A new algorithm for protection of three-phase power transformers using neural networks

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Abstract:
The paper reports a new approach for protection of the three-phase power transformers using the neural networks. There are phenomena such as inrush current, no load current, saturation of current transformers (CTs) and associated disagreement, under load tap changer, and etc., which cause to sensitivity reduction of the differential relay settings. So far, different approaches have been presented to increase this sensitivity, among them Artificial Neural Networks (ANNs). Such methods provide a reasonable performance to recognize the various fault types in the power transformers. These methods are stable against phenomenon as inrush current. Nevertheless, the proposed method has an outstanding preference over the previous schemes in term of elimination the under load tap changer error meanwhile operation of the differential relay. The test results provided here represent the sensitivity improvement by the proposed method over the previous schemes.
Key words: differential relay, protection of three-phase power transformer, neural network, pattern recognition

1.Introduction

The technologies involved with the power system's protection relays moreover the related algorithms, have been continually faced on numerous developments. The oldest types were electromechanical relays, which have been substituted by static relays along with the birth of transistors and other semiconductor devices. In consequence of microprocessor appearance and extension of their capabilities, the other type of relays as digital in conjunction with novel algorithms, have been introduced, which didn't set forth in primitive systems. However, the considerable speed moreover the advanced capabilities of modern microprocessors, give an opportunity to researchers for development and implement of newer and better techniques. Utilization of the adaptive algorithms and the ANNs in the power system's protection area, are well-known templates.

The ANNs are counted as systems that by means of processing a set of empirical data try to exploit the concealed knowledge and rules behind them and then transform the consequence to the ANN's structure. Such systems are called *intelligence* because they learn the general rules through numerical calculations on a set of numerical data or examples. They try to model the Neuro-Synaptic structure of the human brain, based on the computational intelligence. Although the specific abilities of the ANNs aren't comparable with the natural neural systems, but they have characteristics, which distinct them in applications such as pattern recognition, robot control, and generally elsewhere learning a linear/non-linear mapping, is required. The capabilities such as learning and development moreover the parallel processing and robustness, are some of the mentioned outstanding features of the ANNs. Such capabilities encourage power system's researchers to employ the ANNs in the solution procedure of existing problems such as Economic Dispatch, Protection considerations, Control and Monitoring, and etc [1]. From the motivations set for the ANNs application in power systems, can be pointed to their abilities in noise detection, robustness, error tolerance, generalization, and etc. In fact, robustness of the ANNs against variations of the system parameters, is an important factor, which makes the ANN as a suitable option for power system protection. Specially, pattern recognition feature of the ANN has been noticed for protection problems.

At most protection algorithms the measured voltage and current at the relay's location, are used to estimate the system's state. Consequently, they represent the appropriate action through classification of the system states into normal, fault, and etc. It can be said that one of the basic goals at most of the protection algorithms, is to categorize the system states from the input patterns. Regard to the considerable abilities of the ANNs in pattern recognition and classification, their applications in the power systems is acceptable. Fault detection, determination the type and direction of faults, and etc., are some of the well-established ANN's applications for the power system protection [2-6].

This paper focuses on the ANN's application for differential protection of the three-phase power transformers. The inside and outside faults respect to the protection zone, are considered as different patterns and the ANN's algorithms will be used to recognize these patterns. Utilization of the ANN to pattern recognition of such transformers makes it enable to be robust against specific phenomena related to the three-phase power transformers and provides a better response and consequently increases the relay's performance in comparison with the traditional approaches. In this paper the ability of the ANNs to operate in a high sensitivity manner against both inside and outside faults, inrush currents and especially under load tap changers will be shown.

2.Differential Relays

Differential relays transfer the primary and secondary side currents of the three-phase power transformer to a common base and consequently compare them. If there is no fault inside the protection zone then there is no equilibrium between the two currents. But, if there is a fault then non-equilibrium will be occurred between the currents. Therefore a differential current becomes appeared and consequently the protection system will be tripped at both primary and secondary sides. Such protection scheme has some restrictions in terms of the no load current, the saturation and disagreement of the CTs, existence of the under load tap changers, and etc., which decrease the relay's sensitivity. In order to increase this parameter respect to the mentioned factors, a series of different approaches as the ANN will be proposed.
The structure of the proposed differential relay is shown in Fig. 1. As can be seen, it consists of three ANN units, which each of them is specified to one phase. Also a logical unit is embedded into this structure to provide the appropriate tripping commands based on the output of the previous three units. The entries of these units consist of 1st, 2nd, and 4th harmonic components of the differential current moreover the primary to secondary voltage ratio of each phase. The salient feature of the proposed method respect to the previous approaches, is elimination the under load tap changer error of the three-phase power transformer and thereby increment of the relay's sensitivity.

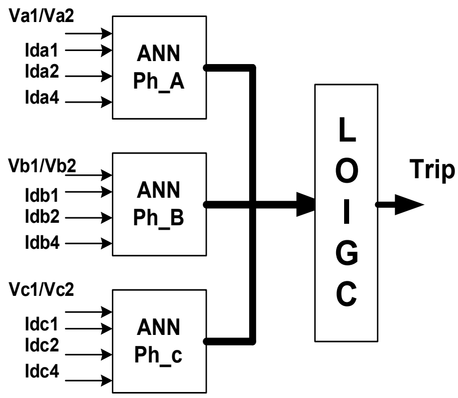

Fig. 1. Structure of the proposed differential relay

3.Feedforward Multi -layer ANNs as Pattern Identifiers

In the Feedforward multi-layer ANN, the neurons link to each other at a multi-layer structure. The neurons located in one layer receive the outputs of the previous neurons as input. In the other hand, they send their output to the neurons located at the next layer. The output of this collection is only depends on the previous inputs and no on the previous outputs. Such networks have a high capability to pattern classification. A Feedforward three-layer network is able to do the most complicate meshing schemes and approximately is able to estimate every type of function [7]. Thereby, such networks have been widely used in power system protection area.
The structure of a Feedforward three-layer network, which its internal connections have been completely made, is shown in Fig. 2. Suppose this network has N inputs. The input layer's nodes are similar to a mapping, which converts the N-dimension space into the required meshes. Every neuron located at the mid-layer represents a set of related points to that group, too. The output layer neurons determine the number of stages. The network's weights and biases are also determined meanwhile the training phase. The trained network should response to different inputs based on a specific rule.

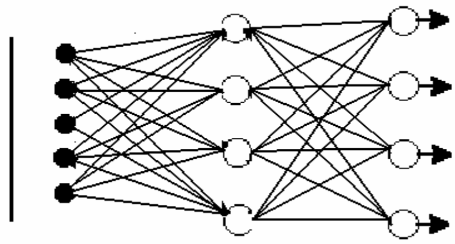

Fig. 2. A three-layer Feedforward neural network

4.Design of an ANN for Differential Protection

This section describes the procedure of design an algorithm for differential relays based on the ANNs. This process consists of the following steps:

1. Preparation the appropriate training data
2. Selection the appropriate ANN structure
3. Training the ANN
4. Evaluation the ANN using the test data

The design process is iterative. The network will be trained in the step 2, corresponding to a set of desired features. Meanwhile this process, the network structure and parameters must be changed and the network must be retrained. Nevertheless, the trained network may doesn't reflect the proper action against the test patterns. If after repetition the above procedure, over and over, the trained network doesn't provide an acceptable performance, then possibly, the training data are unsuitable. So, it is essential to modify these data and repeat again the steps 2 to 4 [9]. The important design notes and different training considerations for a differential relay will be discussed at the next section.

4.1.Preparation of the Training Patterns

The training patterns must be contained the required information for problem extension. This helps to the ANN to cover different aspects of the problem, in depth.

4. 1. 1. Simulation of the Power System to Prepare the Patterns

A three-phase 230/63 kV power system comprised a 60 km transmission line, as shown in Fig. 3. has been used to produce the required test and training patterns. The simulation was done by means of EMTDC software. The transformer connection is considered as star-star, here. Table. 1. represents the associated data with this power system. The combination of faults shown in Table. 2. have been produced using this system to train the ANN. As can be seen, all types of the faults as LG, LLG, and etc., have been considered. These faults are located at different points F1, F2, and F3. Also, they don't involved with inrush current but involve different tap settings between –9 to 9 with tap step of 1.5 percent and also comprise load changing .

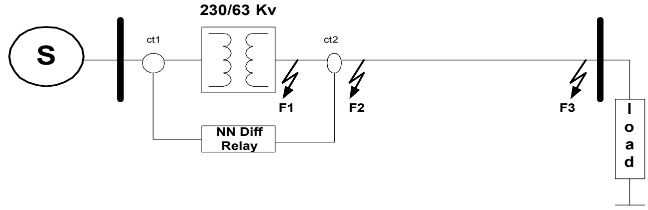

Fig. 3. The utilized network for pattern generation

Transformer Reactance	j 0.13
Line Impedance (+ and – sequences) Ω/km	0.072 + j 0.416
Line Impedance (zero sequence) Ω/km	0.346 + j 1.066
Generator Impedance Ω	41.7
Load MW	100

Table. 1. Power system data

Fault Types	AG, BG, ABC, … at points F1, F2, and F3
Tap Changer	Different values between –9 to +9 with step of 1.5
Voltage Angle	0,30,60 and 90
Load	20,40 and 100

Table. 2. Conditions associated with test pattern generation

Some of results of this simulation are shown in figure 4-11:

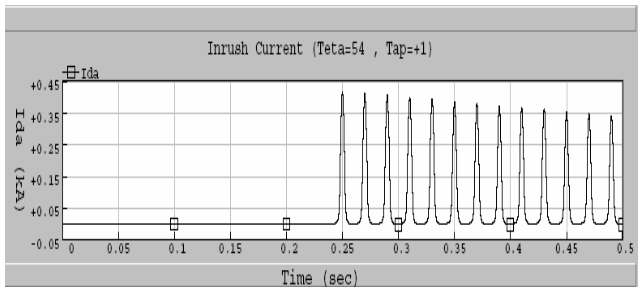

Fig. 4. Inrush Current (Teta=54, Tap =+1)

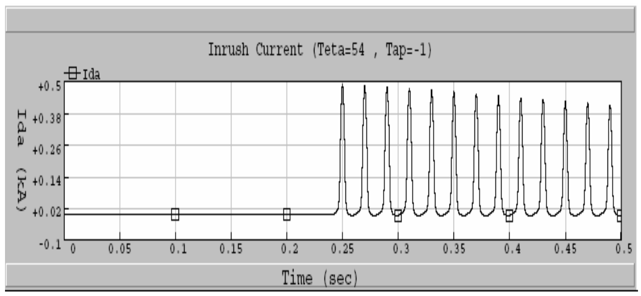

Fig. 5. Inrush Current (Teta=54, Tap =-1)

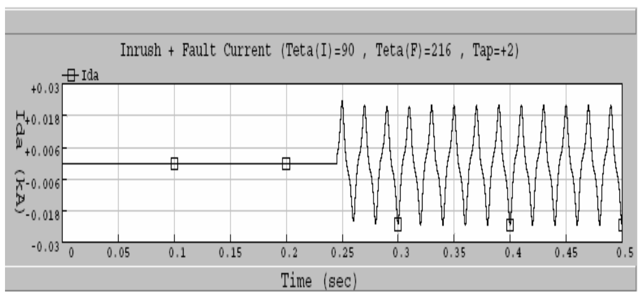

Fig. 6. Inrush Current + Fault Current (Teta(I)=90 , Teta(F)=216 , Tap=+2)

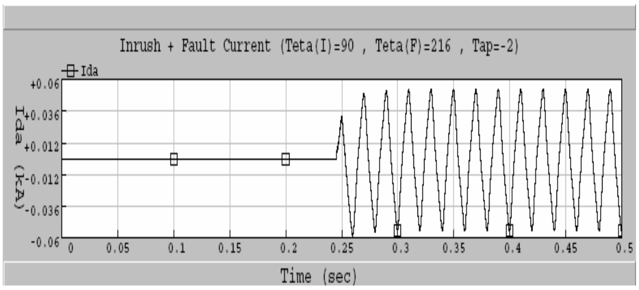

Fig. 7. Inrush Current + Fault Current (Teta(I)=90 , Teta(F)=216 , Tap=-2)

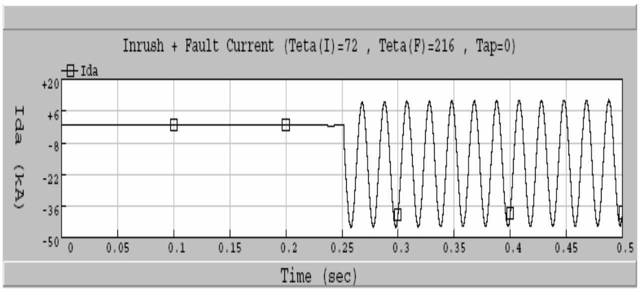

Fig. 8. Inrush Current + Fault Current (Teta(I)=72 , Teta(F)=216 , Tap=0)

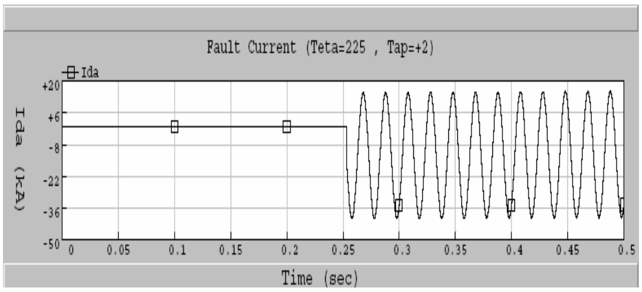

Fig. 9. Fault Current (Teta=225 , Tap=+2)

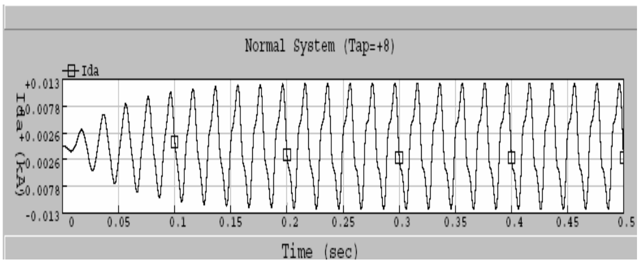

Fig. 10. Normal Current (Tap=+8)

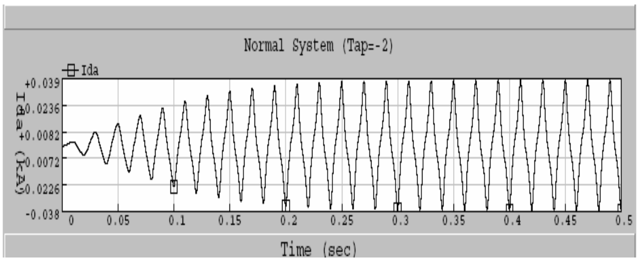

Fig. 11. Normal Current (Tap=-2)

4.1.2.Patterns Creation and Front -End Processing

The generation process of the input patterns, which are obtained from the voltage and current templates, is shown in Fig. 12The three -phase voltage and current templates are obtained at the relay's location by means of EMTDC. These templates were filtered through a second order low-pass filter from the type of Butterworth, with cutting frequency of 450Hz . Then, information is passed to a DFT filter and thereby the magnitudes of voltages and currents will be obtained for different phases. The number of templates for each cycle was 16while the voltages and currents will become normalized at the range of –1 to +1.

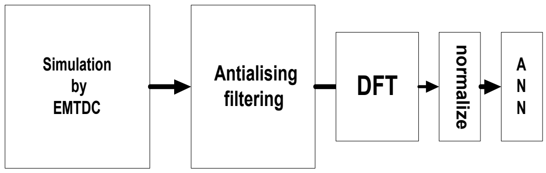

Fig. 12. The generation process of the training patterns

4.2.Structure of the Proposed ANN

In the utilized ANN, the parameters such as the number of inputs and mid-layer neurons have been determined as try and error. Meanwhile this process, it experienced that a four-layer ANN based on Marquadt-Levenberg algorithm is completely suitable for our training purposes. Also, the tangent hyperbolic and linear functions were respectively used at mid and final layers as transfer function. This network has four input comprised 1st, 2nd, and 4th harmonic components of the differential current, which are obtained and normalized through a DFT filter. The last input is the primary to secondary voltage ratio of each phase. The number of neurons at the first mid-layer was 8 and at the second mid-layer was 6. Finally, one neuron has been considered for the output layer. The ANN's output for the faults inside the protection zone is one while for the faults outside the protection zone is zero.

4.3.Training the ANN

In order to train the proposed ANN, the neural network toolbox of MATLAB software, was used. The training phase performed using the existence patterns in Table. 2. that consist of diverse fault types at different locations. The inrush current and tap changing effect have been considered in this collection, too. As pointed previously, the Marquadt-Levenberg was used to train the ANN. The learning process takes about 1000iterations as long as the overall squares of error reached to the desired level.

4.4.Network Evaluation

For the sake of test the relay operation, a series of test patterns, which haven't been used in the training phase, was employed. These patterns have been generated through simulation of the test power system using EMTDC. They were a diverse band of patterns comprised faults at different locations with or without inrush current and also at different tap settings. In consequence of evaluation phase, it observed that the ANN is able to recognize the different conditions of the inside faults along with a reasonable accuracy. Table. 3. shows the relay's output for these patterns. As can be seen, the network is able to classify both inside and outside fault types, properly. Also, it is able to discriminate them from the inrush current phenomenon.

TAP	INRUSH WHITOUT FAULT		FAULT IN F1		FAULT IN F2		FAULT IN F3	
	Φ		WHIT INRUSH	WHITOUT INRUSH	WHIT INRUSH	WHITOUT INRUSH	WHIT INRUSH	WHITOUT INRUSH
0	30	NO-Trip	Trip	Trip	NO-Trip	NO-Trip	NO-Trip	NO-Trip
1.5	20	NO-Trip	Trip	Trip	NO-Trip	NO-Trip	NO-Trip	NO-Trip
0	15	NO-Trip	Trip	Trip	NO-Trip	NO-Trip	NO-Trip	NO-Trip
-4.5	45	NO-Trip	Trip	Trip	NO-Trip	NO-Trip	NO-Trip	NO-Trip
9	15	NO-Trip	Trip	Trip	NO-Trip	NO-Trip	NO-Trip	NO-Trip
-3	90	NO-Trip	Trip	Trip	NO-Trip	NO-Trip	NO-Trip	NO-Trip
-9	10	NO-Trip	Trip	Trip	NO-Trip	NO-Trip	NO-Trip	NO-Trip
-6	25	NO-Trip	Trip	Trip	NO-Trip	NO-Trip	NO-Trip	NO-Trip

Table. 3. Algorithm test results

5.Conclusion

This paper focused on the ANN's application, as pattern identifier, to simulation the differential relays and to improve their sensitivity against phenomena specific to the three-phase power transformers. The obtained results show that the proposed ANN-based differential relay represents a proper action. It can operate with proper sensitivity and even without tap changing effect. By the way, it has been shown that the proposed algorithm is able to discriminate different fault types, whether inside or outside of the protection zone from the inrush current, very well. Therefore more reliable and sensitive operation is expectable for the differential relay, using the ANNs.

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