection of power transformer, *Proceedings of IEEE 8th Conf. Ind. Electron. Appl. (ICIEA)* (2013) 32–37.
- [8] A.G. Phadke, J.S. Thorp, A new computer-based flux-restrained current-differential relay for power transformer protection, *IEEE Trans. Power Appar. Syst.* PAS-102 (1983) 3624–3629.
- [9] S. Member, A novel transformer protection method based on the ratio of voltage and fluxional differential current, *Proceedings of IEEE Transm Distrib. Conf. Expo.* (2003) 342–347.
- [10] Y.C. Kang, B.E. Lee, S.H. Kang, Transformer protection relay based on the induced voltages, *Int. J. Electr. Power Energy Syst.* 29 (2007) 281–289.
- [11] K. Inagaki, M. Higaki, Y. Matsui, K. Kurita, M. Suzuki, K. Yoshida, T. Maeda, Digital protection method for power transformers based on an equivalent circuit composed of inverse inductance, *IEEE Trans. Power Deliv.* 3 (1988) 1501–1510.
- [12] G. Baoming, A.T. de Almeida, Z. Qionglin, W. Xiangheng, An equivalent instantaneous inductance-based technique for discrimination between inrush current and internal faults in power transformers, *IEEE Trans. Power Deliv.* 20 (2005) 2473–2482.
- [13] D.Q. Bi, X.H. Wang, W.X. Liang, W.J. Wang, A ratio variation of equivalent instantaneous inductance based method to identify magnetizing inrush in transformers, *Proceedings of Eighth Int. Conf. Electr. Mach. Syst.* (2005) 1775–1779.
- [14] H. Abniki, H. Monsef, P. Khajavi, H. Dashti, A novel inductance-based technique for discrimination of internal faults from magnetizing inrush currents in power transformers, *Proceedings of the Mod Electr. Power Syst. Conf.* (2010) 1–6.
- [15] M.R. Zaman, M.A. Rahman, Experimental testing of artificial neural network based protection of power transformer, *IEEE Trans. Power Deliv.* 13 (1998) 510–517.
- [16] Z. Moravej, D.N. Vishwakarma, S.P. Singh, Application of radial basis function neural network for differential relaying of a power transformer, *Comput. Electr. Eng.* 29 (2003) 421–434.
- [17] M. Tripathy, R.P. Maheshwari, H.K. Verma, Power transformer differential protection based on optimal probabilistic neural network, *IEEE Trans. Power Deliv.* 25 (2010) 102–112.
- [18] H. Balaga, N. Gupta, D.N. Vishwakarma, GA trained parallel hidden layered ANN based differential protection of three phase power transformer, *Int. J. Electr. Power Energy Syst.* 67 (2015) 286–297.
- [19] A. Wiszniewski, B. Kasztenny, A multi-criteria differential transformer relay based on fuzzy logic, *IEEE Trans. Power Deliv.* 10 (1995) 1786–1792.
- [20] M. Shin, C. Park, J. Kim, Fuzzy logic-based relaying for large power transformer protection, *IEEE Trans. Power Deliv.* 18 (2003) 718–724.
- [21] F. Zhalefar, M. Sanaye-pasand, A new fuzzy-logic-based extended blocking scheme for differential protection of power transformers, *Electr. Power Compon. Syst.* 38 (6) (2010) 675–694.
- [22] D. Barbosa, U.C. Netto, D.V. Coury, M. Oleskovicz, Power transformer differential protection based on Clarke's transform and fuzzy systems, *IEEE Trans. Power Deliv.* 26 (2011) 1212–1220.
- [23] D. Bejmert, W. Rebizant, L. Schiel, Transformer differential protection with fuzzy logic based inrush stabilization, *Int. J. Electr. Power Energy Syst.* 63 (2014) 51–63.
- [24] A. Rahmati, M. Sanaye-Pasand, Protection of power transformer using multi criteria decision-making, *Int. J. Electr. Power Energy Syst.* 68 (2015) 294–303.
- [25] S.A. Saleh, M.A. Rahman, Real-time testing of a wpt-based protection algorithm for three-phase power transformers, *IEEE Trans. Ind. Appl.* 41 (2005) 1125–1132.
- [26] M. Gómez-Morante, D.W. Nicoletti, A wavelet-based differential transformer protection, *IEEE Trans. Power Deliv.* 14 (1999) 1351–1356.
- [27] M.M. Eissa, A novel digital directional transformer protection technique based on wavelet packet, *IEEE Trans. Power Deliv.* 20 (2005) 1830–1836.
- [28] D. Guillén, H. Esponda, E. Vázquez, G. Idárraga-Ospina, Algorithm for transformer differential protection based on wavelet correlation modes, *IET Gener. Transm. Distrib.* 10 (2016) 2871–2879.
- [29] H. Zhang, J.F. Wen, P. Liu, O.P. Malik, Discrimination between fault and magnetizing inrush current in transformer using short-time correlation transform, *Electr. Power Syst. Res.* 24 (2002) 557–562.
- [30] IEEE Guide for Protecting Power Transformers, *IEEE Std C37.91*, 2008.
- [31] A. Hosny, V.K. Sood, Transformer differential protection with phase angle difference based inrush restraint, *Electr. Power Syst. Res.* 115 (2014) 57–64.
- [32] IEEE Standard Requirements for Instrument Transformers, *IEEE Standard C37.91*, 2008.