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Providing the Differential Protection Algorithm of Three-phase Power Transformer Based on Components of the Park's Instantaneous Power

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ABSTRACT

In this paper, a new algorithm is used for differential protection of three-phase power transformer. In this method, by using the concepts of Park's instantaneous power and without using a long and extensive calculation, we can detect the internal winding faults, magnetizing inrush current and also the external faults. The suggested method has been simulated in the application environment of MATLAB software on the various models of fault in a three-phase power transformer as a sample. And also the instantaneous active and reactive powers are compared with each other on various modes of fault. At the end, a method has been provided for detecting fault accurately and sending disconnect commands to the transformer, with a lower fault percentage than the previous protection methods and in a short time.

Keywords: Inrush Current, Differential Protection, Three-phase Power Transformer, Instantaneous Active Power, Instantaneous Reactive Power

INTRODUCTION

Three-phase power transformers are one of the important and vital components in the electrical network. Transformer is one of the main components of the production and transmission system and its absence in the network causes the disruption of the transfer cycle and the decrease of the reliability of the system. Therefore, disconnection of the transformers and the circuit cause irreparable harms for the network and it will cause a lot of damages. And also it is worth noting that the disruption, repair and replacement of the transformers are very expensive. Thus, protecting the transformers is always in the agenda of power networks' beneficiaries and agents. Given its importance and necessity, various protections are considered for the transformer, for which the highest cost is accounted for. One of the main transformer protections is differential protection. This kind of protection is extensively used for transformers with powers that are more than 10 MVA [1]. In the method of differential protection, the currents of the primary and secondary sides of the transformer are compared with each other and in the case of detecting a fault; the disconnection command will be send to the transformer. The first problem that causes lack of an accurate detection of fault in the differential relay is the transient inrush current in the one or two of the first cycles after connecting the transformer to the network. The inrush current depends on the type of core, the instance of switching and the power of the transformer, and its scope is between 8 to 10 times of the nominal current of the winding and it will also cause the incorrect operation of the differential protection [2]. Therefore, the necessity of the on time detection and operation of the differential relay while facing these kinds of faults is crucially important.

We face three general methods while studying and surveying the differential protection; second harmonic, artificial intelligence and also the study of the instantaneous power of differential which are discussed with respect to the historical trend as the article goes on.

In 2007, "Girgis" has studied the second harmonic in the transformers of the new generation with special steel core and he specifies that in the modern power transformers, the second harmonic might be very low during a transient inrush and this would jeopardize the security of the relay and also this would cause its inaccurate operation [3]. And also in 2009, "Wiszniewski" and et al studied the

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traditional differential protection by measuring the second harmonic. They stated that since this kind of protection is not sensitive enough for detecting the defects of the winding, the faults of the earth before it has had its influences and it would cost a lot [4]. In addition to studying the second harmonic, "Madzikanda" also studied the fifth harmonic and expressed that the second harmonic is a factor that limits the signal and also the fifth harmonic can be applied as a signal-blocking factor [5].

In 2013, "Rasoulpoor" and "BaNejad" studied the distinction between the transient inrush current and the mode of internal fault by using the discrete wavelet transform (DWT). And by using the correlation coefficient (CC) calculation between the vectors of the percentage of energy of the small shock waves' transfer per unit, they state this result that the correlation coefficient numbers for the transient inrush current have a oscillatory nature, but for the current of the mode of internal fault they are similar or close to one another [6]. And also in 2014, "Oliveira" and et al detected the mode of internal fault in the transformer by using the DWT and signal transmission method. This has results including using the DWT for surveying the differential signals generated by the transport phenomena which has been proven to be effective and efficient for and he expressed the spectral change of the waveform's energy and the effective coefficients in order to differentiate the parasites [7]. In 2014, "Noshad" and et al studied the differential protection of the three-phase transformer based on the DWT and Clarke transformation, considering the phenomenon of magnetic super saturation. And they also showed that using the coefficients of energy and standard deviation for differentiating the various modes of fault is a proper standard [8].

There have been so many studies in the field of artificial intelligence in the recent years. Including the study in 2012 in which "Att Hapoul" and et al surveyed the use of neural network in the differential protection of transformer and its results is in a way that the DWT and back-propagation neural network (BPNN) are used for detection the mode of fault [9]. Also in the same year, "Dey" and et al used the phase logic and the application of Clarke transformation for differential protection of transformer and the obtained result of this makes the increase of stability and sensitivity of the differential relay in power transformer possible [10].

In the study of differential powers also in 2010, "Hooshyar" and et al surveyed the difference between the internal faults and the transient inrush current by taking the differential active power into consideration and they obtained this result that the best and most reliable component in the discussion of distinction between the internal faults and the transient inrush current in the calculation of instantaneous active and reactive power [11]. And also in 2012, "Oliveira" and "Cardoso" studied and analyzed the various modes of fault in the differential protection of three-phase power transformer by using the components of Park's instantaneous active and reactive power and they state that this method is more reliable and practical [1 and 2].

In spite of various works that have been done in the field of differential protection in the recent years, it seems that by using the study of the components of instantaneous active and reactive power in different modes of fault, we can differentiate the mode of creation of the fault from the transient modes of system sooner and with a lower cost. In this article, we take this point into consideration that the instantaneous active power is associated with the internal fault of the winding of transformer with a transient inrush current and by comparing these two factors with each other on all of the fault modes of a disconnection signal that has been sent and has cause the disconnection between the transformer and the network. Some of the advantages of this method are less and simpler calculations, more speed of fault detection and also reduce of the costs.

In the second section we study and calculate the differential instantaneous power, as the article goes on the simulation principles and the kind of the sample transformer that is going to be experimented on are expressed. In the fourth section we complete analyze various faults in different situations on the sample transformer and at the end, we study the results of the experiments that have been done and we provide some suggestions for continuing this work by using this algorithm.

Calculating the Components of the Differential Instantaneous Power:

The phase numbers of windings have been used in order to simplify the calculation of the components of the instantaneous power. The current of the winding's phase with connecting the triangle can be obtained from the calculation of the currents that are being measured.

$$\begin{bmatrix} i_R \\ i_S \\ i_T \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} . \begin{bmatrix} i_{L1} \\ i_{L2} \\ i_{L3} \end{bmatrix} \quad (1)$$

In the formula 1, i_R, i_S and i_T are the currents of the windings' phase of the primary side by connecting the triangle and i_{L1},i_{L2} and i_{L3} are the linear currents of the windings of the sample transformer (according to figure no. 1) and the component of the zero sequence of the currents has been ignored. In order to avoid the performance of relay about the external faults, the zero sequence of the current must be eliminated from the differential design, in addition, when the components of the active and reactive power are calculated, the components of the zero sequence are eliminated.

The components of the Park's vector are:

$$[v_{D1} \quad v_{Q1}]^T = T.[v_{RS} \quad v_{ST} \quad v_{TR}]^T \quad (2)$$

$$[v_{D2} \quad v_{Q2}]^T = T.[v_{rn} \quad v_{sn} \quad v_{tn}]^T \quad (3)$$

$$[i_{D1} \quad i_{Q1}]^T = T.[i_R \quad i_S \quad i_T]^T \tag{4}$$
$$[i_{D2} \quad i_{Q2}]^T = T.[i_r \quad i_s \quad i_t]^T \tag{5}$$

In which the T matrix of the changes of Park is as follows:

$$T = \begin{bmatrix} \frac{\sqrt{2}}{\sqrt{3}} & \frac{-1}{\sqrt{6}} & \frac{-1}{\sqrt{6}} \\ 0 & \frac{1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} \end{bmatrix} \tag{6}$$

Then, the components of power of the primary and secondary side of Park are calculated:

$$p_k = v_{Dk}.i_{Dk} + v_{Qk}.i_{Qk}, \quad k = 1,2 \tag{7}$$
$$q_k = v_{Qk}.i_{Dk} - v_{Dk}.i_{Qk}, \quad k = 1,2 \tag{8}$$

In these equations v_D, v_Q, i_D and i_Q are the components of the current of primary and secondary and voltage vectors. Finally, the components of differential active and reactive power are:

$$p_{d(with\ copper\ losses)} = p_1 - p_2 \tag{9}$$
$$q_{d(load\ dependent)} = q_1 - q_2 \tag{10}$$

As it was said before, the occurrence of an internal fault causes an increase in the instantaneous active power. Reducing the winding losses causes an increase of the sensitivity of the differential active power for detection of the internal faults of the winding. The reformed differential active power is obtained from the formula below:

$$p_d = p_1 - p_2 - [R_1.(i_{D1}^2 + i_{Q1}^2) + R_2.(i_{D2}^2 + i_{Q2}^2)] \tag{11}$$

That in this formula R_1 and R_2 are the resistances of the primary and secondary winding. By reducing the losses of the lack of load or even by taking the changes of the resistance of the winding with the degree of temperature into consideration, we can increase the sensitivity. These are the factors that have not been considered here. The differential instantaneous reactive power depends on the load of the transformer, and it includes the given reactive power to the reactance of a short-circuit current. This dependency can be minimized by subtracting the contribution of the leakage inductance:

$$q_d = q_1 - q_2 - \left[L_1.\left(\frac{di_{Q1}}{dt} i_{D1} - \frac{di_{D1}}{dt} i_{Q1}\right) + L_2.\left(\frac{di_{Q2}}{dt} i_{D2} - \frac{di_{D2}}{dt} i_{Q2}\right)\right] \tag{12}$$

In which L_1 and L_2 are the leakage inductances of the primary and secondary side.

Preliminary Principles and the Simulation Models:

The three-phase transformer that is being tested has the capacity of 10.3 KVA, conversion ratio of DYn5, voltage level of 230/132 KV and it also has a tap changer on the primary winding. In all of the samplings the fault is done on the phase R.

Has been shown in figure number 1 [1]. In the figure 1-a the technical schema of the transformer and in the figure 1-b a view of the windings of the sample transformer in the mode of internal fault has been shown.

In order to do the internal fault in the transformer, we divide the windings of each phase into two or more parts so that we can create the internal fault in each point of this winding. In this article, two modes of the internal fault of the winding that their occurrence is most probable are simulated. In each of these two modes the creation of the phase's fault to earth and the turn to turn fault, a shunt resistance has been used. And the value of this resistance has been used in a way that is easily observable for creating a strong effect, and at the same time it is large enough to limit the short-circuit current and therefore, it protects the sample transformer against a complete breakage in a short time. The value of this shunt resistance is 0.5 kilo-ohm in the fault mode of phase to earth and in turn to turn fault is so low and close to 1 ohm.

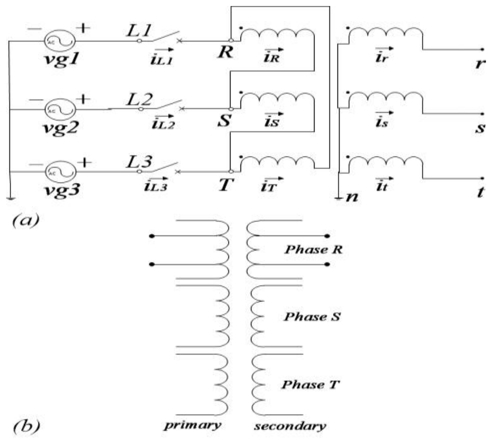


Fig. 1: The schema of the sample transformer that is being tested.

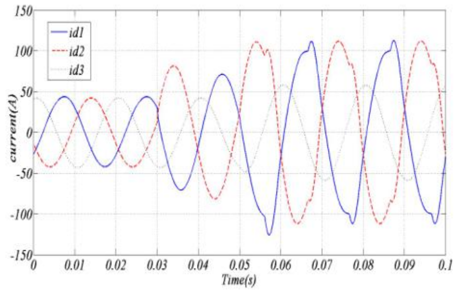
Results: The differential Instantaneous Power in Various Faults:

Simultaneous internal and external fault:

In this simulation, transformer is in the mode of total load and first at the time 0.03 second and by a 1 kilo-ohm shunt resistance, we create an external fault in the output terminal of the phase R and then at the time 0.05 second, we create an internal fault in the winding of the phase R.

Internal fault of phase to earth and simultaneous external fault:

In this simulation, like what it was stated before, first we create an external fault and then at the time 0.05 second we connect a part of the secondary winding of the phase R by a 0.5 kilo-ohm shunt resistance. Its results have been shown in figure number 2.



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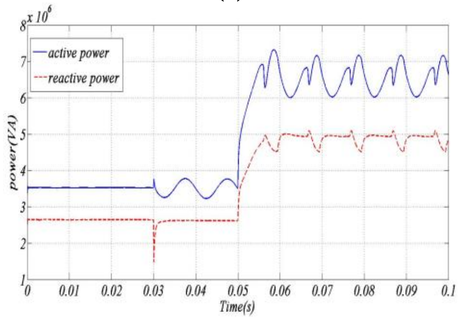


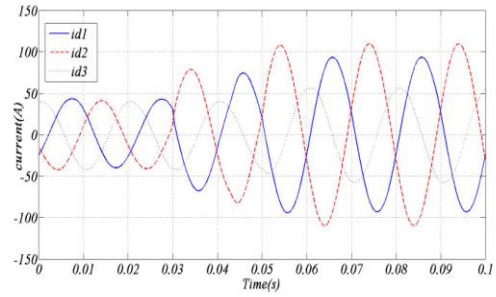
(b)

Fig. 2: External fault of phase to earth and simultaneous external fault.

The figure 2-a shows the three-phase differential currents in the mode of fault creation. As it can be seen, after the occurrence of the internal faults in the windings of the sample transformer, these differential currents has a significant increase and also the effect of harmonics on the waveform are seen as well. But in the figure 2-b a view of the situation of the instantaneous active and reactive power is shown which is in accordance with the suggested algorithm, in the way that at the time 0.03 second an external fault occurs, the fluctuations of these powers are little, but at the time 0.05 second that the internal fault is created in the transformer, the instantaneous active power has a great leap compared to instantaneous reactive power. The comparison between these two performance factors is relay.

Internal turn to turn fault and simultaneous external fault:

In this fault, the condition is exactly like the preliminary one but this time at the time 0.05 second by a switch and 1 ohm shunt resistance about 35 percent of secondary windings of the phase R have a short connection with each other. It must be mentioned that this internal fault can be created for any value of the transformer's windings, and the obtained results can be analyzed. The obtained results are shown in figure number 3.



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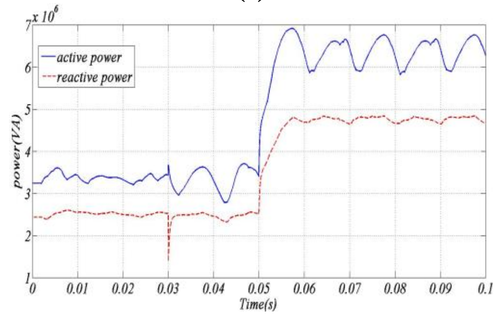

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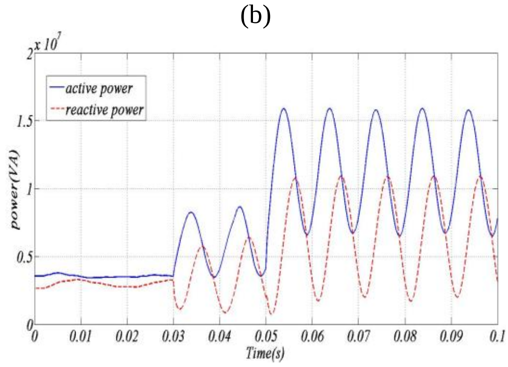


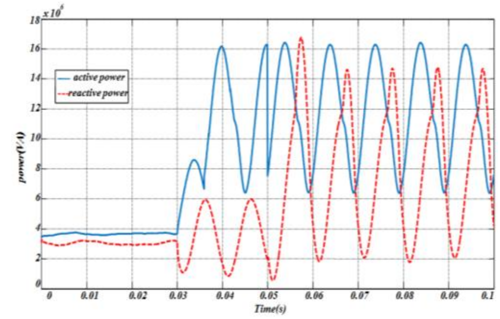
(c)

Fig. 3: Turn to turn internal fault and simultaneous external fault.

Just like it was said in the previous mode, it can be seen in the figure number 3-c that at the time of 0.05 second the internal fault occurs between the windings of the phase R. The changes of the instantaneous active power becomes much more than the instantaneous reactive power and it turns to an effective factor on the accurate performance of the differential protection system. And also the figure number 3-a shows the modes of the three-phase differential currents before and after occurrence of the internal and external faults.

Internal and external fault in the saturation mode CT of the two ends of transformer:

In this simulation, first we create two fault modes, then by changing the knee point of the CTs of the two ends of the sample transformer, we do something that these CTs saturate in the modes that the external and internal fault happens and we do the power-related sampling in this mode, as it has been shown in the figure number 4.



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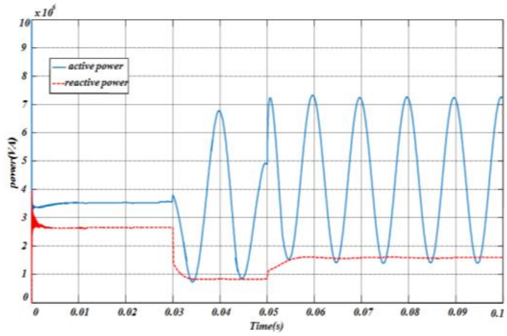


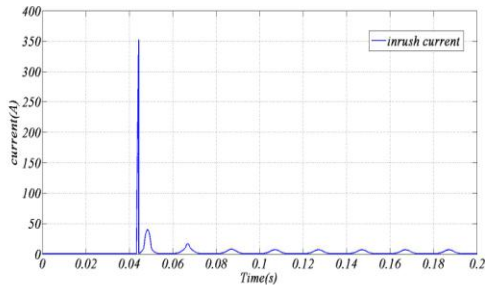
(b)

Fig. 4: The internal and external fault in the saturated mode f CT of the two ends of transformer.

As it can be seen in the figure number 4-a, after the occurrence of the external fault at the time 0.03 second, the CTs of the two ends of the sample transformer saturate and from this point forward, it is seen that the fluctuations of the instantaneous active power which is considered as an operative factor in this algorithm, compared to the internal fault mode occurs at the time 0.05 second has the same form and size and this factor can cause a lack of accurate performance of the protection system, by considering the suggested algorithm while facing the external fault. And also in the figure number 4-b these fluctuations of the instantaneous reactive power have been shown in the saturation mode of the CTs and from the secondary view of the sample transformer. In this sampling, the main factor that causes the CTs' saturation is the intense external fault that occurs in the secondary terminal of the transformer. But by choosing the proper CT such as optical CTs and also the type of core that has been used in the transformer, we can do something to prevent it from saturation with the sudden external fault so that we are able to accurately detect the distinction between these modes of fault by using this suggested algorithm.

The internal fault in the presence of magnetic inrush current:

As we know, the magnetizing inrush current exists in some initial periods of time in which the three-phase power transformer is connected to the network. This factor can create some difficulties in the work of differential protection, but with the suggested method that was given in this article, this disturbing factor is differentiated with the internal fault mode and due to it an accurate detection of the internal fault is done. In the figure number 5 these distinction mode of fault has been shown.



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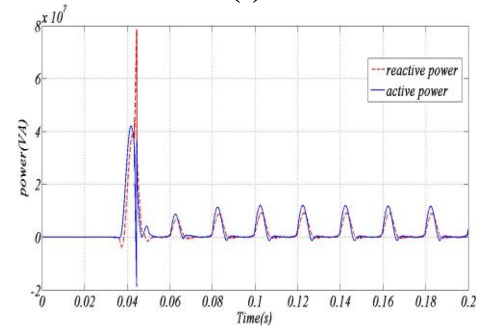


(b)

Fig. 5: The internal fault of the sample transformer in the presence of the inrush current.

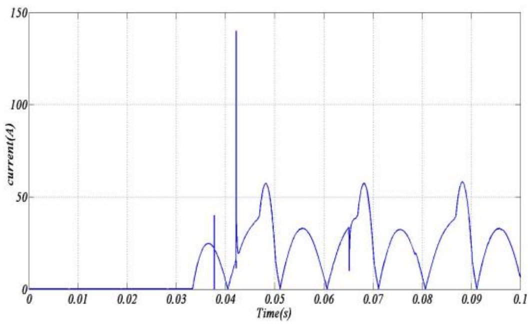
As it can be seen in the figure number 5-a, after connection of the switch of the transient inrush current's mode, how is it that this factor is able to create some difficulties in the work of differential relay. But by considering the suggested algorithm as it has been shown in the figure number 5-b, at the moment of switching the instantaneous active power has significant changes compared to the instantaneous reactive power. This comparison can be a factor for accurately detecting the fault and transient magnetic inrush current. And due to this factor the differential protection system has an accurate performance.

The effect of the tap changer changes on the results of the suggest method:

In this mode with the change of the tap changer in various modes, it is seen that these changes don't have an effect or a damage on the process of the suggested method. In other words, although we have some changes of the level of voltage with this method, but this factor does not have a noticeable influence on the instantaneous active and reactive power and it proves the reliability of this method in detecting and distinguishing between transient modes and the internal fault more than before.

Special mode: Studying the super saturation phenomenon:

This phenomenon happens when the transformer that is carrying some load is connected to the network and it causes a sudden large flow of current throughout the windings of the transformer and makes the performance of the differential protection system go wrong. The reason for this phenomenon is a transient mode and it occurs on some initial periods of time during which the charged transformer is connected to the network. Therefore, the differential protection system must perform in such a way that prevents its wrong performance against this transient phenomenon.



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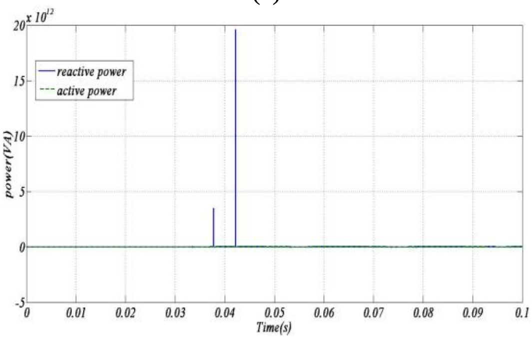

(b)

Fig. 6: The fault of the super saturation mode in the sample transformer.

In this simulation of the sample transformer, at the time 0.033 second, it is connected to the network by the switch. By considering the figure number 6-a, it is seen that after connecting the transformer to the network, a sudden and large current flows through its windings, that this factor can cause an unintended performance of the protection system. But we see in the figure number 6-b that at the same moment of switching, the instantaneous reactive power has a significant leap compared to the instantaneous active power. This difference can be the cause of the accurate performance of the differential protection system by considering the suggested algorithm.

Conclusion:

In this article a new algorithm has been provided for the differential protection of the three-phase power transformers. In this method, the instantaneous active power is considered as the operative signal, which provides a high sensitivity for detecting the internal faults even in the presence of the external fault. One of the other advantages of this method is not the harmonic components of the required differential current and the inherent limitations of DFT have been overcome. The limitation of signal is not dependent to the second harmonic of the differential currents in internal fault and the inrush current, in addition to this, the fault of lack of compliance of current is minimized given the change of the transformer's tap changer and it causes an increase of the sensitivity of the differential protection system. The empirical results and the presented simulation show that the suggested solution succeeds in distinguishing the transient mode and the conditions of the internal fault and even the sensitivity of the differential protection has gone higher at the time of low level internal fault's occurrence. The suggested method can be performed as an independent differential protection design or this method can be used as the improvement of the existing protection systems.

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