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A New Simple Method to Avoid Maloperation of Transformer Restricted Earth Fault Relay during External Fault Events

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ABSTRACT

The restricted earth fault (REF) protection is provided for electrical power transformer in order to sense internal earth faults, mainly because it is more sensitive than the main differential protection. However, The REF relay may maloperate when current transformer (CT) saturation happens following a severe external fault. In this paper, a new simple algorithm is proposed for REF protection scheme which is realized by considering four fundamental conditions. These conditions are defined based on the differential and neutral currents as well as sum of phase currents. When these conditions are simultaneously satisfied, the relay detects the internal ground fault. This algorithm is implemented and evaluated by MATLAB program based on obtained result data from simulation of a real power system using PSCAD/EMTDC software package. The well-known Jiles-Atherton (JA) model is used to simulate the transient behavior of CTs. The satisfactory results obtained from exhaustive investigation justify the high security of the proposed protection scheme.

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NOMENCLATURE

I_d	Differential current	I_{sum}	Residual current
I_n	Neutral current	$\mathrm{I}_{\mathrm{d}}^{\mathrm{TH}}$	Threshold value of differential current
I_a, I_b, I_c	Phase currents	$\mathrm{I}_{\mathrm{n}}^{\mathrm{TH}}$	Threshold value of neutral current

1. INTRODUCTION

Power transformers are the most important and expensive equipment of high voltage substations. Thus, they should be protected against any internal faults by sensitive protective relays. Differential protection is the most commonly used transformer protection scheme. It can cover most of short circuits inside the transformer protection zone including terminal and winding faults [1]. However, when an earth fault happens close to neutral point of the transformer Y winding or the fault impedance is high, the fault current may not be sufficient to drive the differential protection scheme. The restricted earth fault (REF) protection scheme is designed to respond to such earth faults [2]. But, current transformer (CT) saturation caused by either the magnetizing inrush currents or severe external faults may make the REF relay maloperate [3-5]. It should be noted that the strictly CT dimensioning can improve the protection system immunity against CT saturation; however, the issue is not solved completely [6]. Hence, some methods have been proposed to make this protection scheme stable during inrush current and external faults. The first alternative was a high-impedance REF prtection scheme, but this method needs phase and neutral CTs with exactly the same magnetizing characteristic as well as a high knee-point voltage [7, 8]. Nowadays, numerical low-impedance REF relays have received more attention because they do not need the rigid CT requirements of the high-impedance type [9]. However, during CT saturation, a false differential current appears in the low-impedance REF relay and this may cause the relay maloperation [10-12]. Adaptive restraint currents and directional supervision methods can improve this relay

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performance but even with these methods, the maloperation issue remains in many cases [13]. A research shows that by combining the REF and earth fault (EF) units, the protection stability against maloperation improves to some extent [14]. However, if the neutral current is enough high during a potential case of maloperation, this method will not be helpful. The Krstivojevic and Djurić [15, 16] proposed a new REF algorithm based on a time domain phase comparator that yields desirable results for inrush current condition and only single phase to ground type of external fault. Ebadi et al. [17] have designed a new REF relay based on artificial intelligence which is slower than conventional method. They also employed time-frequency analysis to create an effective supervision method for conventional REF relays [18].

Based on above descriptions, more efforts must be done to tackle this issue. In this paper, a new algorithm is proposed that significantly improves the REF protection immunity during external faults. Furthermore, during an internal fault event, the neutral current vector is in opposite direction of the residual current vector. On the other hand, they have the same direction during an external fault event. So, the magnitude of differential vector of these two currents is calculated using different formulas for internal and external faults. In this study, four different conditions are defined based on the calculated differential current vector. The proposed REF protection scheme issues the trip signal when all defined conditions are simultaneously satisfied. The logic behind the algorithm is very simple and it can be easily implemented in practical applications. Moreover, it is very fast to detect internal faults.

The rest of this paper is organized as follows: In section 2, the test study is introduced. Section 3 presents the proposed method. Simulation results are presented in section 4. Finally, the conclusion is made at the end of the paper in section 5.

2. TEST STUDY

For performance evaluation of the proposed method in internal and external fault events, a part of the Iranian high voltage substation depicted in Figure 1 is simulated using PSCAD/EMTDC software package. This 50 Hz power system includes a 230/63 kV power transformer with nominal power of 160 MVA, a grounding transformer and CTs with turns ratios of 600:1 and 2000:1 installed at the Y and Δ sides of the power transformer, respectively. More details about the power system under study have been presented by Ebadi et al. [18]. It is notable that the precise Jiles–Atherton model is applied to simulate CTs. The parameters of Jiles–Atherton model according to magnetization characteristics of CTs can be found in literature [19].

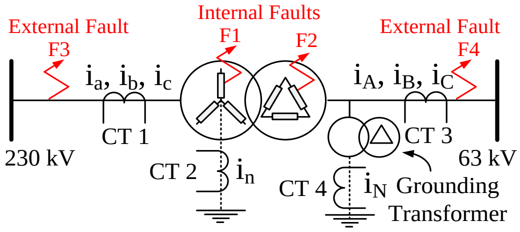

Figure 1. The single line diagram of power system under study

3. PROPOSED METHOD

A typical differential (operating) current of low-impedance REF relays is given by Equation (1):

$$I_d = (I_a + I_b + I_c) - I_n = I_{sum} - I_n \tag{1}$$

where I_a, I_b and I_c denote phase currents, and I_n is the neutral current. I_{sum} Indicates the sum of phase currents that is called “residual current”.

Figure 2(a) shows that the neutral and residual currents flow in the same direction (according to the assumed direction of the currents) during external fault. Thus, the magnitude of differential current vector can be calculated using Equation (2):

$$|I_d| = \big||I_{sum}| - |I_n|\big| \tag{2}$$

On the other hand, the neutral and residual currents flow in opposite direction during internal fault as can be seen in Figure 2(b). Thus, according to expression Equation (3), the magnitude of differential current vector is equal to the sum of magnitudes of the neutral and residual current vectors, in this case. It must be noted that if the circuit of faulty side of power transformer is opened and it is energized from other side, the magnitude of differential current will be equal to neutral current (see Figure 3(c)).

$$|\mathrm{I_d}| = |\mathrm{I_{sum}}| + |\mathrm{I_n}| \tag{3}$$

From the comparison of expressions Equations (2) and (3), it can be concluded that the following constrains are met only in internal fault condition. Thus, these constraints can be used to detect internal fault from external fault.

$$|\mathrm{I_d}| > |\mathrm{I_{sum}}| \text{ and } |\mathrm{I_d}| \geq |\mathrm{I_n}| \tag{4}$$

Therefore, to diagnose an abnormal condition that may origin from an internal ground fault, the differential and neutral currents can be compared to predetermined threshold values as follow expression. Then, the internal ground fault can be detected using Equation (4). Consequently, the new detection mechanism of REF relay is designed as shown in Figure 3.

$$|\mathrm{I_d}| \geq \mathrm{I_d^{TH}} \text{ and } |\mathrm{I_n}| \geq \mathrm{I_n^{TH}} \tag{5}$$

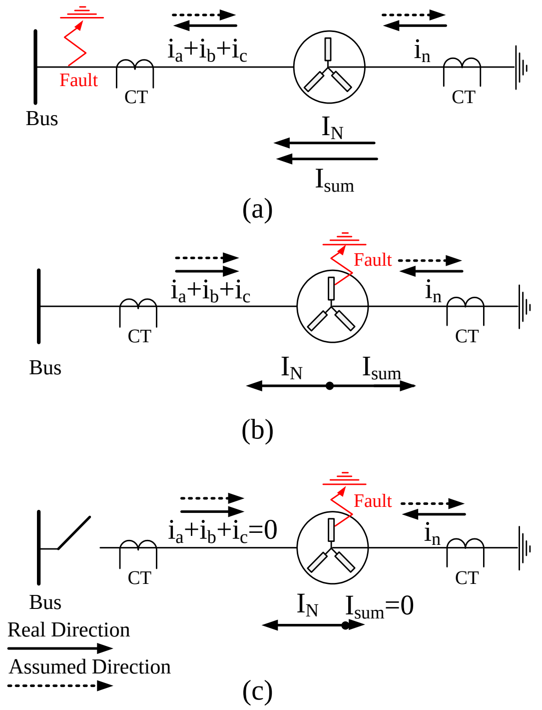

Figure 2. The Y side of power transformer during external fault (a), internal fault with non-zero phase currents (b) and internal fault with zero phase currents (c)

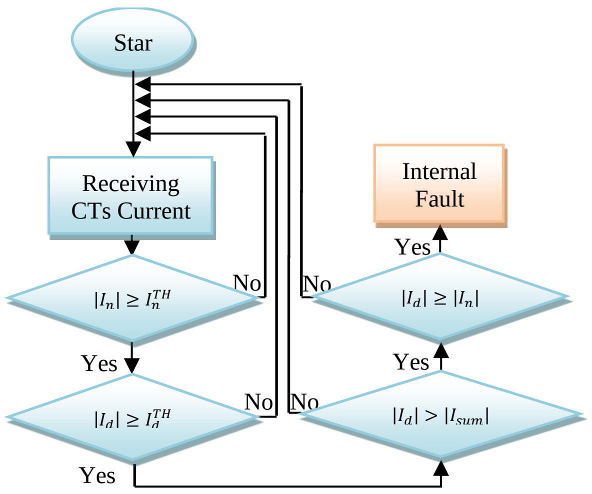

Figure 3. The proposed algorithm for detecting internal ground fault from external faults

4. SIMULATION RESULTS

In this section, initially, the performance of the proposed method is compared to a conventional method with recommended setting [20] for a number of fault events. It must be noted, I_d^{TH} is set to 10% which is the minimum value for differential current in REF relay setting [20]. Also, 1% as a very small value is chosen for I_n^{TH}. By applying these settings, a strict evaluation of the proposed method performance is achieved. Then, the detection accuracy of the proposed method is evaluated for a wide range of internal and external fault events in comparison with the conventional method and an intelligent method [17]. It must be noted that two methods are simulated using MATLAB program but there is no interface between this program and PSCAD. Furthermore, MATLAB processes only saved simulation data obtianed using PSCAD.

4. 1. Performance Evaluation during Some Sample Fault Events

In this subsection, three different fault scenarios are considered to study the performance of the proposed and conventional methods. The first scenario is a severe double line to ground external fault with zero fault resistance which occurs on the Δ side of the power transformer at time=100 ms, while it is connected to the voltage source from the Y side and supplies a full-load power. The second scenario is a severe single line to ground internal fault with zero fault resistance which occurs on the Y side terminal of the power transformer at time=100 ms. The third scenario is a light internal fault similar to second scenario with 3 kΩ of fault resistance. Also, the voltage source and load of two last scenarios are similar as the first scenario.

Figure 4 shows that despite that the differential current is zero during the external fault assuming use of unsaturable (ideal) CTs; however, a high magnitude spurious differential current appears using real CTs. Thus, according to Figure 5, the current trajectory calculated based on the conventional method inserts into operation region (see Figure 5) and it maloperates 47.8 ms after fault inception, but the new method remains stable (see Figure 6)

The differential current for the severe internal fault is depicted in Figure 7. It is seen that the differential current waveform obtained from real CTs is deeply distorted as compared to real CTs. According to Figure 8, the current trajectory of the conventional method inserts quickly into

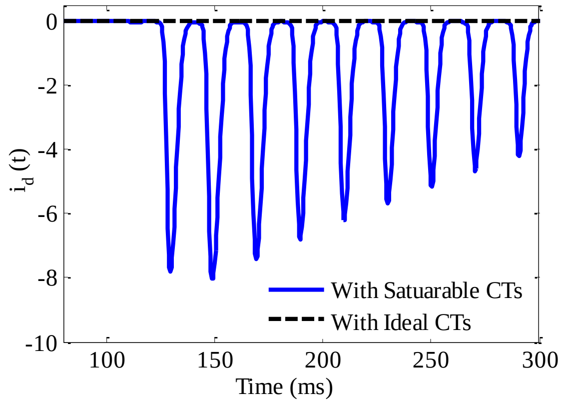

Figure 4. Differential current during the external fault

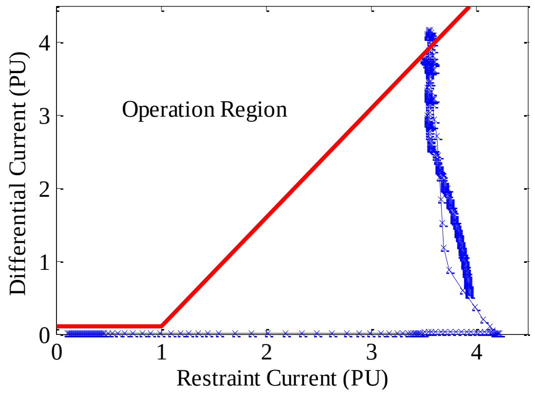

Figure 5. Caculated current trajectory for the external fault based on the conventional method

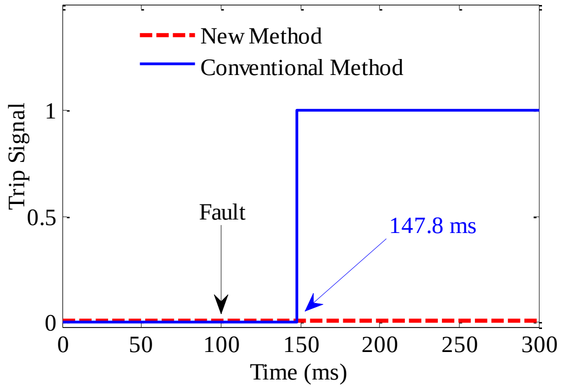

Figure 6. Trip signals of the proposed and conventional methods for the external fault

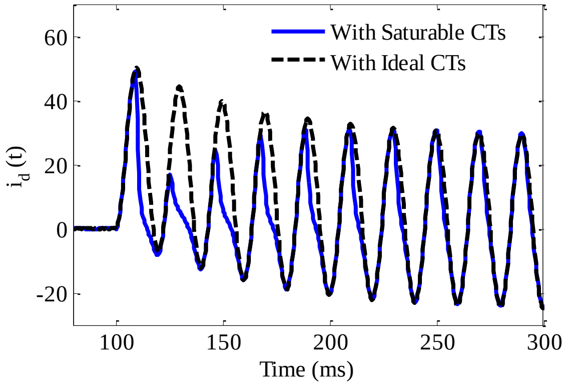

Figure 7. Differential current during the severe internal fault

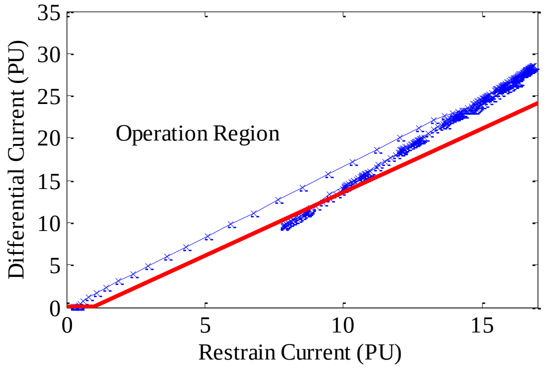

Figure 8. Calculated current trajectory for the severe internal fault based on the conventional method

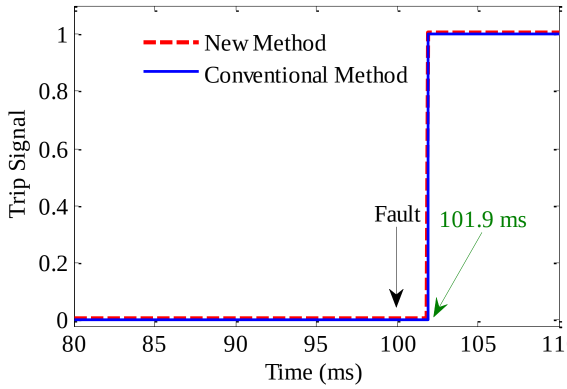

Figure 9. Trip signals of the proposed and conventional methods for the severe internal fault

the operation without any issue. The conventional method needs only 1.9 ms to detect the fault, exactly similar to new method (see Figure 9). It means that the fault detection time is less than one cycle, for this severe fault case.

Figure 10 indicates the differential current during the light internal fault. As can be seen in Figure 11, the current trajectory computed based on the modeled conventional method inserts into the operation region. The time taken by the conventional and the new method for detection of the fault is 17 ms (see Figure 12) that is still less than one cycle.

4. 2. A Comprehensive Comparative Accuracy Assessment

To obtain a comprehensive and comparative assessment of the proposed method

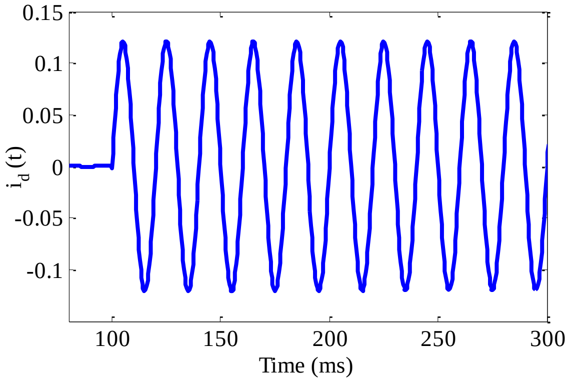

Figure 10. Differential current during the light internal fault

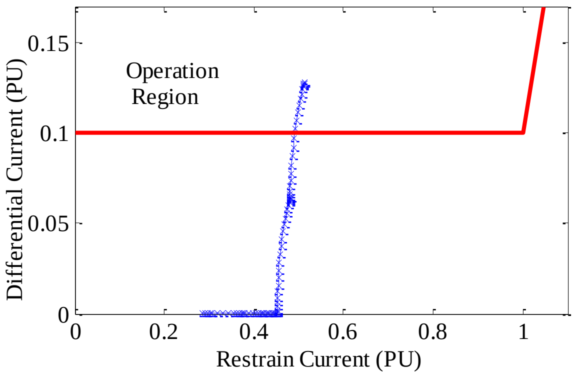

Figure 11. Calculated current trajectory for the light internal fault based on the conventional method

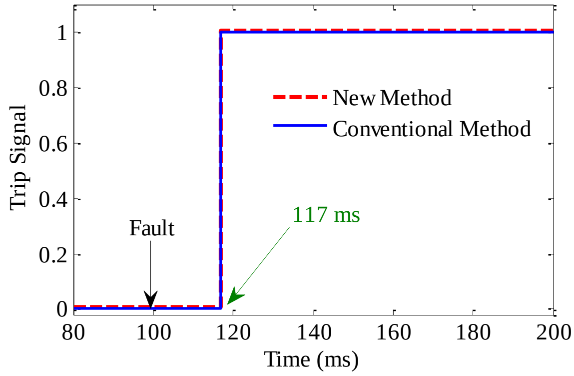

Figure 12. Trip signals of the proposed and conventional methods for the light internal fault

detection accuracy, its performance is evaluated for a wide range of internal and external faults in comparison with the conventional method [20] and the intelligent method [17].

To simulate internal fault events, voltage source is connected to the Y winding of power transformer under study and it supplies full-load power. For fault locations, 10 points on the one phase of Y winding and 11 points on the one phase of Δ winding are chosen. These 10 points is placed at distances equal to 0%, 10%, …, 90% of winding length from the terminal end. Also, the mentioned 11 points are distributed uniformly on the winding so that the first is at the middle of the winding and the last is at the end of winding connecting to the output terminal. Besides, three different values are considered for the fault resistance. The lowest value is 0 Ω, the highest is set so that to obtain the lightest fault which is detectable by the conventional method (I_d=10 %) and the third value is set to a value between them. Also, to take into account the fault inception angle effects, 11 points distributed uniformly over a cycle are chosen as fault occurrence time. On the other hand, the remnant flux of CTs are selected from -85%, 0% and +85% of rated flux. All in all, 1053 internal ground fault cases are simulated for this part of study.

Besides, 880 cases of external faults are simulated by considering a large number of single line-to-ground faults, line-to-line faults, double line-to-ground faults and three-phase faults. In order to precisely evaluate the proposed method performance, very severe faults are simulated by considering low values for fault resistances. On the other hand, external faults can be categorized into two scenarios. In the first scenario, the faults occur on the Y side (F3) while the voltage source is connected to the Δ winding of the power transformer at full load condition. In the next scenario, the faults occur on the Δ side (F4) while the power transformer is fully loaded and the Y winding is connected to the voltage supply. It is worth noting that various values for fault inception time and residual flux of CTs are considered in the simulations, like as internal fault cases.

Based on obtained results from simulated test case in the PSCAD/EMTDC software, three mentioned methods have been implemented and evaluated in the MATLAB environment. As given in Tabel 1, it can be seen that all internal faults have been detected by three methods without any issue. However, the conventional and intelligent methods could not remain stable during 203 and 13 external fault cases, respectively. Besides, the proposed method has maloperation for only 9 external faults. It means that the proposed method with total accuracy of 99.53% has the best performance compared to the conventional and intelligent methods with accuracy of 88.1% and 99.32%, respectively. It can be concluded that that the high accuracy of the proposed method as well as its simplicity make it possible for practical implementation.

TABLE 1. Comparison results of different methods

Method	# of misoperation for 1053 cases of internal fault	# of maloperation for 880 cases of external fault	Total Accuracy (%)
Conventional Method [20]	0	203	88.10
Intelligent Method [17]	0	13	99.32
Proposed Method	0	9	**99.53**

5. CONCLUSION

A restricted earth fault relay may maloperate during severe external fault events due to CT saturation. To tackle this issue, this paper presents a new simple algorithm which has high stability in such situation. To evaluate the proposed protection scheme performance, a real power system has been simulated using PSCAD/EMTDC program considering a huge number of internal and external faults conditions. In order to show the superiority of the proposed method, its performance has been compared with a conventional and an intelligent REF relay. This study proved that the proposed method, in spite of its simplicity, can accurately detect internal faults from external faults while it is as fast as the conventional method. Since the REF relay should be immune against maloperation during inrush current in addition to the external fault, a new method for this purpose can be developed as a future work.

6. AKNOWLEDGEMENT

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7. REFERENCES

1. Ganji, M., Bigdeli, M. and D. Azizian, D., “Mitigation Transformer Inrush Current using Modified Transient Current Limiter”, ***International Journal of Engineering, Transactions B: Applications***, Vol. 32, No. 5, (2019), 701-709. DOI: 10.5829/ije.2019.32.05b.12
2. Ebadi, A., Hosseini, S.M. and Abdoos, A.A., “Immunity Improvement of a Low-Impedance Restricted Earth Fault Relay by Making its Mechanism Intelligent Based on Support Vector Machine”, ***Computational Intelligence in Electrical Engineering***, Vol. 9, No. 2, (2018), 29-40. DOI: 10.22108/isee.2018.111464.1132
3. Ebadi, A., Hosseini, S.M. and Abdoos, A.A., “Designing of a New Transformer Ground Differential Relay Based on Probabilistic Neural Network”, ***Energy Engineering & Management***, Vol. 9, No. 4, (2020), 2-13. DOI: 10.22052/9.4.2
4. Krstivojevic, J.P. and Djurić, M.B., “New Algorithm for Transformer Ground Fault Protection”, in MedPower 2014 (IET), Athens, (2014), 1-6. DOI: 10.1049/cp.2014.1698
5. Dinesh Babu, K.N., Ramaprabha, V. Rajini, V. and Nagarajan, V., “A Case Study on REF Low Impedance IED Mal Operation”, in IEEE 6th International Conference on Power Systems, New Delhi, (2016), 1-5. DOI: 10.1109/ICPES.2016.7583997
6. Taghipour Gorji, R., Hosseini, S. M., Abdoos, A. A. and Ebadi, A., “A Hybrid Intelligent Method for Compensation of Current Transformers Saturation Based on PSO-SVR”, ***Periodica Polytechnica Electrical Engineering and Computer Science***, Vol. 65, No. 1, (2021), 53-61. DOI: 10.3311/PPee.16248
7. Apostolopoulos, C. And Tsakiris, D., “Design And Performance Evaluation of a High-Impedance REF Scheme for MV/LV Transformers”, ***IEEE Transactions on Industry Applications***, Vol. 51, No. 6, (2015), 5398-5409. DOI: 10.1109/TIA.2015.2435003
8. Subramanian, P.V. and Ajithal, L., “Practical Considerations for High Impedance Restricted Earth Fault Relay Settings”, ***Journal of the Institution of Engineers (India): Series B***, Vol. 96, No. 1, (2015), 107-110. DOI: 10.1007/s40031-014-0124-x
9. Ebadi, A., Hosseini, S.M. and Abdoos, A.A., “A New Artificial Intelligence based Supervision Method for Low-Impedance REF Relays”, ***Electric Power Systems Research***, Vol. 195, (2021), 107177. DOI: 10.1016/j.epsr.2021.107177
10. Nasution, M.F., Mustafa, F. and Shaulgara, S., “Case Studies of Magnetizing Inrush Current Effect on Differential & REF Transformer Protection”, in 2nd International Conference on High Voltage Engineering and Power Systems (ICHVEPS), Bali, (2019), 1-6. DOI: 10.1109/ICHVEPS47643.2019.9011114
11. Nimtaj, B., Mahmoudi, A., Palizban, O. and Kahourzade, S., “A Comparison of Two Numerical Relay Low Impedance Restricted Earth Fault Algorithms in Power Transformer”, in 8th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology, Khon Kaen, (2011), 7921-795. DOI: 10.1109/ECTICON.2011.5947959
12. Nim Taj, B., Mahmoudi, A. and Kahourzade, S., “Comparison of Low-Impedance Restricted Earth Fault Protection in Power Transformer Numerical Relays”, ***Australian Journal of Basic and Applied Sciences***, Vol. 5, No. 12, (2011), 2458-2474.
13. Aires, M.N.O., Medeiros, R.P., Costa, F.B., Silva, K.M., Chavez, J.J. and Popov, M., “A wavelet-based restricted earth-fault power transformer differential protection”, ***Electric Power Systems Research***, Vol. 196, (2021), 107246. DOI: 10.1016/j.epsr.2021.107246.
14. Davarpanah, M., M. Sanaye-Pasand, M. Iravani, R., “Performance Enhancement of the Transformer Restricted Earth Fault Relay”, ***IEEE Transactions on Power Delivery***, Vol. 18, No. 1, (2012), 467-474. DOI: 10.1109/TPWRD.2012.2208204
15. Krstivojevic, J.P. and Djurić, M.B., “A New Method of Improving Transformer Restricted Earth Fault Protection”, ***Advances in Electrical and Computer Engineering***, Vol. 14, No. 3, (2014), 41-48. DOI: 10.4316/AECE.2014.03005
16. Krstivojevic, J.P. and Djurić, M.B., “A New Algorithm for Avoiding Maloperation of Transformer Restricted Earth Fault Protection Caused by The Transformer Magnetizing Inrush Current And Current Transformer Saturation”, ***Turkish Journal of Electrical Engineering and Computer Sciences***, Vol. 24, No. 6, (2016), 5025-5042. DOI: 10.3906/elk-1409-92
17. Ebadi, A., Hosseini, S.M. and Abdoos, A.A., “A New Restricted Earth Fault Relay Based on Artificial Intelligence”, ***International Journal of Engineering, Transactions A: Basics***, Vol. 32, No. 1, (2019), 69-70. DOI: 10.5829/ije.2019.32.01a.08
18. Ebadi, A., Hosseini, S.M. and Abdoos, A.A., “A New Time-Frequency Analysis Based Supervision Method for the Transformer Restricted Ground Fault Relay”, ***International Journal of Electrical Power and Energy Systems***, Vol. 129, (2021), 106858. DOI: 10.1016/j.ijepes.2021.106858
19. Gil, M. and Abdoos, A.A., “Intelligent busbar protection scheme based on combination of support vector machine and S-transform”, ***IET Generation, Transmission & Distribution***, Vol. 11, No. 6, (2017), 2056-2064. DOI: 10.1049/iet-gtd.2016.1686
20. MiCOM P642, P643 & P645, “Transformer protection relays”, Technical Manual, (2011), 321-326.

Persian Abstract

چکیده

حفاظت خطای زمین محدود شده برای آشکارسازی خطاهای داخلی زمین ترانسفورماتور قدرت بکارگرفته می‌شود بطوریکه جهت این کار از حفاظت اصلی دیفرانسیل حساس‌تر می‌باشد. با این حال، رله خطای زمین محدود شده ممکن است بدلیل اشباع ترانسفورماتورهای جریان حین خطای خارجی عملکرد کاذب داشته باشد. در این مقاله، یک الگوریتم ساده برای این طرح حفاظتی پیشنهاد می‌گردد که بر پایه چهار شرط اساسی استوار می‌باشد. این شرایط بر مبنای جریان‌های دیفرانسیل، نول و مجموع جریان فازها تعریف می‌گردند. هنگامیکه این شرایط بطور همزمان برقرارند، بمعنای خطای داخلی زمین می‌باشد. این الگوریتم در محیط نرم‌افزار MATLAB پیاده‌سازی و ارزیابی شده و برای این کار از نتایج شبیه‌سازی یک سیستم قدرت واقعی در نرم‌افزار PSCAD/EMTDC استفاده گردیده است. مدل مشهور جیلز اثرتون برای شبیه‌سازی رفتار گذرای ترانسفوورماتورهای جریان استفاده می‌شود. نتایج حاصله امنیت بالای طرح پیشنهادی را تایید می‌نماید.