

Adaptive ANN based differential protective relay for reliable power transformer protection operation during energisation

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Article Info

Article history:

Received Aug 6, 2019

Revised Oct 20, 2019

Accepted Oct 28, 2019

Keywords:

Ann based

Differential relay

Energization

Relay mal-operation

Transformer protection

ABSTRACT

Power transformer is the most expensive equipment in electrical power system that needs continuous monitoring and fast protection response. Differential relay is usually used in power transformer protection scheme. This protection compares the difference of currents between transformer primary and secondary sides, with which a tripping signal to the circuit breaker is asserted. However, when power transformers are energized, the magnetizing inrush current is present and due to its high magnitude, the relay mal-operates. To prevent mal-operation, methods revolving around the fact that the relay should be able to discriminate between the magnetizing inrush current and the fault current must be studied. This paper presents an Artificial Neural Network (ANN) based differential relay that is designed to enable the differential relay to correct its mal-operation during energization by training the ANN and testing it with harmonic current as the restraining element. The MATLAB software is used to implement and evaluate the proposed differential relay. It is shown that the ANN based differential relay is indeed an adaptive relay when it is appropriately trained using the Network Fitting Tool. The improved differential relay models also include a reset part which enables automatic reset of the relays. Using the techniques of 2nd harmonic restraint and ANN to design a differential relay thus illustrates that the latter can successfully differentiate between magnetizing inrush and internal fault currents. With the new adaptive ANN-based differential relay, there is no mal-operation of the relay during energization. The ANN based differential relay shows better performance in terms of its ability to differentiate fault against energization current. Amazingly, the response time, when there is an internal fault, is 1 ms compared to 4.5 ms of the conventional 2nd harmonic restraint based relay.

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1. INTRODUCTION

Power systems are designed and implemented to generate, transmit and distribute electricity or power to end user consumers in the industrial, commercial and residential sectors. There are several subsystems in an electric power system which include generation, transformation, transmission and distribution [1-2]. For system design, great emphasis is put on protection. The objective of protection is to disconnect the faulted element in event of fault to avoid any more damage to the power system or equipment.

A fault is an undesired condition and may refer to a short circuit, overcurrent, overvoltage, high temperature situation among others [3-6]. Power transformers form part of the power system and this project encompasses transformer protection.

Power transformers are essential and expensive components of electric power system. Similar to other elements, they may be subject to faults [7-8]. Transformer protection involves many types of protection including differential protection. Differential relay compares the currents at primary and secondary sides of the transformer and operates if there is a significant difference between the currents [9-11]. Transformer protection should be reliable and fast to prevent consequent damage to the equipment or system. However, during transformer energisation, the differential relay operates as it perceives the situation as a faulty event. This is due to a very high current present during energisation which is known as magnetising inrush current [12-13]. This is a mal-operation of the differential relay and it must be remediated. Figure 1 briefly explains that if the operating point lies the 'operate region', trip command will be issued. While, when the operating point lies in the 'block region', operating of the relay will be blocked. There are two settings that must be known for this type of differential relay whereby K_2 represents the slope which is I_{diff}/I_{bias} and I_{d1} represents the minimum pick-up which is the threshold value of I_{diff} for the relay to operate.

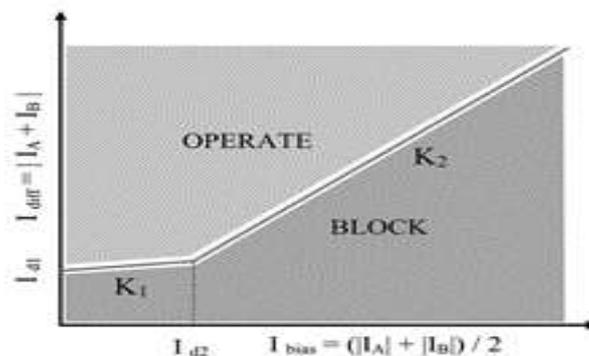


Figure 1. Tripping characteristics of current differential relay[14]

In short, the basic principle of differential protection is based on Kirchhoff's first law which compares the currents flowing in and out of the protected object, which in this case, is the transformer [4,15]. It is an effective method to protect transformer against internal faults. Practically, differential relays face many problems due to non-linear occurrences such as current transformer characteristics, transformer ratio change, magnetising inrush current and transformer over excitation [16]. These cases make the differential relay operate even though there is no fault situation. To overcome this setback, percentage differential relays have been developed which provide blocking to relays depending on the harmonic components of the magnetising inrush current [17]. The magnetising inrush current has a great portion of second harmonics which several analysis have shown [18-19]. However, it is noted that the fault current does not have it. Thus, an accurate discrimination between energisation current and fault current is a necessity to avoid mal-operation of relays. The requirement for transformer protection has become a major issue due to the need for precise, quick, and reliable distinction between magnetisation inrush current and internal fault current [20]. An ANN can also be trained so that it can adapt to the energisation situation. ANNs were originally modelled on biological brains and can often be recalled as neural networks [21]. ANN is seldom described as a computing system and the basic concept of ANN is that it can learn on its own [4, 22-23]. The Simulink toolbox in MATLAB is used for this project. The MATLAB software also includes the Neural Net Fitting Toolbox which can be used to represent the technique named as ANN (Artificial Neural Network) classified under artificial techniques [24]. This paper presents, based on the 2nd harmonic restraint method, how the ANN is trained and later adopted onto the ANN based differential relay. The conventional relay is first designed and mal-operation during energisation is shown. This relay algorithm is then modified so that the improved differential relay can discern between magnetising inrush and internal fault currents, and therefore not mal-operate during transformer energisation. The ANN is trained based on the improved algorithm. The resetting of the relay is also demonstrated by applying differential duration of faults.

2. RESEARCH METHOD

The process of designing and training an ANN based differential relay involves the following steps.

- The transformer differential protection scheme is modelled in MATLAB Simulink.
- The simple differential relay is designed to show its mal-operation during energisation.
- An improved differential relay is designed based on the 2nd harmonic restraint method to discriminate between magnetising inrush and internal fault currents and to show that mal-operation during energisation is resolved.
- The resetting of the differential relay based on the 2nd harmonic restraint method is also demonstrated for different duration of internal faults.
- Using the Neural Network Fitting Tool, a neural network is trained to differentiate between magnetising inrush and internal fault currents.
- The trained neural network is implemented as the improved differential relay to show that mal-operation during energisation does not happen.
- The resetting of the ANN based relay is also demonstrated for different duration of internal faults.

To train the ANN, a 2nd harmonic restraint based relay was designed. Its operation is detailed in the following flowchart in Figure 2. Essentially there will be 2 sections in the relay subsystem where one section will detect if the fault is internal or external and the other section will detect if the primary current of the transformer is a fault current or magnetising inrush current. The results from these 2 sections are considered using an AND logical operator and sent to the memory device, which is an SR-flip-flop as shown in Figure 5. This part will be the automatic resetting part integrated in the proposed design. The relay output will be in terms of tripping and non-tripping signal (1 and 0 respectively).

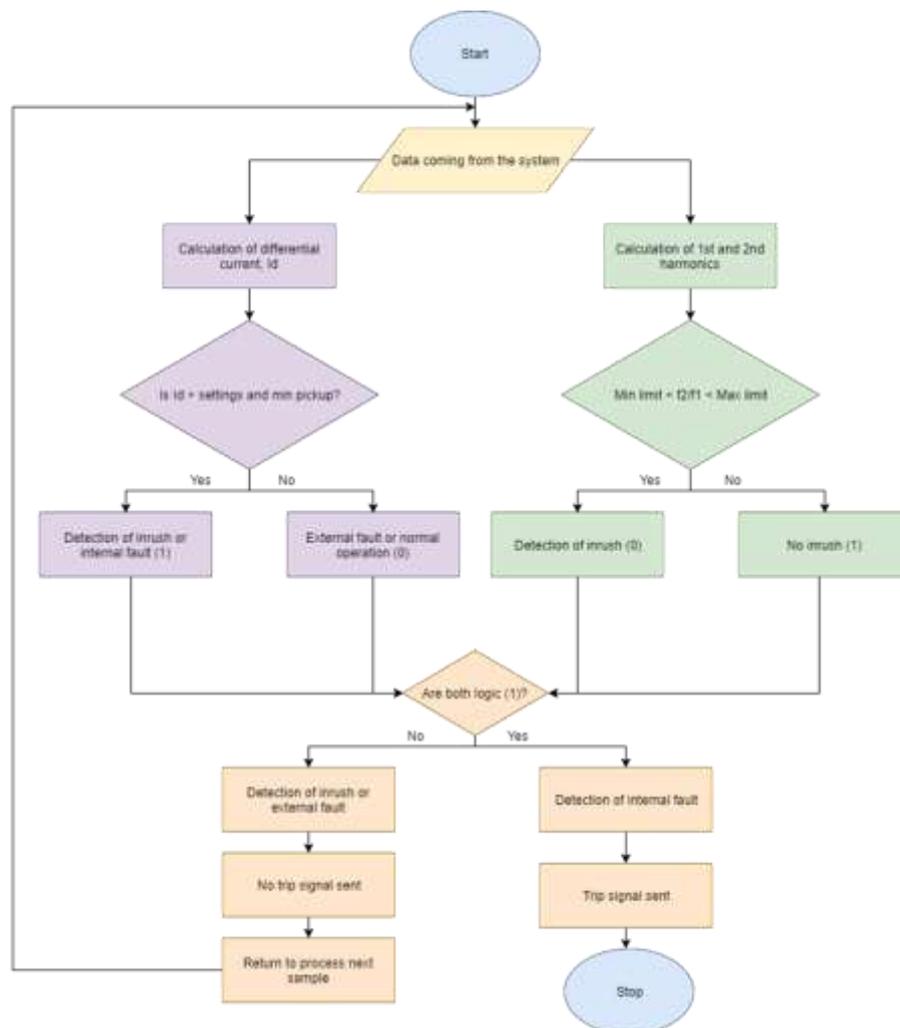


Figure 2. 2nd Harmonic based Relay Principle

2.1. Conventional differential relay

The transformer protective scheme is designed and the conventional differential relay is simulated to show the problem, which is the relay mal-operation during transformer energisation. The normal protection scheme is shown in Figure 3. Practically, when a power transformer is energized at no load, a transient current, 6 to 10 times of the rated current occurs only at the primary side of the power transformer. This transient current is known as the magnetising inrush current [25]. To simulate this situation on MATLAB Simulink, the transformer model is saturated and the circuit breaker is initially open and closes after a pre-set time. The entire simulation is inspired by the strategy adopted by Othman et al [26]. The limitation of the conventional design on Figure 4 is that it lacks a system to differentiate between the fault and magnetising inrush current. The following section remedies to this by implementing an inrush current detection subsystem.

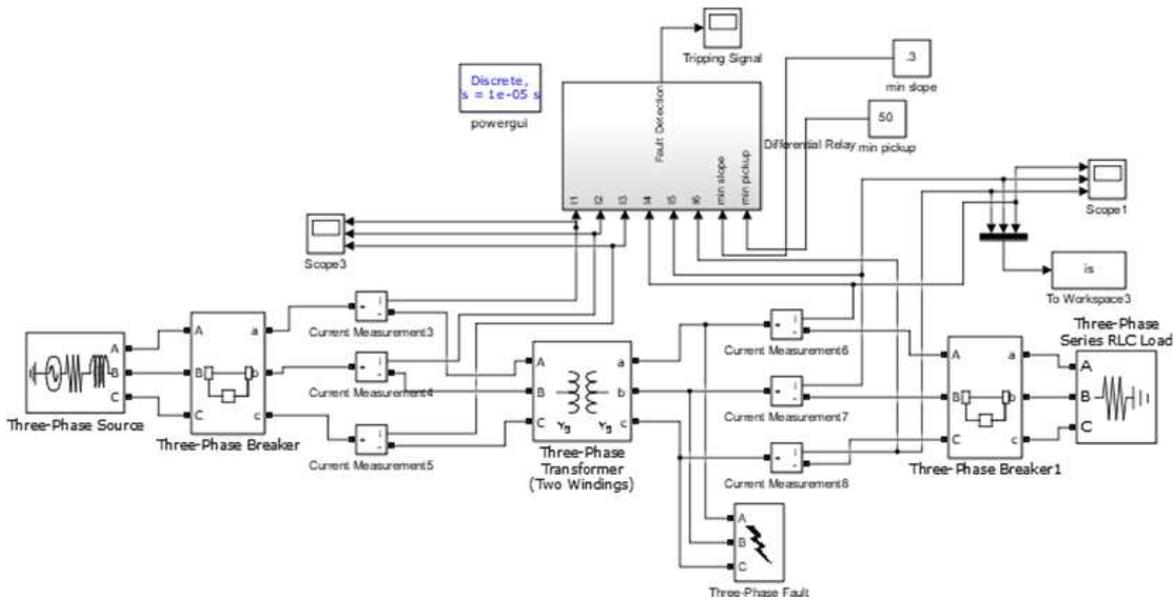


Figure 3. Transformer differential protection scheme

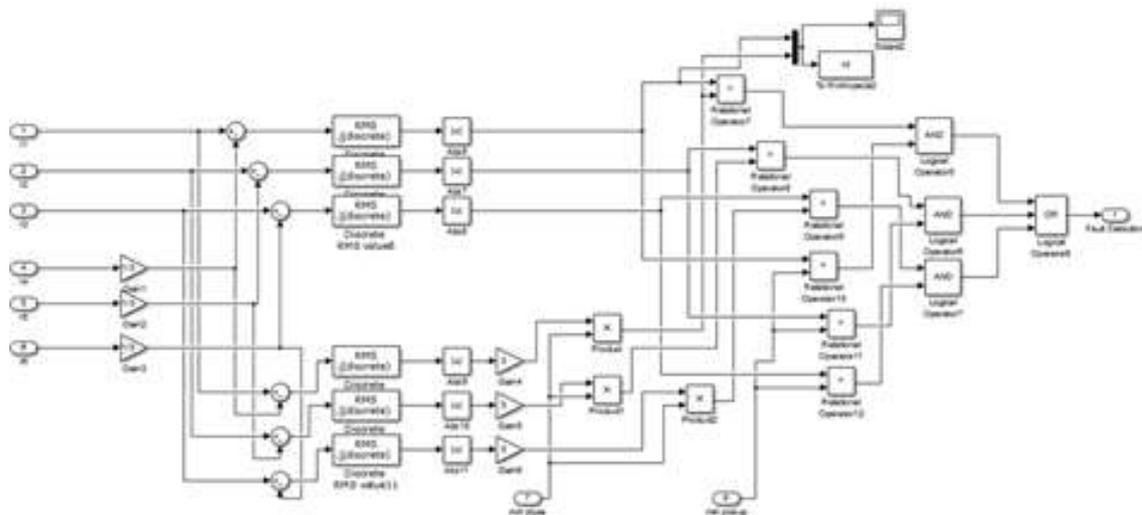


Figure 4. Conventional differential relay

2.2. Differential relay based on 2nd harmonic restraint method

A subsystem as shown in Figure 5 is added to the previous conventional relay design and an automatic resetting is also implemented. There is an inrush detection and fault detection subsystem. The resetting will occur in a periodic manner and the user can set the period.

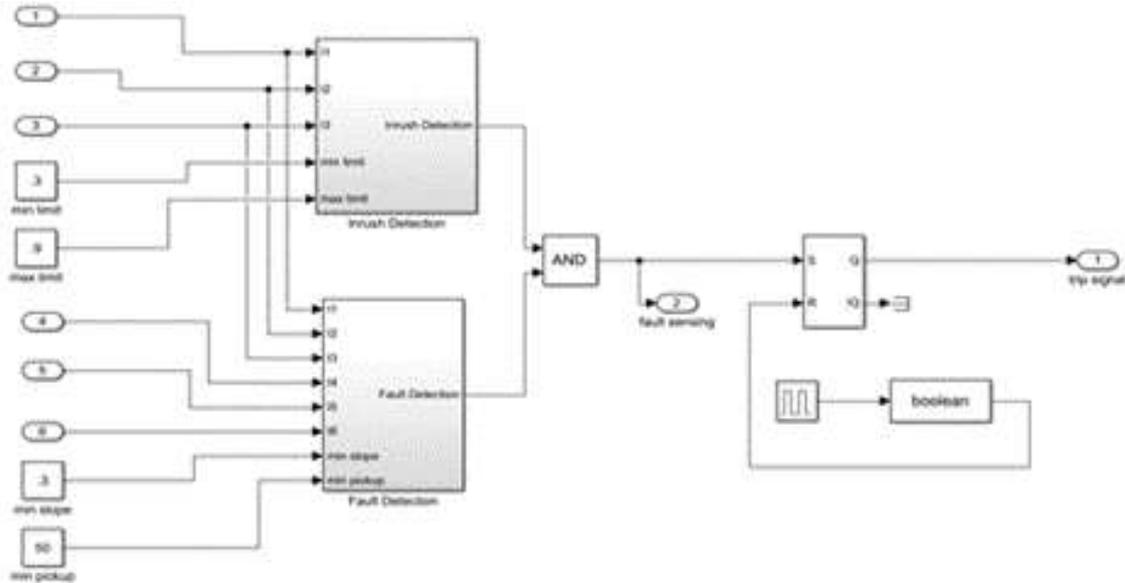


Figure 5. 2nd Harmonic based differential relay

2.3. ANN based differential relay

An ANN as shown in Figure 6 is trained using the nftool in MATLAB and a simpler differential relay is obtained. The training is done based on the data from 2nd harmonic restraint relay while taking the internal fault current as input and the tripping signal as output.

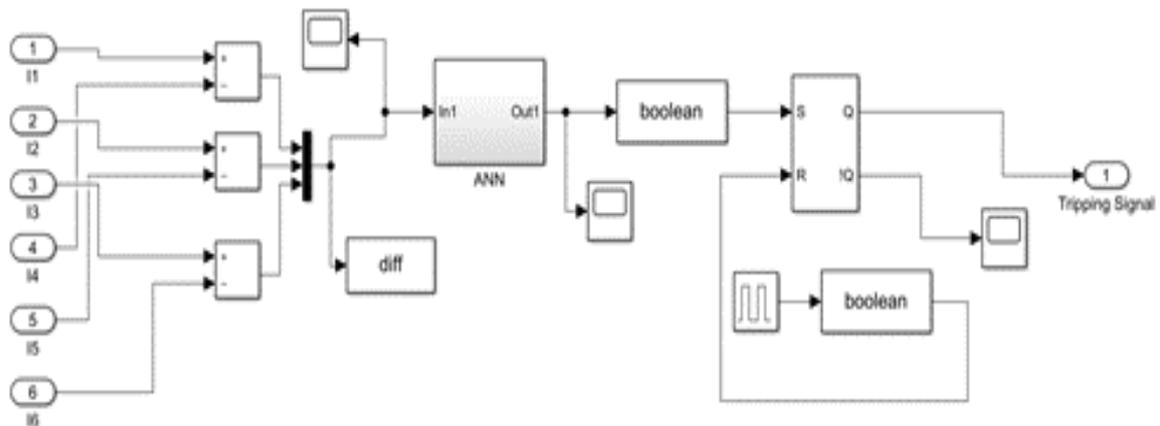


Figure 6. ANN based differential relay

3. RESULTS AND DISCUSSION

The results obtained from the 2nd harmonic restraint differential relay and the ANN based differential relay are essentially similar. The results of the conventional and ANN based differential relay are thus compared and the resetting of the relay is demonstrated by applying instantaneous and log duration faults.

3.1. Conventional differential relay operation

3.1.1. Internal fault simulation for conventional relay

The simulation is run for 0.3s and a fault is applied at 0.1s. The results show that, as per Figure 7, the fault currents are of high magnitude, 6000-8000A and the tripping signal is issued during that time. It is noted that the current is not 0 when a trip is issued as the connection of the output of the differential relay is not connected to the circuit breakers for simulation.

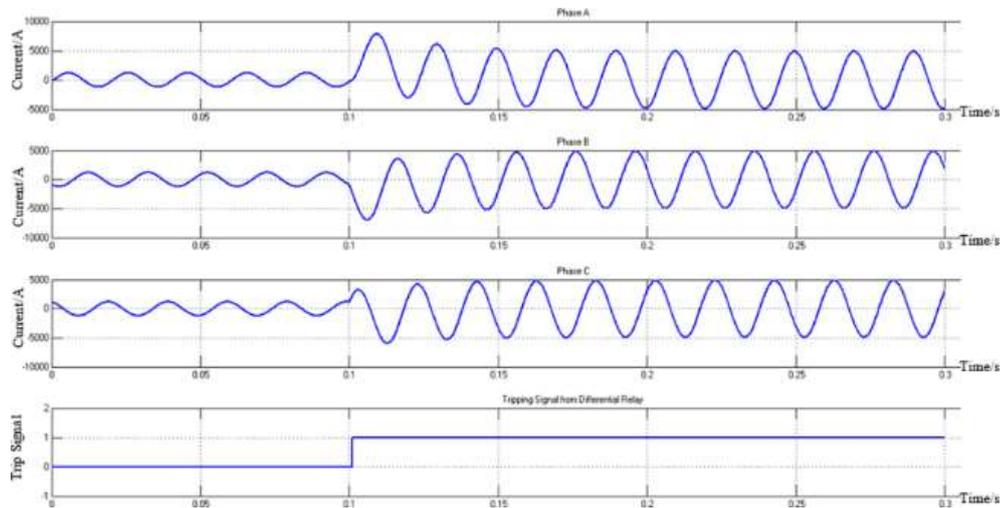


Figure 7. Signal from conventional relay and primary side current of transformer during internal fault simulation

3.1.2. Transformer energisation simulation for conventional relay

For energization, as shown in Figure 8, the circuit breakers are made to close at 0.1s, and due to the presence of inrush current of almost 3000A, a trip is issued by the conventional relay.

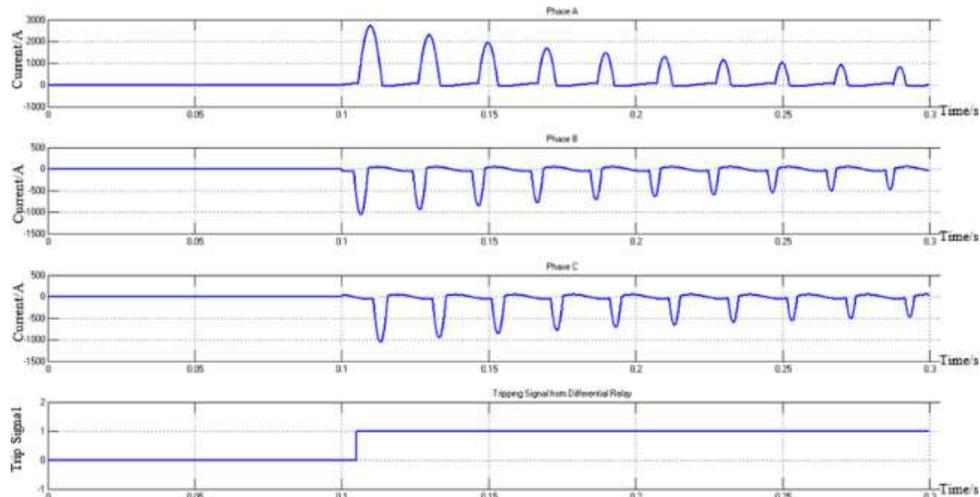


Figure 8. Magnetising inrush current at primary side of transformer and signal from conventional relay during energisation simulation

3.2. ANN based differential relay simulation

The nftool in MATLAB is used for the ANN based differential relay design. The number of neurons was set to 5. The performance of the network is evaluated by mean square error and the regression method.

The training algorithm is the Back propagation which is based on the Levenberg-Marquardt minimisation method (LMBP). The training was deemed successful by nftool after 13 iterations and a Simulink diagram was generated and implemented in the design.

3.2.1. Long duration internal fault simulation for ANN based relay

The simulation is run for 0.3s. The fault applied is a long duration fault starting at 0.1s. The trip signal is obtained accordingly as shown in Figure 9. The response time of the relay is seen to be approximately 1ms. At 0.2s, the signal goes to zero and back to 1. This happens for less than 0.002s. It demonstrates that the differential relay has been reset at 0.2s. The very large currents of around 6000A to 5000A demonstrate the fault occurrence. The current waveforms do not show zero at tripping as during simulation, the relay output is not connected to the circuit breaker.

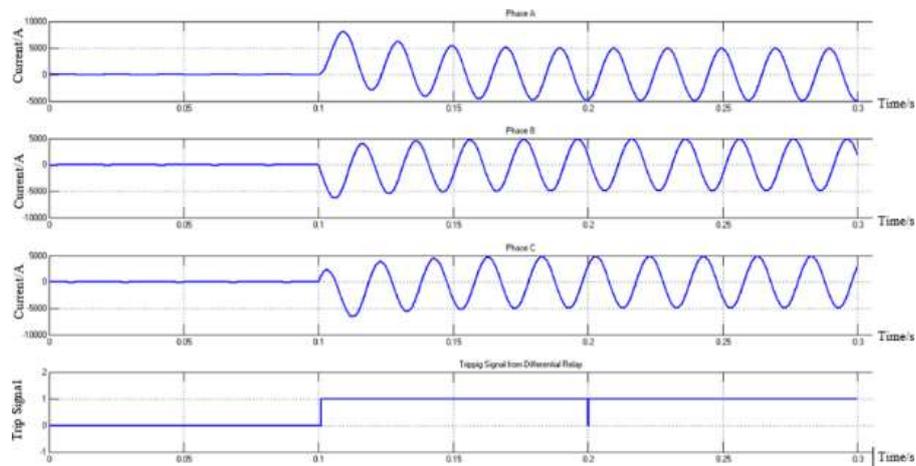


Figure 9. ANN based relay output and primary side currents of transformer during long duration internal fault

3.2.2 Instantaneous internal fault simulation for ANN based relay

The simulation is run for 0.5s and the fault is applied from 0.1s to 0.3s. Proper operation of the differential relay is observed, whereby a trip signal is sent during the fault time as shown in Figure 10. The response time of the relay is seen to be approximately 1ms. As the resetting occurs every 0.2s, the fault is not cleared immediately at 0.3s, but is cleared at 0.4s, when the relay resets.

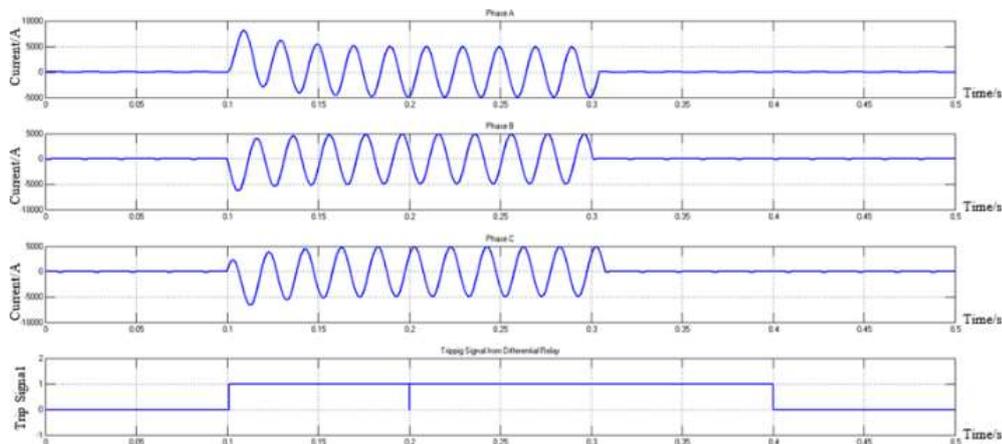


Figure 10. ANN based relay output and primary side currents of transformer during instantaneous internal fault

3.2.3 Transformer energisation simulation for ANN based relay

The simulation is run for 0.3s where the circuit breakers are closed at 0.1s. Figure 11 shows that no tripping signal is sent from the differential relay. There is no mal-operation of the differential relay. The magnetising inrush current is observed as the transformer is in unloaded condition

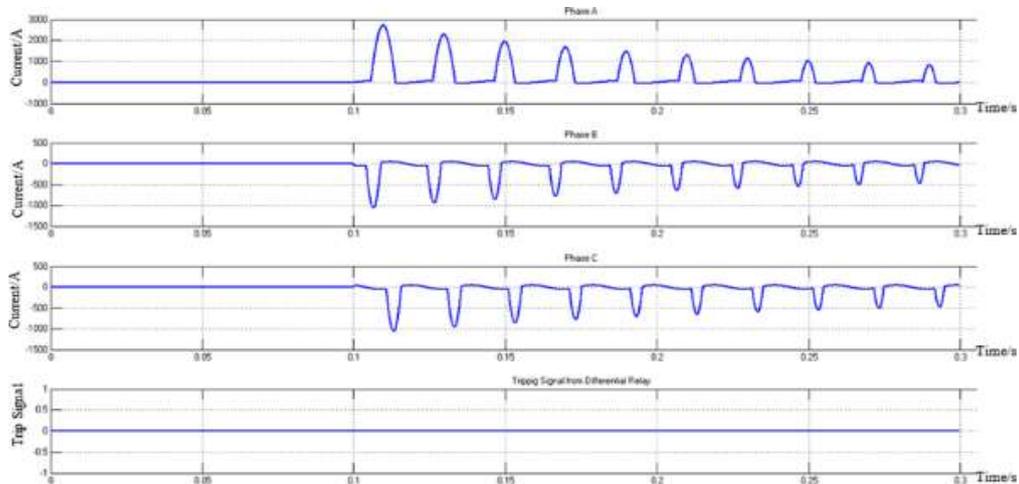


Figure 11. ANN based relay output and primary side currents of transformer during transformer energization

As there is no mal-operation of the relay after careful training using the internal fault current as reference, it is deduced that ANN based differential relay is an adaptive relay. ANN based differential relay is also observed to have a simpler algorithm compared to the conventional and 2nd harmonic restraint based relay. For this project's simulations, a wye-wye grounded transformer type was used. A different type of transformer can be used if the ANN is trained properly to adapt to the different situations. The ANN generates an output which is not linear. The output must be processed through a function to be able to obtain a trip signal. The constant 0.3 was used as it represents the minimum slope ('min slope') of the 2nd harmonic restraint differential relay. The coding can be modified by the user depending on the way in which the output representation is desired. Thus, if another ANN differential relay is used, it may not necessarily have the same function block. ANN based differential relay is also observed to have a simpler algorithm compared to the conventional and 2nd harmonic restraint-based relay. The ANN based differential relay also shows better performance in terms of its ability to differentiate fault and energization current also response time where if there is an internal fault, the response is in 1ms compared to 4.5ms for the 2nd harmonic restraint-based relay. Thus, overall, the ANN based relay is simpler in structure and better in performance compared to the 2nd harmonic restraint relay. The automatic resetting of the relay was shown by simulating different durations of internal fault, namely long duration and instantaneous faults. It has been observed that if the fault is cleared and resetting occurs, the tripping signal is cleared, that is, changes from 1 to 0. ANN, essentially, is an adaptive system and must be carefully trained according to the system used.

4. CONCLUSION

This paper presents the ANN based differential relay that is successfully trained so that it can discriminate between magnetising inrush and internal fault currents. An adaptive ANN differential relay algorithm was implemented which proved to be more reliable than the conventional one. Differential relay mal-operation was prevented during transformer energisation by implementing a 2nd harmonic restraint element in the adaptive relay. Using the principle that the magnetising inrush current is rich in harmonic content, the restraint part will identify when energisation occurs. The ANN was trained on 2nd harmonic restraint principle. The ANN based differential relay is observed to have a simpler algorithm. An automatic resetting operation was integrated in the proposed modified differential relay. Overall, the ANN based differential relay is adaptive and does not mal-operate during transformer energisation. The ANN based differential relay also shows better performance in terms of its ability to differentiate fault and energization current while providing a response time when there is an internal fault, of 1 ms compared to 4.5 ms for the conventional 2nd harmonic restraint-based relay.

ACKNOWLEDGEMENTS

The author would like to acknowledge the support from Kurreemun Khudsiya Bibi Zainab, now attached with the Ministry of Public Infrastructure and Land Transport, who is the original implementor of the work under her final year project which was awarded the Best Final Year Project Award in the nationwide 2018 IEEE Malaysia Section Final Year Project Competition. Upon her consent, the work has been allowed for further improvement for pursuance of the main author's research work extension. The work is also financially supported by the UPM Geran Putra Berimpak referenced UPM/800-3/3/1/GPB/2019/9671700.

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