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Current Signal Processing based Methods to Discriminate Internal Faults from Magnetizing Inrush Current

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Abstract - **Two new methods, Current Change Ratio (CCR) and Percentage Area Difference (PAD) were proposed to solve a problem of how to distinguish between internal faults and inrush condition when transformer is switched on. This problem may delay operation or may mal-operate some protection schemes like deferential protection. The methods were concluded after observing and analyzing the behavior and shape of large number of both inrush and internal fault signals that had been obtained using a model transformer in a laboratory. The methods were practically tested on a three phase transformer with rated power of 20kVA at Cardiff University's laboratory and the data were processed using LabVIEW and MATLAB programs. The results showed that internal faults can be correctly distinguished from inrush condition within a short time (from 5ms to 10ms), particularly the minor internal faults such as the inter-turn fault which is submerged to inrush current and make it is too difficult to be detected. The advantages of these algorithms are simple in design and faster than the second harmonic method which is the most popular method used for solving this problem.**

Index Terms: Internal fault, inrush current, LabVIEW and MATLAB programs, current change ratio, percentage area difference, transformer protection.

I. INTRODUCTION

Protection system is an important part in any power system as it continually monitors the status of the equipment and can act almost immediately to any fluctuations occur in the power system. This is important as it can isolate any faulty unit within the system to a localised area and minimise as much damage as possible to the faulty equipment or any equipment in the vicinity without disrupting power flow to unaffected areas. Power system equipment repairs can be lengthy and expensive as well as replacement difficulties and fire risk to other equipment surrounding. Therefore, any protection system must be reliable, dependable and secure to ensure that any damage due to a fault is kept to a minimum [1].

For some decades, the differential protection is the main protection system for most power transformers. It is implemented to avoid any mal-operation may occur in protection relays. The 2nd harmonic restraint is commonly used as a protection technique to prevent the differential protection systems from operating during either external faults or inrush condition [2-3].

Nevertheless, this method cannot be relied on for all cases, including internal transformer winding faults and for power transformers that their cores are built using the amorphous material which are characterized by low power loss. In this case, there are 2nd harmonic components of around 7% of the fundamental during the initial inrush conditions leading to potential false trips of the differential relays. Reducing the 2nd harmonic conventional value to solve this problem is not good idea because if the threshold for the 2nd harmonic component is reduced below the conventional value of 15%, there is then a risk of the differential relay not being able to protect the equipment as intended under severe internal faults where the 2nd harmonic component is >15% of the fundamental. Current transformers may also be saturated during internal faults leading to generation of significant 2nd order harmonics [4]. In addition, capacitance of long transmission lines may have a negative impact on the response time of a differential protection system as well as the capacitance and inductance of these lines form such a resonant circuit that increases the harmonics of the short circuit current. In order to overcome this problem, the phase voltage is used as a control signal to get rid of the 2nd harmonic component in internal faults [5]. However, the response time of this solution is low, as well as it works only for severe internal faults.

The method of 3rd harmonic restraint was presented for differential protection systems to overcome the problems of dead angle or 2nd harmonic restraint approaches [6]. However, this method has its own drawbacks as it can suffer from DC biasing that can impact on the results of the harmonic analysis that can cause the protection relays to trip falsely.

Other methods that do not rely on 2nd harmonic components were also proposed including one that depends on the feature of discontinuity zone (dwelling time) in the inrush current [7-8]. However, the phenomenon of reverse charge that occurs in the current transformer will cause this zone to disappear. Therefore, rendering any protection scheme that relies on the dwelling time will be useless in this application. In addition, the time of operation for these schemes to work can be up to one cycle and a half in some cases of faults meaning that significant damage may occur before the system will protect the affected area. Other approaches were proposed based on the analysis of electromagnetic and/or equivalent circuit of the transformer [9-10]. This cannot be practically achievable when a differential relay is used to protect the transformers connected in delta which means that both the current data in delta winding and the equivalent circuit parameters should be obtained experimentally. Differential equation models of transformers and flux restraint are methods were also used in differential protection. However, in these methods, the current values in all windings of transformer are essentially required to be measured and also it is necessary to experimentally obtain either the data of B-H curve or the parameters of equivalent circuit, which makes the work more complex. Another two methods were used for identifying fault conditions. They were built depending on the distortion that occurs in the characteristics of the differential current signal. One of these methods is to check the time intervals when the level of differential current is fluctuating around to zero level [11], while the other one is to measure the duration between the two successive peaks of the differential current [12]. However, both methods take long time in detecting faults.

Currently, waveform comparison and improved correlation coefficient methods [13-14] which are blocking schemes, were implemented for recognizing faults using correlation coefficients between the first and the second-half of current cycle, where the sample observing window is created by sampling one cycle of current signal and continue to sample the following one. The problems of this approach include a long processing time and the DC components of the current waveforms weaken the symmetry between the first and the second half of current cycle.

Recently, there has been an implementation of artificial intelligence (AI) for use in protecting power networks as there is a distinct pattern that can be learned. Artificial Neural Networks (ANNs) [15-16] are currently the most common method of implementing AIs. However, the use of this method has drawbacks, which mainly include that there are no accurate rules to set the parameters of neural network as well as the so long time that is taken for pattern learning process. Wavelet Transform (WT) and Discrete Wavelet Transform (DWT) were also used to distinguish between internal faults and inrush case [4], [17]. Wavelet transform is a mathematical expression that can be used for analysing the frequency of the signal when it changes with respect to time. It decomposes the signal over an iterative execution into bands of low and high frequencies in order to extract the most important feature from the signal. However, the specific harmonics of the desired signal as well as its fundamental waveform and any noise signals in the same frequency band will affect the wavelet coefficients. This means that the signal extracted by the WT is not reliable when there is a high signal to noise ratio.

Another method also based on correlation coefficients was presented. It uses the feature of inrush current waveform in non-saturated (dead angle) zone to discriminate inrush condition from internal faults [18]. A drawback to this method is the reliance on the dead angle zone, which may be disappeared due to the reverse charging of current transformers and that means there will be difficulties in practical applications. In addition, this method relies on information across a whole cycle meaning that any fault detection has an increased time response.

A combination of two wave shape recognition techniques, correlation and energy difference, was proposed as a novel power-based algorithm in [19]. These two techniques provide two discriminative indices, the first index is the similarity between a generated sinusoidal signal and a calculated average power and the second index is the energy difference. To calculate the differences, a window of half a cycle is selected when the peak value of the average power should be in the center of the window. The window begins when the inrush current starts to increase at around a quarter of a cycle, which means that the algorithm needs at least half a cycle from time of energization until the beginning of the window plus some calculation time afterwards, i.e. the response time is increased.

This paper presents new methods which have advantages of being simple in the algorithm design, a decreased response time to internal faults and reliable discrimination between the inrush and the internal fault which coincides with transformer's energisation. This paper is a complement to the authors' publication in [20] which dealt with faults when the transformer operation is in steady state. Here, the authors consider the transient inrush problem that occurs when the transformer operation is in an energization state.

II. PROPOSED METHODS

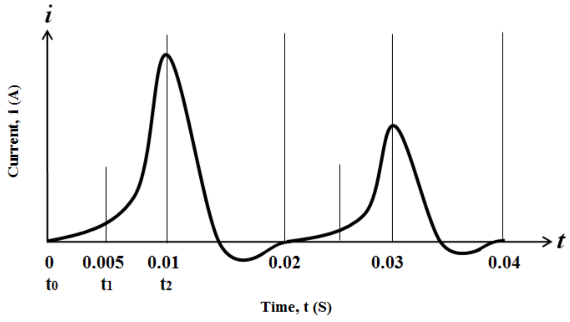
CCR method is individually used when the transformer is on no-load condition while both methods, CCR and PAD are used when the transformer is on-load condition.

A. *Current Change Ratio method (CCR)*

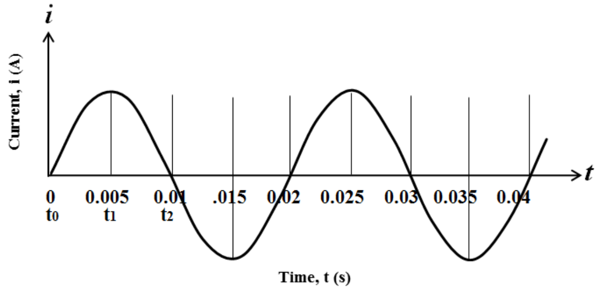
The waveform of internal fault is normally sinusoidal while the inrush waveform is not sinusoidal as shown in Figs 1-a and 1-b. According to this difference between the two shapes, a discrimination method can be found. The idea of this method is based on dividing a half-cycle of the signal into two halves in time intervals t_0-t_1 and t_1-t_2 as shown in Figs 1-a and 1-b. CCR is then calculated by diving the difference in value of currents that corresponding to the time intervals such as

$$\mathrm{CCR} = \frac{i(t_1) - i(t_0)}{i(t_1) - i(t_2)} \qquad (1)$$

In case of internal fault, CCR is close to unity or above because the waveform of the internal fault current is sinusoidal and regularly increases with respect to time which means that in (1), the difference of current values in numerator is very close to that in denominator. But in case of inrush condition, the rate is always small and much lower than 1 because the current in the first half of half cycle is much smaller than the second one as shown in Fig 1-a, thus in (1), the difference in numerator is much smaller than that in denominator. [21]



(a)



(b)

Fig 1 (a) Inrush current waveform (b) internal fault current waveform

B. *Percentage Area Difference (PAD)*

In experimental test, one of interesting findings was that when transformer was switched on and before the knee-point on B-H curve i.e. before core saturation begins, the transformer was correctly transforming primary currents to secondary side in this zone. It was found that in inrush condition, the secondary current was very close to primary (overlapping) in that zone as the transformer turns ratio was 1. However, if the ratio is not 1, the currents on primary and secondary sides can be equalized by adjusting the turn's ratios of the CTs that are deployed on both sides. While in fault condition, there was a difference in values between those currents. This difference depends on the fault current, the higher the fault current, the bigger difference exists and vice-versa. It was found that it is very good choice to select the first quarter of the current waveform as the required zone because it is very close to the zone before saturation and gives good results as well. So the area under the curve of the current signal in the zone is calculated for both primary and secondary currents of each phase. Then the PAD between area in primary (ARP) and area in secondary (ARS) in the zone is calculated by

$$\mathrm{PAD} = \frac{\mathrm{ARP} - \mathrm{ARS}}{\mathrm{ARP}} \times 100\ \% \qquad (2)$$

In this zone, the PAD is low at inrush condition, while it is high in case of internal fault. It can also be noted during inrush condition which appears on primary side only that the absolute values of lower or upper peak of the second half-cycle of primary current is always equal to second half cycle of secondary current when inrush is low or faded out and less than it when the inrush is high. It means the higher first half-cycle of inrush, the lower second half-cycle of inrush. But in case there is an internal fault, the peak of the second half-cycle of primary current is greater than the peak of second half-cycle of secondary current. This is because that in non-saturation zone, the fault current signal which is submerged with inrush will be appeared. So, in last quarter of cycles, PAD during inrush may be high but in negative ratio because the ARS is greater than ARP while PAD is always positive high ratio during the fault as ARP is greater than ARS. This can be used as another indicator if the fault occurs in the second half-cycle of the current. [21]

III. EXPERIMENTAL TEST

A. *Laboratory model*

6 current transformers (CTs) with 40:5 turns ratio were deployed on both sides of three-phase transformer as shown in the schematic diagram in [20]. There was also LEM NORMA D 6000 power analyser system (not shown in the figure) connected to the transformer to be used for monitoring values of current and voltage of each phase. The current signals measured by CTs were converted to voltage signals by using high precision resistor of 0.1Ω in order to be read by NI USB-6259 data acquisition card. LabVIEW 2013 program was designed to trigger the three-phase contactor as well as the switch relay which was used for generating internal faults. These faults were generated via numbered tap points that distributed along the transformer's winding. For laboratory safety and also calculation simplicity, the phase voltage was set to 60 V, 50 Hz and number of turns Np and Ns on primary and secondary sides respectively were 60 turns each, i.e. the turns ratio was 1. [21]

B. *Procedure of experiment*

The sample rate was set to 10 kHz, i.e. 200 current samples per cycle. The run time of LabVIEW program was 0.4 seconds which means that 4000 samples were collected from data acquisition card in each run. All signals were filtered from their harmonic components using low pass filters with 50Hz cut-off frequency in LabVIEW program. The data were then fed to MATLAB program [22] in order to be processed. [21]

IV. INRUSH AND INTERNAL FAULT CASES

The proposed methods are tested on the transformer at two cases, no-load and on-load. In each case, the transformer is switched on, once without internal faults i.e. pure inrush and once with internal faults. The results are presented in the following subsections. [21]

A. *Inrush condition when transformer is at no-load condition*

Initially, the algorithm of the proposed method checks the peak value of half-cycle current signal. If it is greater than no-load current signal, it means there is a disturbance need to be recognized otherwise it is normal condition. The decision is made every half-cycle, which means that it needs only 10 milliseconds to decide whether the disturbance is a fault or inrush.

1) Inrush condition without internal fault: The transformer was switched on/off so many times i.e. at different instants of sinusoidal voltage wave to obtain inrush current signals. The no-load current measured by CTs on primary side was 0.06 Amp. As the transformer was supplied at low voltage of 60 Volts, it can be noticed that inrush decaying time was short as shown in Fig 2-a.

Inrush decaying can be recognized by MATLAB algorithm through subtracting two successive positive and negative peaks of cycles (D2PK) and also the peak of half cycle is subtracted from the next one (DP2P) which indicates the decay of DC offset. When the difference approaches zero, it means that the inrush as well as DC component are faded out.

The simulation results for inrush condition indicated that in the first two cycles, the peak values of half-cycle current signals for all phases were higher than the peak value of no-load current signal but the CCR remained below 0.8 until half-cycle number 5 for phase A, 6 for phase B and 16 for phase C, then it changed to above 0.8 as the shape became close to sinusoid as shown in Fig 2-b. Therefore the case was classified as inrush condition which can also be recognized by D2PK and DP2P and the normal condition started at half-cycle number 6. In either two conditions, the relay must not operate, so there was no trip signal to be issued and the algorithm effectively recognized this case.

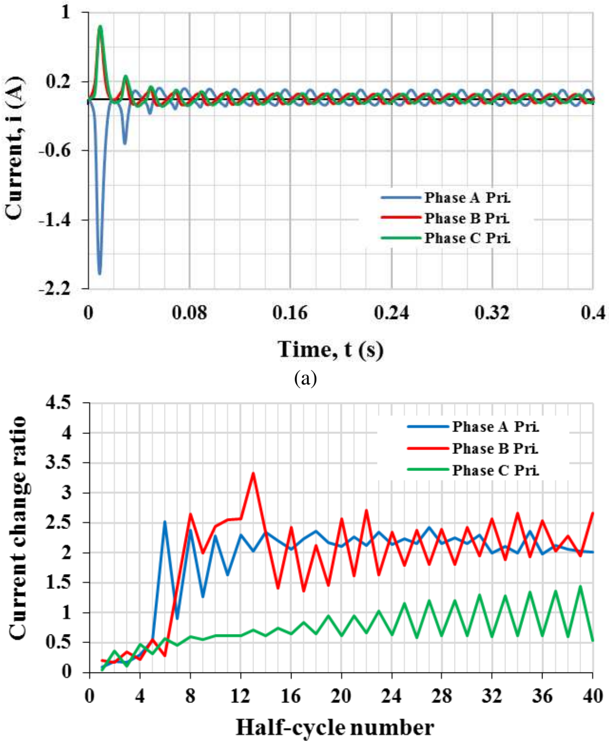
2) Interturn fault with inrush condition: The transformer was energized with four turns were short-circuited on the primary side of phase A. The inrush currents were clear in the first two cycles and having the inrush shape on phases B and C while on a faulty phase A, its shape was closer to sinusoid due to the effect of the fault as shown in Fig 3-a. DP2P and D2PK indicated that the inrush current fully decayed after two cycles.

Since that the fault on phase A forced the inrush waveform to be closer to sinusoid, CCR was greater than 0.8 at the first half-cycle current as shown in Fig 3-b. Therefore the algorithm considered this case as an internal fault.

3) Turn-ground fault with inrush condition: The transformer was energized with a turn-ground fault on phase A. The shape of current waveform is now very close to sinusoid as shown in Fig 4-a.

The simulation results for this fault indicated that the CCR was greater than 0.8 on the faulty phase A across the full duration of simulation as shown in Fig 4-b, while it was less than 0.8 in the first half-cycle of both phases B and C because their current shapes were similar to the shape of inrush condition as shown in Fig 4-a.

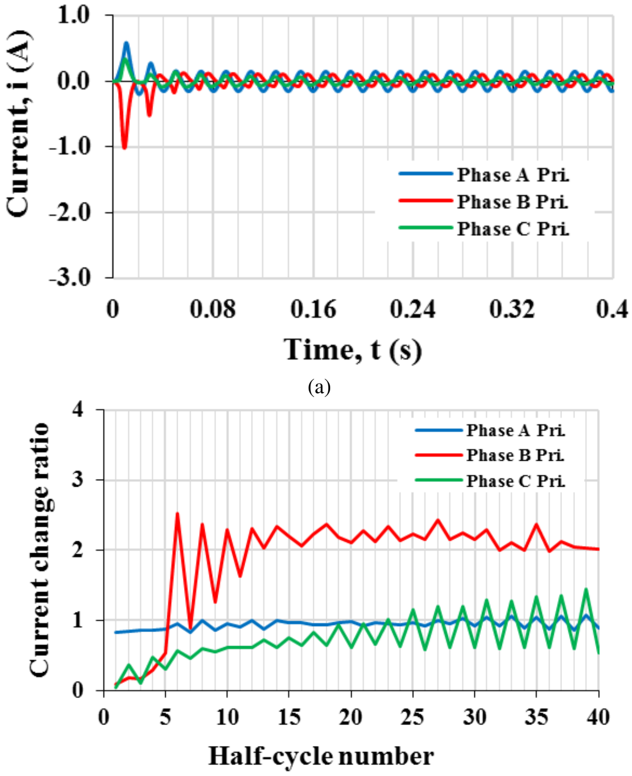
Accordingly, it was classified as an internal fault condition and a trip signal was issued. The algorithm detected this fault on phase A and effectively distinguished it from inrush condition after half-cycle time of transformer energization.



(a)

(b)

Fig 2 No-load transformer was energized without fault (a) Inrush condition (b) CCR



(a)

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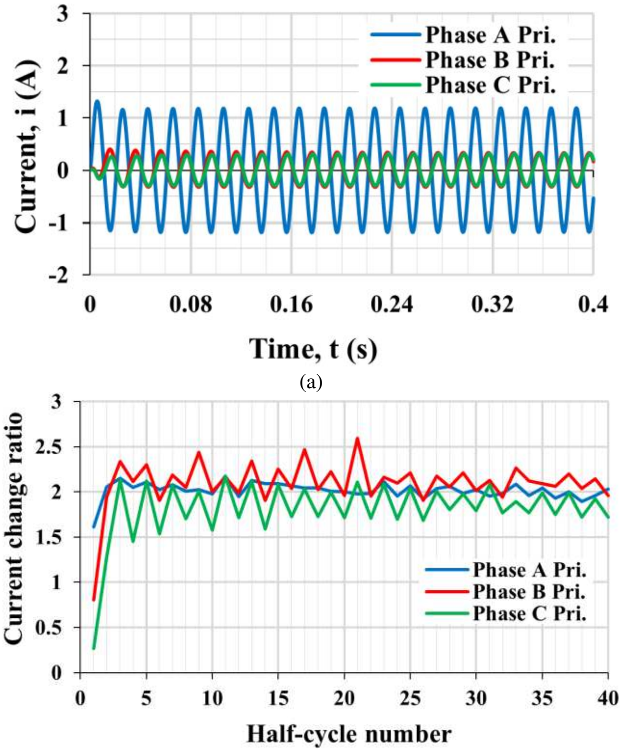
Fig 3 No-load transformer was energized with interturn fault on phase A (a) Current waveforms (b) CCR



(a)

(b)

Fig 4 No-load transformer was energized with turn-ground fault on phase A (a) Current waveforms (b) CCR

B. *Inrush condition when transformer is at on-load condition*

The transformer was connected to a balanced load, so there were six current signals to be processed, three input current signals of three phases A, B and C at the side of energization and the opposite three output current signals at load side.

Since that transformer turns ratio was 1, the difference between primary and secondary current peak values (Diffmax) indicates the status whether it is normal when the difference is equal or less than 0.1(it is ideally zero but 0.1 has been chosen as a margin of error in practical test) or either fault or inrush when Diffmax is greater than 0.1. Therefore, the half-cycle current peaks are not necessary to be compared with the load current unlike the case in the no-load. [21]

1) MATLAB algorithm: There are 50 samples in quarter cycle are used to calculate the area under the current curve on both primary and secondary sides of each phase. Then the PAD is calculated using (2). D2PK and DP2P are also computed to show the status of operation. Diffmax is also computed to be used as an additional indicator that supports in discrimination between normal operation and other conditions. PAD is computed every first and last quarter of cycle as they are the most important zones that should be targeted in the cycle. The algorithm's function is shown in flowchart in Fig 5. After calculating the required quantities, the timer of the loop (TMR) counts every half-cycle starting with number 1 for the first half-cycle and so on. TMR is checked whether it is odd or even. If TMR is odd, it means that it is a first quarter of cycle, so PAD is checked and compared with threshold value which was taken as 30% after observing so many simulations. If PAD is greater than 30%, there is an internal fault has occurred, otherwise, the program continues to half-cycle and checks Diffmax. However, when TMR is even, it represents last quarter of cycles, so steps of execution is followed as shown in the flowchart. [21]

2) Inrush condition without internal fault: Fig 6-a shows the inrush condition when loaded transformer was switched on without internal fault. The steady state current which was measured by CT was around 0.28 Amp. [21]

The simulation results for inrush current condition indicated that the PAD at first quarter of the first cycle (number 1) was 9.49 % for phase A, 16.58 % for phase B and 8.99 % for phase C while it was 22.3 % for phase A, -58.97 % for phase B and 5.71% for phase C at the last quarter (number 2) as shown in Fig 6-b.

Phase A was chosen to demonstrate how the algorithm works. At first process, the TMR was odd, PAD in first quarter of cycles (odd number 1) was less than 30% for all phases, so the program continued to half-cycle and diffmax was checked. For phase A, the value of diffmax was equal to 0.989 at half-cycle number 1, i.e. greater than the threshold value of 0.1. The CCR was then checked, it was 0.19 as shown in Fig 6-c, i.e. less than the threshold of 0.8 which means that it was an inrush condition at the first half-cycle current. When TMR changed to 2 (even numbers), diffmax and CCR were -0.06 and 0.65 respectively. Since that PAD was less than 30%, it was considered as inrush at the second half-cycle. However, the algorithm can be followed using flowchart that shown in Fig 5. The algorithm was able to effectively detect this condition.

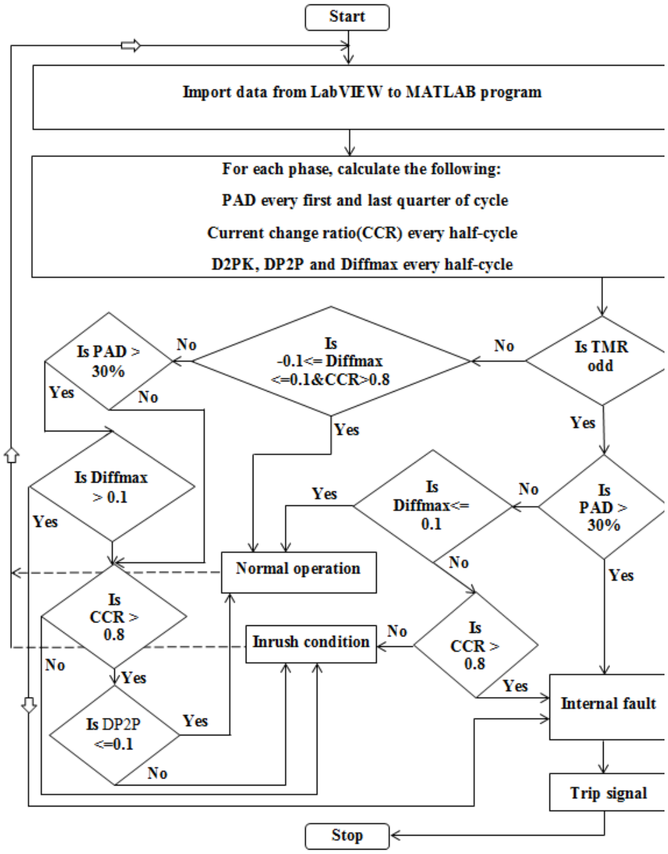


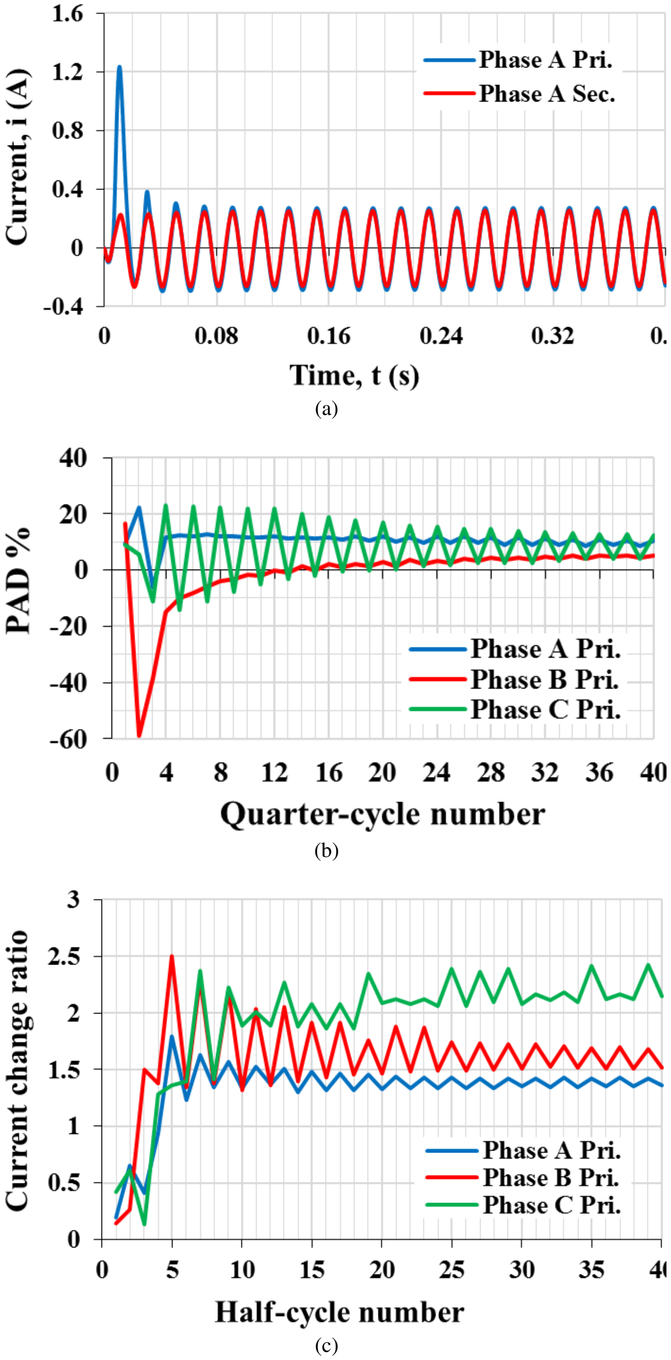
Fig 5 Flow chart for the MATLAB algorithm based on PAD and CCR

3) Interturn fault with inrush condition: Transformer switching on with turn-turn (interturn) fault also resulted in a clear area difference between primary and secondary currents at the first quarter of the signal. This difference increases when more turns are damaged (more turns are short-circuited). Four turns on primary side of phase A were short-circuited as an interturn fault then the transformer was switched on. Obviously, the effect of inrush current was still predominant as the fault was a minor fault and submerged to the inrush particularly at the first cycle as shown in Fig 7-a. This makes a big challenge for the suggested algorithm to detect this minor fault.

Looking at the results that obtained from processing this case, it was clear that PAD of faulty phase A at the first and last quarter of each cycle was greater than 30% due to this fault as shown in Fig 7-b. According to the flowchart of the algorithm shown in Fig 5, this internal fault was detected after the first quarter of the cycle i.e. just 5 ms from the moment of transformer switch on.

At the first half-cycle of current signal on phase A, the Diffmax value was greater than 0.1 and also the CCR was less than 0.8. This was because that the fault was not large enough to change the shape of the inrush current signal into sinusoid and hence the signal was still having the shape of inrush. This means, if there was no PAD, it would be considered as a fault.

However, there was no need for algorithm to check the CCR as the PAD at the first quarter-cycle made the algorithm sending a trip signal not to continue to the half-cycle for checking the CCR. [21]

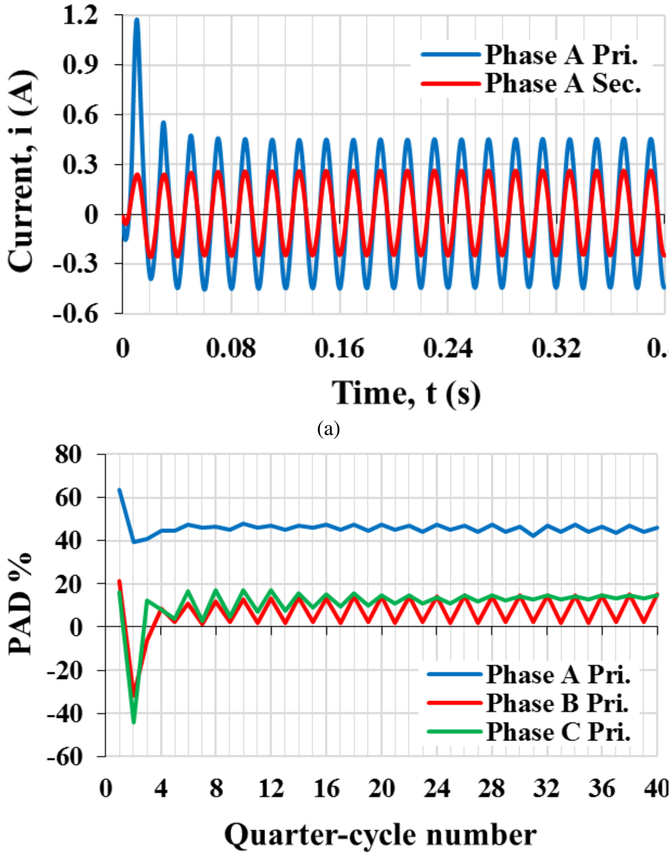


(a)

(b)

(c)

Fig 6 On-load transformer was energized without fault (a) Current waveforms (b) PAD (c) CCR



(a)

(b)

Fig 7 On-load transformer was energized with interturn fault on phase A (a) Current waveforms (b) PAD

4) Turn-ground fault with inrush condition: The loaded transformer was switched on with turn-ground fault on primary side of phase A. Although the inrush current was high at the first cycle, the fault was able to noticeably enforce the shape of inrush to be closer to sinusoid as shown in Fig 8-a. Since that the fault had submerged to the inrush which was a predominant feature at the first cycle, it makes discriminating this case too difficult for protection algorithms. This was also a challenge for the suggested protection algorithm.

This fault made PAD high at the quarters of each cycle on faulty phase A as shown in Fig 8-b. It was 64.82% at quarter-cycle number 1 which means that the fault was detected at the first quarter of current cycle.

As the influence of inrush was still exist in phase B which was not affected by the fault, it can be seen that its PAD was always under 30% while CCR in both phases, B and C was below 0.8 at half-cycle numbers 1, 2 and 3 as shown in Fig 8-c.

The DP2P for all phases dropped to less than 0.1 at cycle number 2. It means that inrush ended after one cycle and a half then normal operation started at second cycle or half-cycle number 4.

Since the fault occurred on phase A, Diffmax did not go back to its normal operation value and remained greater than 0.1 as shown in Fig 8-d. [21]

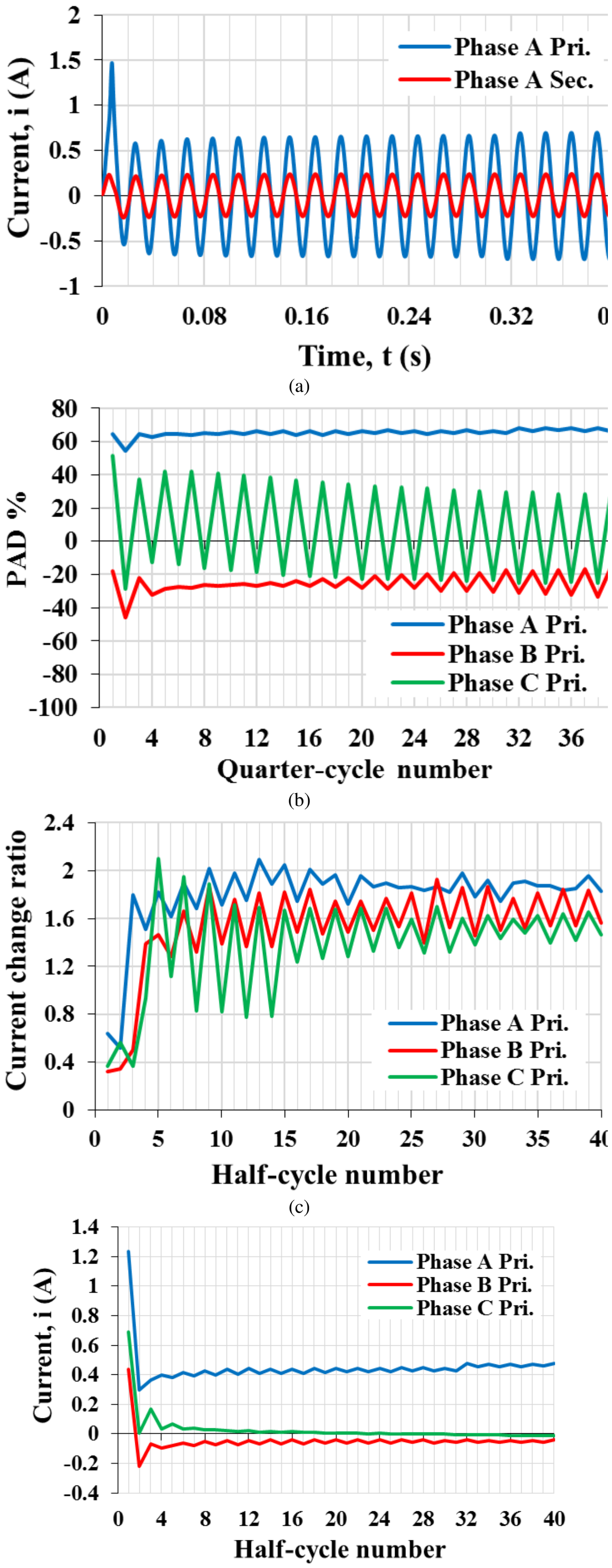


Fig 8 On-load transformer was energized with turn-ground fault on phase A (a) Current waveforms (b) PAD (c) CCR (d) Diffmax

V. CONCLUSION

In this paper, two methods CCR and PAD were proposed to solve the mal-operation problem that occurs in differential protection system of transformers. Several experiments were carried out in laboratory to test the efficiency of these methods. It was proved that these methods were fast, efficient and reliable in discrimination between inrush and internal fault signal as presented in the paper. The response time of the methods was 10 ms for CCR when transformer was at no-load and 5 ms for PAD when the transformer was on-load. This response time is faster than the most popular method, the second harmonic which needs at least one cycle (20ms at 50 Hz systems) to recognize the disturbance. The proposed methods were able to detect turn-turn fault although it was applied to a small-scale model transformer. Certainly, the methods will be more efficient if they are implemented on larger transformer which means significant increase in the turn-turn fault current. The two methods have shown a very high accuracy and all the tests performed on the transformer gave high repeatability levels.

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