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A New Restricted Earth Fault Relay Based on Artificial Intelligence

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ABSTRACT

The restricted earth fault (REF) relay is a type of differential protection which is used for detection of internal ground faults of power transformers. But, during external faults and transformer energization conditions, the probability of current transformer (CT) saturation increases. Thus, the spurious differential current due to CT saturation, can lead to REF relay maloperation. In this paper, a new intelligent REF protection scheme is presented based on the pattern recognition method. In the proposed method, one-cycle data window of differential and neutral currents are used as exemplar patterns of the classifier. The performance of the proposed method is evaluated by obtained data from simulation of a real 230/63 kV power transformer in PSCAD/EMTDC environment. Moreover, in order to accurately simulate the CT behavior during saturation the well-known Jiles-Atherton (JA) model is utilized. The promising obtained results showed that the proposed intelligent method increases the security of the REF relay.

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NOMENCLATURE

I_a, I_b and I_c	The current vetors measured by CTs of Phase a, b and c, Respectively (PU)	$i_a(t)$, $i_b(t)$ and $i_c(t)$	The instantanous currents measured by CTs of Phase a, b and c, Respectively (A)
I_n	The current vetor of neutral conductor mesaured by neutral CT (PU)	$i_n(t)$	The instantanous current of neutral conductor measured by neutral CT (A)
I_{diff}	Differential current of the conventional REF relay (PU)	$i_d(t)$	The instantanous differential current (A)
I_{bias}	Bias current of the conventional REF relay (PU)	IV	Input vector for the classifiers
IV	Input vector for the classifiers	IM	Input matrix for the classifiers
i_d^s	One cycle sorted samples vector of differential current	OM	Output matrix for the classifiers
i_n^s	One cycle sorted samples vector of neutral current	M	the maximum absolute value of i_d^s and i_n^s
σ	The smoothing factor of PNN classifier	C	The penalty factor of SVM classifier

1. INTRODUCTION

Power transformers, one of the most vital and expensive equipment in power systems, are subject to faults, like as any other component of the power system. Therefore, a fast, reliable and secure protection scheme is an essential requirement for detection of internal faults in power transformers [1]. The differential protection is the main protective scheme of power transformers [2]. Although this protection scheme has accurate performance for both phase to phase faults and most of phase to ground faults, it has not enough sensitivity for detection of some single phase ground faults with limited current on the power transformer winding or its terminal [3, 4]. For such conditions, the restricted earth fault (REF) protection is utilized as a complementary scheme [5]. The logic behind REF relay operation is based on the resulted zero sequence current during ground faults [6].

The major concern in REF protection is to avoid mal-operation due to current transformer (CT) saturation during magnetic inrush current of power transformer and external faults [7, 8]. It should be mentioned that proper CT dimensioning can improve

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the REF relay operation but CT saturation cannot be entirely removed [9]. The use of high impedance REF relay is another option to provide a certain level of the security against CT saturation. But essential requirement should be provided for implementation of this scheme such as: identical turn ratio for neutral and phase CTs, similar magnetizing characteristics, matching and high knee point voltage [10]. Today, low impedance (biased) REF relay has been very popular due to technology improvement in microprocessor manufacturing. This type of REF relay need not meet above mentioned obligations for high impedance relays. Moreover, it is more sensitive to internal faults in comparison to high impedance relay but the CT saturation is adversely affected its detection accuracy [11] . In some conventional relays, the adaptive restraint current [12] and directional supervision [13, 14] have been used to improve the REF relay performance but the maloperation is still probable in many operating conditions [15-17].

Recently, a few academic research works have been done to improve conventional low impedance REF relay performance or propose new algorithm for it. For more details, Davarpanah et al. [15] proposed a combination of REF and earth fault relays to overcome maloperations but this method cannot be effective for inrush current and external fault cases with large neutral current. In the other hand, a new REF relay based on time domain digital phase comparator has been presented which has higher security against maloperation than conventional method [16, 17]. However, it has been evaluated for transformer energization and only single phase to ground type of external fault conditions.

In this paper, a novel REF protection scheme is presented based on artificial intelligence. To do this, at first, the performance of a biased REF relay is evaluated for different operating conditions of power transformer in section 2. Section 3 presents detailed descriptions about the proposed algorithm as well as analysis of simulation results. Finally, the paper is terminated with conclusion in section 4.

2. EVALUATION OF A CONVENTIONAL REF RELAY

In this section, before presentation of our proposed algorithm, the performance of a conventional biased REF relay [18] is evaluated in different operating conditions of the power transformer. In this relay, the differential and bias current are calculated using Equations (1) and (2), respectively.

$$I_{diff} = |I_a + I_b + I_c - I_n| \quad (1)$$

$$I_{bias} = 0.5(max\{|I_a|, |I_b|, |I_c|\} + |I_n|) \quad (2)$$

The biased characteristic of this relay as well as recommended setting can be seen in Figure 1. To evaluate the relay performance, a real power system [2] including a 160 MVA, 230/63 kV power transformer, a grounding transformer and related CTs are simulated in PSCAD/EMTDC environment as depicted in Figure 2. The parameters of power transformer and CTs can be found in Tables 1 and 2. For simulation of CTs, the accurate Jiles-Atherton (J-A) model is used. Note that, the J-A parameters of CTs used in this study are presented in literature [20]. By using the J-A model, the effects of saturation, hysteresis remenance and minor loop formation are taken into account based on the characteristic of the magnetic material [19]. Moreover, different amounts of residual flux are considered in the simulation studies in the range of -85 to +85% because installed CTs on both sides of power transformer and neutral paths have closed iron core [20].

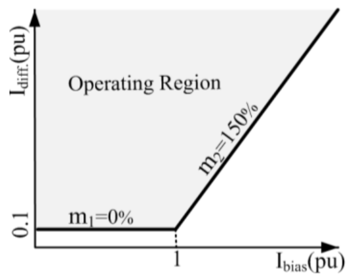

Figure 1. The REF relay characteristic with recommended setting [18]

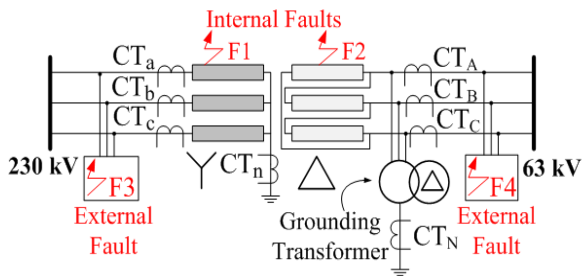

Figure 2. The power system under study

TABLE 1. Parameters of CTs

Technical Data	Y side CTs	Δ side CTs
Rated primary current	600 A	2000 A
Rated secondary current	1 A	1 A
Magnetic path length	84.8 cm	54.8 cm
Core cross section area	32.9 cm^2	10.36 cm^2
CT winding resistance	4.3 ohm	7.77 ohm
Total burden	30 VA	30 VA

TABLE 2. Power transformer specifications

Technical Data	Rated Value
Rated power	160 MVA
Connection	YNd11
HV rated voltage	230 kV
LV rated voltage	63 kV
Short-circuit impedance	14 %
No-load losses	0.06 %
Copper losses	0.2%

The performance of the relay is analyzed in MATLAB environment by using obtained data from simulation of different operating conditions of power transformer including internal faults, external faults and energization.

2. 1. Internal Fault The REF relays are intrinsically used for detection of ground faults which occur either on terminal or winding of power transformer. The magnitude of turn to core fault is minimum for faults near to the neutral point of winding with Y connection and for Δ connection the fault at the middle of winding has the lowest magnitude [21]. In this part of study, different internal faults on Y and Δ sides of power transformer are considered in order to evaluate the biased REF relay performance. To achieve this purpose, at the Y side, the faults with step size of 10% of winding length from the terminal phase is considered, similarly for Δ side, the fault location varies between 0 to 50% with the step of 5%. It must be that the power transformer in all cases fed from Y side. In order to comprehensively study the relay performance, the fault resistance is selected from three different values. The lowest possible fault resistance is set to 0 and the maximum value is selected in such a way that the relay would be excited with the minimum fault current (according to relay recommended setting). Also, the third fault resistance is considered between them.

Also, different residual flux is set for CT from -85, 0 and +85% of the rated value. In order to consider the impact of fault instant on results, 11 points which were uniformly selected from a cycle were used as fault occurrence time. Finally, 1053 simulation cases were selected for analyzing of the REF relay performance during internal fault conditions. For example, the current of single phase A to ground terminal fault with 0 fault resistance at Y side connection is shown in Figure 3. As it can be clearly seen in Figure 3, the CT is severely saturated in the first cycle after fault occurrence. The saturated current turn away from the original signal and consequent differential current appears as depicted in Figure 4. The differential current increases just after fault instance at t=0.1 sec and current trajectory enters the operational region of relay, although the CT saturation affects the differential waveform. Our investigation show that for all 1053 cases of internal faults, the biased REF relay has correct operation (see Figure 5).

2. 2. External Fault In order to study the performance of REF relay for external faults, different conditions are simulated. To achieve this purpose, in one setup, the load and voltage source are connected to Y and Δ side respectively and different faults are applied at F3.

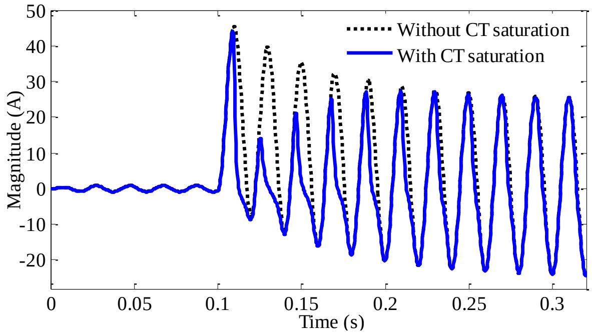

Figure 3. The Current of faulty phase with and without CT saturation

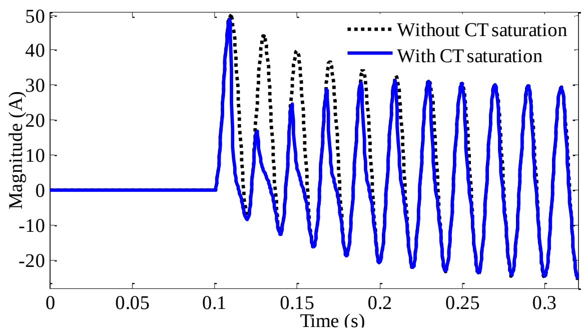

Figure 4. Differential current during internal fault with and without CT saturation

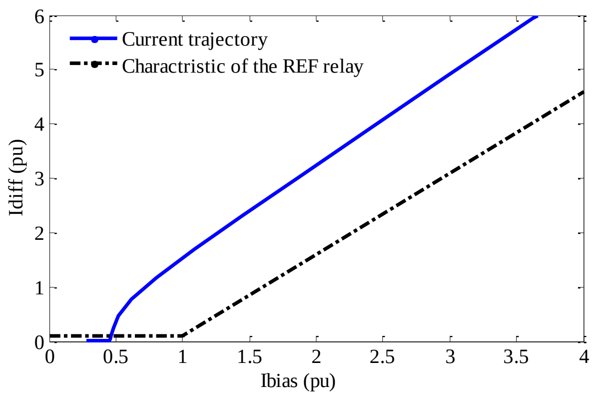

Figure 5. Current trajectory based on the modeled REF relay during internal fault

In another setup, the fault is applied at F4 while the source is connected to Y side and the transformer is loaded from Δ side. In both setup conditions, all types of faults including single-phase to ground, phase to phase, phase to phase to ground and three phase with different low resistances are considered in order to study the most severe conditions. Moreover, similar to studied internal faults, 11 uniformly selected points from a cycle are determined as fault instants.

Totally, taking into account different remnant flux of CTs, 440 cases of external faults are simulated. Since the external fault in one side impact on the REF relay operation of other side, the relay performance can be evaluated in 880 situations of external faults.

For example, in Figure 6, the phase A current of Y side is shown for a three phase fault at Δ side in which the fault occurs at=0.2 s and the CT is severely saturated at the beginning of the second cycle of fault current. As depicted in Figure 7, the differential current increases following the CT saturation. Indeed, the appearance of differential current is due to the CT saturation while without CT saturation, it remains zero. It can be seen in Figure 8, the current trajectory enters the relay operating region and lead to undesired trip issue. At last, the performance evaluation of the REF relay for external faults shows that there are 203 mal-operations from 880 simulated cases i.e. 23.06%. It should be noted that most of external faults have been simulated for the worst probable conditions. In real conditions, the above mentioned probability of maloperations may be lower.

2. 3. Transformer Energization

A large current usually appears during transformer energization due to increase of core flux. This current contains a slowly decaying DC component which can result in CT saturation so that the probability of REF relay maloperation increases. The magnitude and waveform of inrush current are random in nature and depend on voltage switching angle, remnant flux and core magnetizing curve. In order to study the REF relay maloperation under inrush current conditions, different situations of transformer energization are simulated. To do this, the unloaded transformer is energizied from both Y and Δ side while switching angle varies between 0 and 360 degree with step size of 7.2. The remnant flux is considered between -85 and +85% of nominal value for CTs and power transformer. As a result, 510 different cases of inrush current are simulated. As a sample of simulation results, Figure 9 shows the phase A current for the transformer when energized at t=0.1 s from Y winding. As can be seen in this figure, due to severe CT saturation, the secondary current is obviously different from unsaturated one. Thus, as depicted in Figure 10, the spurious large differential current appears. According to Figure 11, it leads to undesirable operation of the REF relay. The obtained results show that the REF relay has 74 maloperations from 510 simulated cases which leads to detection error of 9.2%.

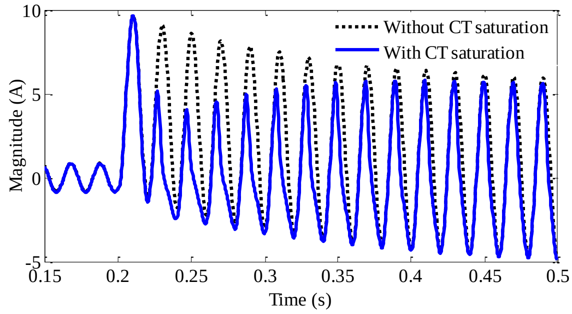

Figure 6. The current of phase A for three phase external fault

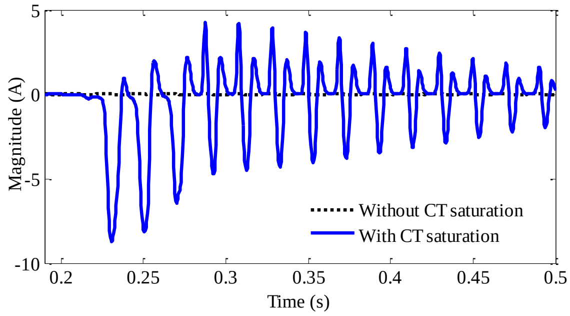

Figure 7. Differential current during external three-phase fault

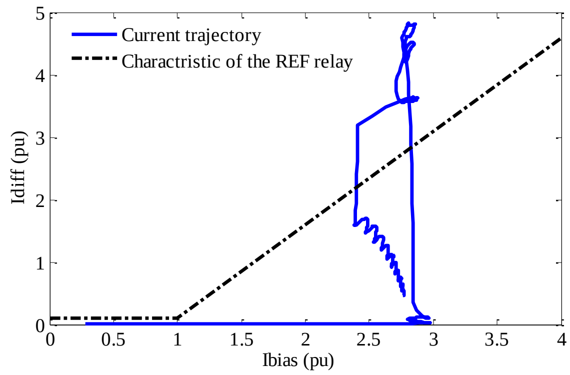

Figure 8. Current trajectory based on the modeled REF relay during external fault with CT saturation

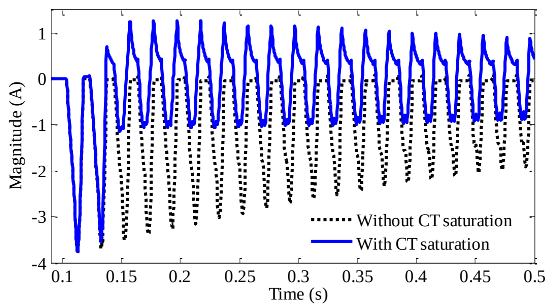

Figure 9. The current of phase A during transformer energization

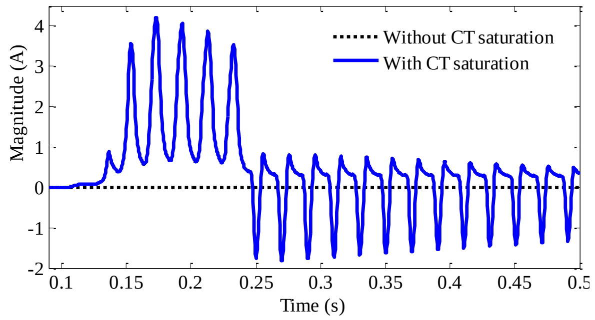

Figure 10. Differential current during transformer energization

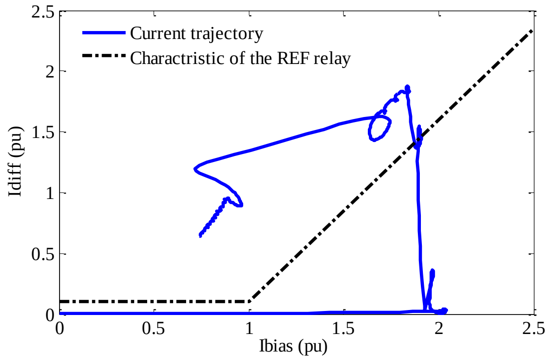

Figure 11. Current trajectory based on the modeled REF relay during transformer energization with CT saturation

3. PROPOSED METHOD

As demonstrated in section 2, in internal fault conditions, the differential current of the REF relay is due directly to fault current flowing while for external fault and inrush current conditions, only CT saturation can lead to appearance of differential current. Therefore, having different waveforms, the differential current can be used for discrimination of above mentioned conditions. Moreover, because of neutral current increment in earth faults, this current can be used as a complementary data to improve the discrimination ability. Thus, a new intelligent algorithm is presented based on waveform identification using a pattern recognition method. In the proposed algorithm, different operating conditions of power transformer are recognized using intelligent classifiers. Since many patterns are required for classifier training, different operating conditions of power transformer are simulated while effective parameters on results are considered. Then, appropriate data (differential and neutral currents) obtained from simulation results are used as input of the classifier in order to implement the training phase. In the next step, the trained classifier is evaluated using test data and after verification it can be used as an intelligent REF protection scheme. The implementation steps of the proposed method are shown in Figure 12.

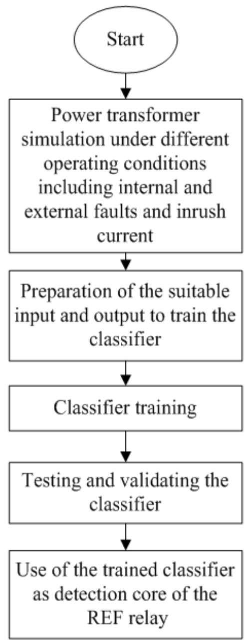

Figure 12. The flowchart of the proposed method

3. 1. Preparing exemplar patterns

The first step of the pattern recognition method is construction of input patterns and desired output. For REF relays, the most important operating quantity is instantaneous differential current which is given in Eq. (3). Therefore, it is used as the first feature for creating input vector of the classifier.

$$i_d(t) = i_a(t) + i_b(t) + i_c(t) - i_n(t) \quad (3)$$

On the other hand, since both turn to core fault and single phase to ground fault result in neutral current, this current (i_n) is considered as the second feature. According to above descriptions, in order to create the training patterns, one-cycle data window of $i_d(t)$ and $i_n(t)$ are randomly selected from each simulated case of different operating conditions. Similarly, this process is repeated for preparation of test patterns using unseen data window.

In this study, the sampling frequency is set to 2500 Hz in the simulations. Therefore, a cycle contains 50 samples for power systems with frequency of 50 Hz. In real power system, the sampling frequency can be increased up to 10 KHz. A large number of samples increases the signal resolution but it imposes a huge computational burden on classifier during training process and even can lead to divergence. On the other hand, a few samples give poor resolution of the signal which contains less detail about waveform. For practical applications in power systems, high-frequency components usually do not appear in signals. So, the considered sampling frequency (2500 Hz) can provide sufficient information about signals.

Besides, if raw data of the sampled window is used in training stage, a huge number of exemplar patterns should be involved to obtain a well-trained classifier. This is because the wave shape of sampled one-cycle data window of differential and neutral signals depends heavily on the starting point of sampling. The large amount of required data may have negative effect on training process. To overcome this problem, a simple solution is presented based on the sorting of raw data of the sampled currents i.e. $i_d(t)$ and $i_n(t)$. With that, for internal fault, relatively similar waveforms are obtained from data windows with different start points of sampling, because they are sine or semi-sine signals. For example, three possible cases of data window from a sine signal with magnitude of 1 A is depicted in Figure 13-A. According to Figure 13-B, after sorting these different current waveforms, the sorted samples of current waveforms are similar, irrespective of their sampling start points. In this way, the negative impact of sampling start point on classifier training is significantly reduced. Thus, the classifier ability increases in discrimination of internal fault patterns (with sine and semi-sine waveforms) from inrush current and external fault patterns with non-sinusoidal waveforms.

According to previous descriptions, if i_d^s and i_n^s denote the one-cycle sorted samples of differential and neutral currents, the input vector for training stage is defined as follow.

$$IV = \frac{1}{M}\begin{bmatrix} i^S_{d\ 50\times1} \\ \cdots \\ i^S_{n\ 50\times1} \end{bmatrix}_{100\times1} \quad (4)$$

In this relation, M is the maximum absolute value of i_d^s and i_n^s. The coefficient $\frac{1}{M}$ is used to limit the inputvector elements between -1 and +1.

As mentioned before, in order to construct the input matrices for classifier training and testing, input vectors extracted from a large number of internal and external faults and transformer energization conditions should be provided.

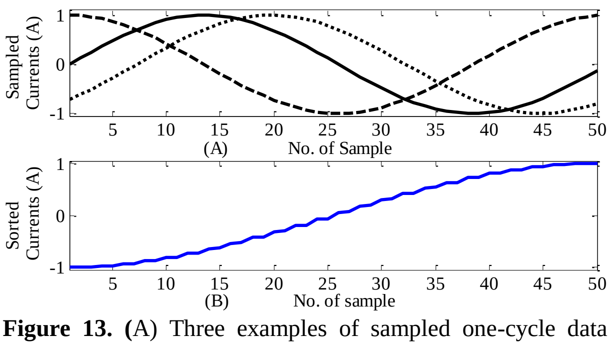

Figure 13. (A) Three examples of sampled one-cycle data windows, (B) Obtained waveform after sorting

To do this, the obtained results of simulation studies in section 2, including 1053 cases of internal fault and 1390 cases of external faults and transformer energization are employed. As can be seen in expression (5), in the input matrix, the columns of part T belongs to input vectors of internal faults and similarly part B includes input vectors related to external faults and transformer energization conditions. As given in Eq. (6), in the output matrix, the element '1' is used for internal faults and '0' indicates to other operating conditions in which trip signal is not required.

$$IM = [T_{100\times1053} \ \vdots \ B_{100\times1390}]_{100\times2443} \quad (5)$$

$$OM = [1_{1\times1053} \ \vdots \ 0_{1\times1390}]_{1\times2443} \quad (6)$$

3. 2. The Results of Training and Test To investigate the effect of classifier type on detection accuracy of the proposed algorithm, three well-known classifiers i.e. ANN [22, 23], PNN [24] and SVM [25] are considered as detector core of the proposed method. Table 3 provides a comparison of detection accuracy between above mentioned classifiers and conventional REF relay. This table gives complete information about adjustable parameters of each classifier, number of misclassified cases, training and execution time. All calculations have been performed under computer with dual core 2.5 GHz CPU, and 8 GB of RAM. All steps of the proposed detection method have been implemented in the MATLAB environment.

In this study, the adjustable parameters of classifiers are set through trial and error because some experience and knowledge about structure of a classifier is sufficient to obtain the optimum performance. The optimum structure of the ANN has three layers with 100, 50 and 1 hidden neurons, respectively. Moreover, log-sigmoid transfer function is used for all layers. The ANN can detect all 1053 cases of internal faults correctly but it has 7 and 16 maloperations for transformer energization and external faults, respectively; which can yield the overall accuracy of 99.05%. The PNN has only one adjustable parameter i.e. smoothing factor that is set to 0.1. The PNN classifier can detect all internal faults while there are 5 and 13 cases as malopeartions for transformer energization and external faults which lead to the best detection accuracy of 99.2% among all classifiers. The SVM classifier with radial basis kernel function and penalty factor of C=10000 results in detection accuracy of 98.89%; which is the lowest among utilized classifiers. For the SVM classifier, there are 1, 6 and 20 misclassified cases for internal fault, transformer energization and external faults, respectively.

Moreover, the execution time is calculated by measuring the interval time between presentation of data into a method and the time instant at which the decision is made. In this study, the average execution time for each classifier has been calculated and presented in Table 3. The ANN has the slowest performance with execution time of 8 ms. Also, the training time of ANN classifier is the longest i.e. 12 s, despite use of Levenberg-Marquardt method as a fast training algorithm. The PNN has the shortest training time i.e. 0.1 s and also it has the execution time of 5 ms which leads to low delay in sending the trip signal. Although the SVM classifier has the shortest execution time of 4 ms but it has the lowest detection accuracy among the utilized classifiers. The training time of the SVM classifier is 1.9 s which is shorter than ANN and longer than PNN. Besides, the obtained results for conventional biased REF relay show that it has very fast response with execution time of 0.1 ms but there are 47 and 203 misclassifications for transformer energization and external fault, respectively. So, the detection accuracy of the conventional REF relay is 89.76% which is the lower than implemented intelligent methods.

3. 3. Final Structure of the Proposed Relay In the previous section, the accuracy and efficiency of intelligent classifiers in the detection of internal faults from other conditions have been proved. However, the full-time activated classifier imposes unnecessary computational burden on the CPU. To overcome this issue, the classifier should be activated only when necessary.

To achieve this purpose, the differential current (according to Equation (1)) must be compared with a peak up value, similar to conventional relays. Figure 14 shows the implementation steps of final scheme of the proposed intelligent REF relay.

3. 4. Comparative Evaluation of the New REF Relay Speed The new proposed REF protection scheme has better detection accuracy in comparison to the conventional relay. But the precision is not the only criterion for evaluation of the proposed protection method and the fault clearing time is of a great importance. Since the PNN based relay has the best detection accuracy, its speed is also compared with conventional REF relay in two different scenarios i.e. severe and light faults.

Figure 15 shows the differential current as well as trip signals of these relays for a single-phase to ground fault with zero resistance. This fault occurs at t=100 ms at the terminal of Y side. Due to high magnitude of differential current, the current trajectory enters the operating region of conventional REF relay and the trip signal is issued in about 2 ms after the fault instant, while the intelligent relay (with pick up value of 10%) sends the trip command after 25 ms.

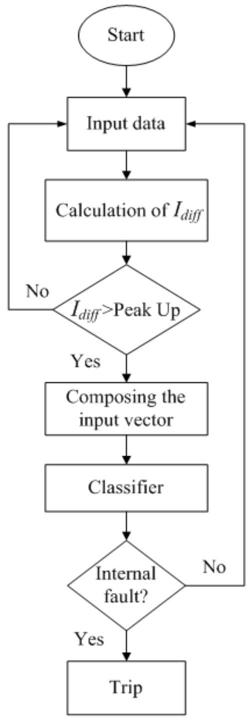

Figure 14. Implementation of the proposed REF relay

TABLE 3. Comparison results of the proposed intelligent method with conventional type

Method	Adjustable parameters	# of misoperation for 1053 cases of internal fault	# of maloperation for 510 cases of inrush current	# of maloperation for 880 cases of external fault	Training time (s)	Execution time (ms)	Total accuracy (%)
ANN based	# of layers: **3** # of neurons: **50;25;1** Activation functions: **All log-sigmoid**	0	7	16	12	8	99.05
PNN based	σ=**0.1**	0	5	13	0.1	5	**99.26**
SVM based	C=**10000** Kernel function: **Radial basis function**	1	6	20	1.9	4	98.89
Conventional	Recommended setting according to Figure 1	0	47	203	-	0.1	89.76

In the second scenario, the fault resistance is set to a high value (3 kΩ) in order to reduce the differential current to the lowest value which can be detected by the conventional REF relay. In this situation, the conventional REF relay can detect fault 17 ms after fault occurrence while the proposed intelligent method needs about 25 ms for detection and sending the trip signal (See Figure 16).
Indeed, because of use of one-cycle data window in training process, the proposed intelligent REF relay needs about one-cycle fault data. This time is about 20 ms for power systems with frequency of 50 Hz. Moreover, about 5 ms is required for detection process. So, the proposed intelligent protection scheme can remove the fault about 25 ms after fault instant. Although the proposed new scheme has lower performance speed but its detection accuracy is better than conventional type REF relay. Thus, the high precision as well as acceptable detection time (about 25 ms) of the proposed intelligent method, make it suitable for practical applications in power systems.

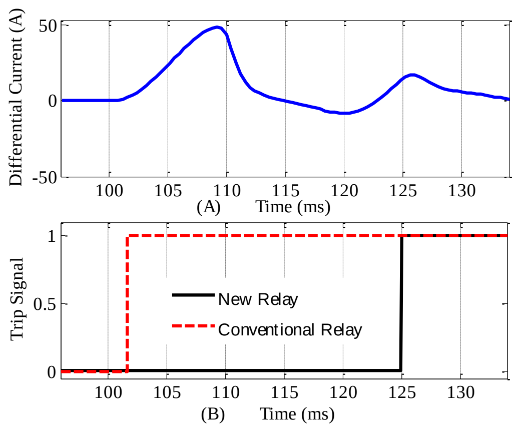

Figure 15. (A) Differential current during severe internal fault, (B) trip signals

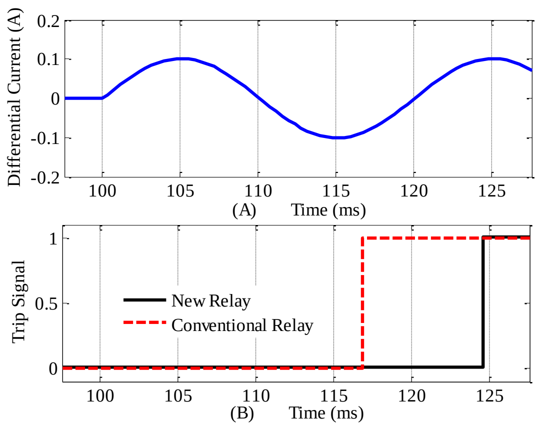

Figure 16. (A) Differential current during light internal fault, (B) trip signals

4. CONCLUSION

The CT saturation has bad effect on the REF relay performance. In the proposed method, a new intelligent REF protection scheme is presented based on the recognition of exemplar patterns in different conditions.

Internal faults, external faults and transformer energization conditions are simulated while effect of important parameters on results are considered. One cycle data window of differential and neutral currents of different operating conditions of power transformer is used as the input of classifier. In order to obtain the best performance, some well-known classifiers i.e. ANN, PNN and SVM are used as detection core of the proposed method. The obtained results justify that the proposed method has the following advantages:
1) The performance of the proposed method is not affected by CT saturation.
2) Since the proposed intelligent method is constructed based on recognition of exemplar patterns, it can be used for transformer with different voltage ratio and capacity.
3) The detection speed of the proposed method is less than 25 ms so that it is suitable for practical applications.

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A New Restricted Earth Fault Relay Based on Artificial Intelligence

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چکیده

رله خطای زمین محدود شده نوعی حفاظت دیفرانسیل است که برای آشکارسازی خطاهای داخلی زمین ترانسفورماتوور قدرت بکار می‌رود. اما طی شرایط خطای خارجی یا برقدار شدن ترانسفورماتور قدرت احتمال اشباع ترانسفورماتورهای جریان بالا می‌رود. بنابراین، جریان دیفرانسیلی ظاهر شده در چنین شرایطی ممکن است موجب عملکرد نابجای این طرح حفاظتی گردد. در مقاله حاضر، یک طرح حفاظت خطای زمین محدود شده جدید هوشمند بر پایه روش تشخیص الگو ارائه می‌گردد. در طرح پیشنهادی یک سیکل از مقادیر جریان‌های دیفرانسیلی و نول بعنوان الگوهای نمونه طبقه‌بندی کننده هوشمند بکار گرفته می‌شود. عملکرد روش ارائه‌شده با استفاده از اطلاعات بدست آمده از شبیه‌سازی یک ترانسفورماتور قدرت واقعی ۲۳۰/۶۳ kV در محیط نرم‌افزار PSCAD/EMTDC، ارزیابی گردیده‌است. بعلاوه، برای شبیه‌سازی دقیق رفتار ترانسفورماتورهای جریان حین اشباع مغناطیسی، مدل معتبر جیلز اثرتون بکار رفته است. نتایج پیاده سازی این طرح حفاظتی هوشمند، ایمنی بسیار مناسب آن در مقابل عملکرد کاذب را تایید نموده است.

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