Improved Transformer Differential Protection by Adaptive Pickup Setting during Momentary Over-Fluxing Condition

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Abstract. *The differential relaying scheme is universally adopted as the main protection for power transformer. In certain situations, like temporary over-fluxing, this differential protection may malfunction. This is due to unbalance in primary and secondary current, as the saturated core does not reflect equal ampere-turn on either side. This article presents detection of over-fluxing condition against the internal fault based on the fifth harmonic component of differential current. As per the estimated level of the fifth harmonic concerning the fundamental component of differential current, the pickup setting of percentage bias characteristic will be modified to avoid maloperation. Once the over-flux condition is sensed, the algorithm activates timer-based V/f protection to protect the equipment. The proposed algorithm is validated on PSCAD™ software and after the collection of data, MATLAB software is used for further validation. The proposed algorithm is validated under various test conditions like normal load, external fault, internal fault, and over-fluxing. It is observed that the algorithm accurately detects internal fault in the transformer or blocks the relay operation under momentary over-fluxing situations. Further, to assassinate the competency of the proposed scheme, a practical test is performed on a single-phase transformer available in laboratory. The data for various test cases are captured with the help of DSO, and the collected data has been migrated to computer where the proposed algorithm is examined. After analyzing all the results, it is cleared that the proposed algorithm can prevent transformer isolation during momentary over-fluxing conditions.*

Keywords

Differential relay, fault, harmonic components, MDFT, over-fluxing, power transformer.

1. Introduction

A transformer is a very imperative part of the power system. A nonlinear inherent property of the core may cause over-flux or over-excitation situations in the transformer. Moreover, a change in V/f ratio of the transformer and subsequent over-flux condition arises from various phenomena like sudden load cut off, generator running on low frequency due to inadequate mechanical power, tripping of a heavily loaded transmission line, improper shunt compensation etc. There are some dedicated protections available like V/f relay preventing the transformer from the hazardous effects posed due to the above-mentioned situations. However, the severity of over-fluxing condition may breach the balance between primary and secondary side currents of the transformer, and false operation of the differential protection scheme may result. So, it is indeed a proactive need to provide adaptive pickup characteristics under the momentary over-fluxing situation to avoid malfunctioning of the differential protective scheme.

The setting of over-fluxing relay (V/f) is normally adjusted to 1.1 to 1.3 per unit [1] with adjustable time delay under temporary disturbance. Despite having this protective measure, the raise of imbalance between primary and secondary side currents may activate the differential protection relay. Furthermore, some inter-harmonics and voltage notching are generated in the system when sensitive loads are removed from the terminal end of the transformer. The electrical isolation of the transformer is also not able to remove these voltages [2]. Xiangning Lin et al. mentioned in their book [3] on page 3 that the V/f protection scheme will issue trip signal if this ratio (V/f) exceeds 1.1 per unit. They have specified that these types of situations arise slowly, and it is considered as one type of incipient fault. Also, they have stated that if the over-flux is detected, transformer should be isolated. However, if the condition is momentary, then immediate tripping is an undesired condition. IEEE standard allows over-flux situation up to 1.25 per unit [4].

With the help of flux locus [5], transformer magnetizing condition is well defined. Increment of flux in power transformer is also one of the most effective parameters that are utilized to detect winding and faulted phase [6]. The bright side of flux related algorithm is that it does not require hysteresis data and analysis due to time-domain operating conditions. With the help of core magnetic flux characteristics [7], power transformer protection is also suggested as an improved conventional protective scheme. Ratio of flux linkages in both primary and secondary sides of the core is also an important parameter for the transformer protection. Using comparative analysis like ratio of the flux linkages, an algorithm is proposed for transformer protection [8]. Similarly, fluxional current is also an important function to provide protection [9]. Even all in one unique protective scheme for transformer is suggested in research article [10] including CT saturation, over-voltage and over-fluxing conditions to avoid maloperation with stability consideration. However, such scheme also falsely operates during flux-based protection because of a lack of preventive measures.

Then, over-current and over-fluxing conditions have been addressed by transformer numerical Inverse Definite Minimum Time (IDMT) based relaying scheme in [11]. Although the IDMT-based relay prevents false operation against immediate tripping during over-flux condition, it will delay main protection. A novel algorithm with ultra-saturation detection of transformer has been proposed by Bahram Noshad in [12]. In this article, the algorithm only detects ultra-saturation condition of the transformer with the help of Discrete Wavelet Transform (DWT), and makes the relay restrained. However, consequences during extra high saturation phenomena and during persistence of the ultra-saturation for a long time were not clarified. Neha Bhatt et al. [13] presented causes and effects of over-fluxing in transformers and compared various techniques for its detection. Estimation of current in a saturated transformer has been proposed in [14]. Here, authors have used extended Kalman filter and Gauss-Newton method for estimation of current. However, they have used various assumptions in their proposed work which is not always possible to presume.

Harmonics are capable of discriminating inrush and fault conditions with proper analysis of harmonic interference [15]. Inrush detection technique based on the second harmonic content is compared with various techniques like cross blocking technique, average percentage blocking process, harmonic sharing system, and shows its effectiveness for inrush discrimination [16]. Harmonics are also generated during geomagnetic disturbance and based on that, transformer monitoring and its analysis can take place [17]. Abbas Ketabi et al. [18] have analyzed impact of various factors on transformer switching overvoltages. They have also analyzed the duration of overvoltages during various situations. Harmonic blocking and restraint techniques for transformer differential protection have been proposed in [19].

Self-adaptive transformer differential protection scheme is elaborated in [20], with slope shifting ability of percentage bias characteristics. However, overfluxing criteria remain untouched in protective framework. Even, most of the researchers proposed their work on V/f based technique [21] to tackle overfluxing condition. Maheshwari et al. [22] stated over-excitation condition detection with the help of the fifth harmonic-based technique in their work. However, in the proposed algorithm, only the relay restraint feature was mentioned, and if the internal fault exists during that time, then the suggested scheme cannot detect it.

In this article, adaptive basic pickup setting of percentage bias differential relay is proposed to prevent maloperation of the transformer protective scheme during momentary over-fluxing conditions with the help of the fifth harmonic component of differential current. This technique introduces less complexity and minimizes a calculative burden with a higher proactive impact. The proposed technique is competent enough to prevent immediate differential tripping during the momentary over-fluxing conditions. Moreover, V/f protection is activated simultaneously to tackle the transformer in continuous over-fluxing situation without affecting the operation of the differential relay. It is operated simultaneously with percentage bias differential protection after detection of over-fluxing condition.

The article is structured as follows. Section 1. briefs general information and work carried out by researchers. Section 2. describes the system diagram and related details. Section 3. explains the proposed technique with the formulation. Section 4. demonstrates result validation and its analysis. Last, a practical test on hardware prototype with results is briefed in Sec. 5.

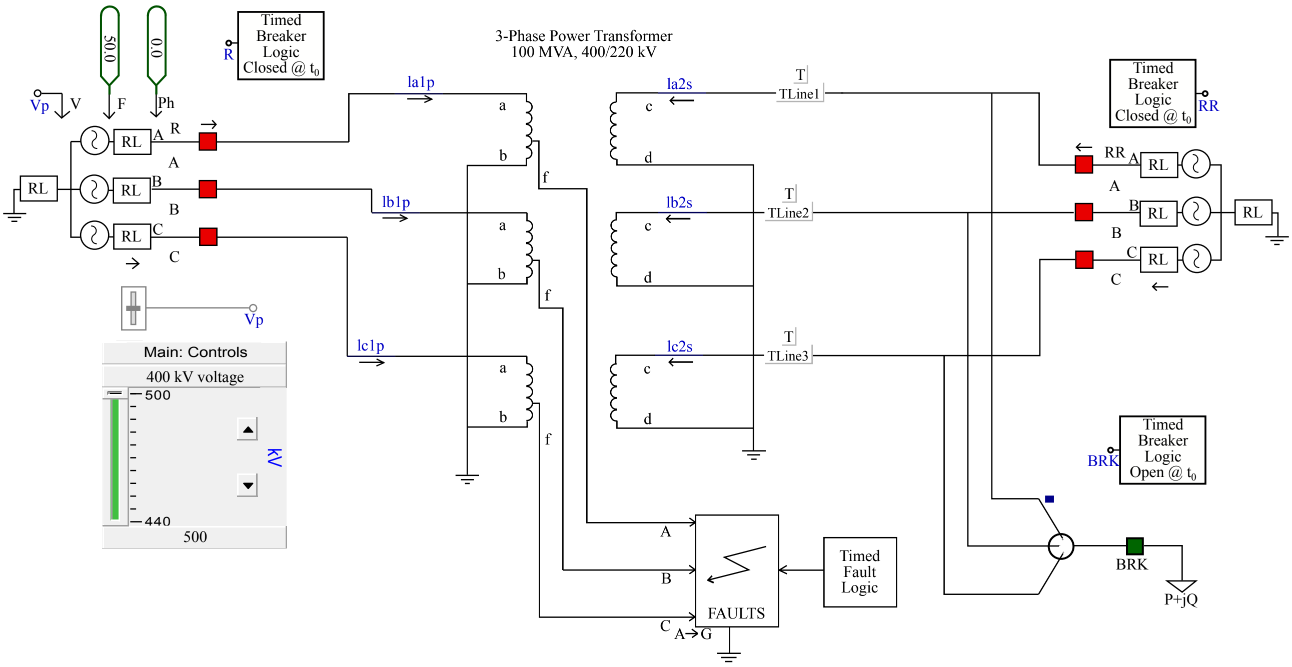

Fig. 1: Schematic line diagram of Indian power system.

2. Simulated System for Validation of the Proposed Technique

Figure 1 shows a system diagram of the Indian power system with a YY connected transformer, having a rating of 400/220 kV, 100 MVA, 3-phase (3 single-phase), 50 Hz. This power system is simulated in PSCAD software to validate the proposed algorithm developed in MATLAB. 400 kV side of the transformer is connected with a generator. In contrast, secondary side of the transformer is connected to load and 220 kV, 80 km transmission line. Various test cases of normal load on secondary side, external faults and internal faults are simulated by changing fault parameters. Moreover, over-fluxing cases are created by gradually varying primary voltage using variable input slider, as shown in Fig. 1.

3. Problem Statement and Proposed Algorithm

Due to various factors, the transformer core becomes saturated, and leads to an over-excitation condition of the transformer. Moreover, when the over-excitation condition arises due to increased winding voltage, the corresponding current also increases up to some extent. After that, the increment in current will no longer take place due to core saturation. However, the corresponding secondary side current does not exactly reflect as per the primary winding current of the transformer properly, due to the saturation state of the transformer core. Hence, the balance between primary and secondary current at relay junction will be lost and the differential current will be produced. This differential current, without having internal fault condition, may lead the differential relay to mal-operate.

Figure 2 illustrates the proposed algorithm to prevent maloperation of transformer differential relay during the over-fluxing condition. First of all, the current from both the sides of the transformer is fetched from the secondary sides of CTs. With the help of Modified Discrete Fourier Transform (MDFT) [23], differential current (I_{diff}; Eq. (1)), the biased current (I_{bias}; Eq. (2)), fundamental and the fifth harmonic components of the I_{diff} has been calculated.

Further, the disturbance in the transformer has been identified with the help of differential and restraining current ($I_{diff} > K_1 \cdot I_{bias}$, where K_1 is the slope of the differential relay and it is taken 30 % [24]). If this condition is satisfied, then only further investigation is required. If the above-mentioned condition is not satisfied, then the condition is of normal or external fault and the algorithm will then return to the first step. Now, if the differential current (I_{diff}) is greater than K_1 times the restraining current (I_{bias}), then the algorithm will further check whether the condition is over-excitation or real internal fault.

As per the author's investigation and with reference to [19], if the fifth harmonic component of differential current is maintained within 25 % of the fundamental current, the over-excitation condition is acceptable, i.e., the transformer can withstand that much over-excitation. Hence, if the ratio of the fifth harmonic component of differential current to the fundamental component of a differential current falls within 25 %, then the case is considered as an internal fault condition, a trip command should be immediately issued and the considered transformer should be isolated from the system. Contrary, if this ratio rises above 25 %, then the condition is interpreted as an over-flux condition and the *basic current setting* of the differential relay should be modified (shift up) to prevent maloperation of the transformer differential relay. The biased current setting (slope) is not shifted as its alteration depends on CT performance.

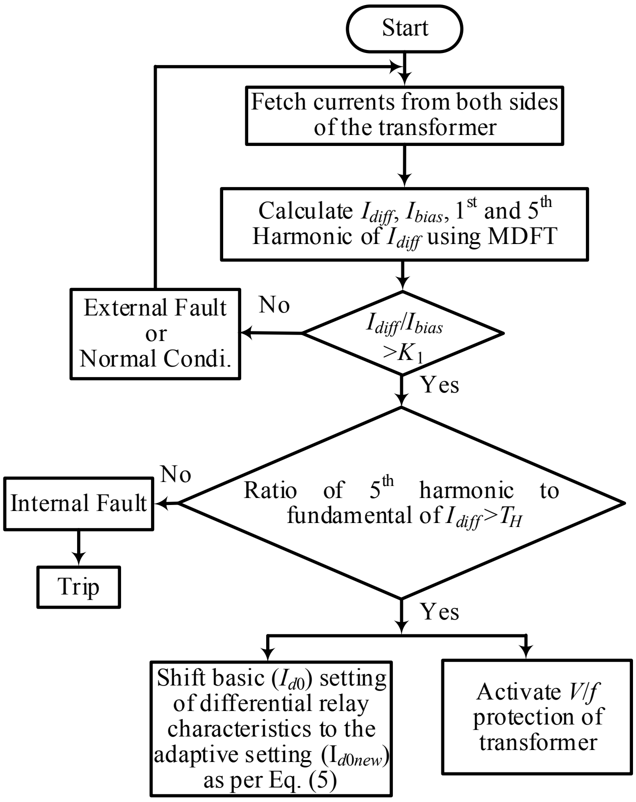

Fig. 2: Flowchart of the proposed algorithm.

Moreover, V/f protection should be activated simultaneously to protect the transformer core from hazardous effects due to over-fluxing/excitation conditions. The following calculations are derived using MDFT to validate the proposed scheme in MATLAB software:

$$I_{diff} = I_p - I_s, \tag{1}$$

$$I_{bias} = \frac{I_p + I_s}{2}, \tag{2}$$

where I_p and I_s are the primary and secondary side currents of the transformer.

The modification of the basic current setting (pickup current) of the transformer differential relay can be carried out using a ratio of the fifth harmonic component of differential current to the fundamental component of differential current denoted as S_m:

$$S_m = \frac{5^{\text{th}} \text{ harmonic of } I_d}{\text{fundamental component of } I_d}, \tag{3}$$

$$\Delta I = (S_m - T_h)\, I_{d0}, \tag{4}$$

where ΔI is the change required in setting due to over-fluxing, T_h is the threshold (25 %) defined as discussed above and I_{d0} is the basic current setting.

Hence, the new basic current setting can be defined as:

$$I_{d0new} = I_{d0} + \Delta I. \tag{5}$$

The parameter value in Eq. (5) is the estimated new basic current setting for the differential relay. This basic current setting of the differential relay has been adaptively shifted at the time of higher fifth harmonic and will prevent the relay maloperation from the over-fluxing condition.

4. Software Result Analysis and Its Discussion

4.1. Performance of the Proposed Technique during Normal/External Fault Condition of the Transformer

During normal or external fault condition of the transformer, normal current will flow from the transformer primary and secondary winding and, hence, the magnitude of differential current will remain nearly zero, as shown in Fig. 3.

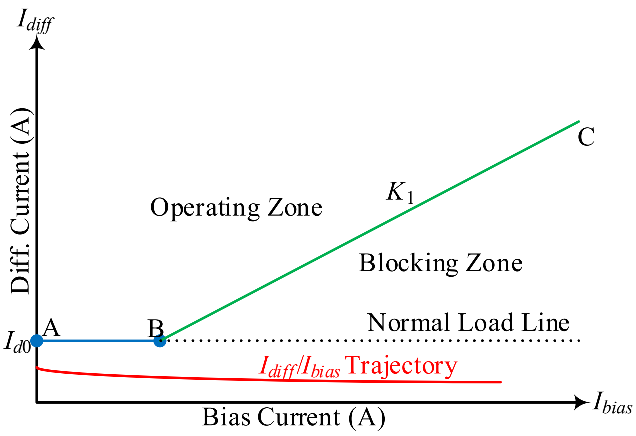

Fig. 3: I_{diff}/I_{bias} trajectory during normal/external fault condition.

From Fig. 3, one can observe that during normal and external fault conditions, the I_{diff}/I_{bias} trajectory (red line in Fig. 3) remains well below the defined

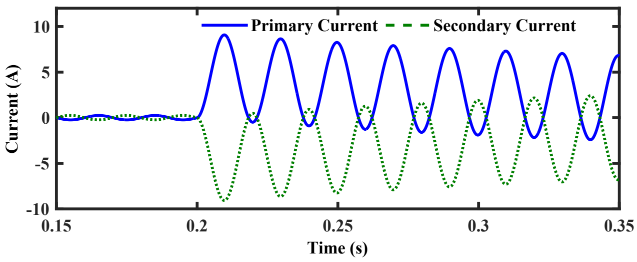

Fig. 4: Transformer primary and secondary side current (CT secondary) waveforms during normal condition (up to 0.2 s) and external fault condition (0.2 s to 0.35 s) with decaying DC component of fault current.

operating boundary, i.e. I_{d0} and slope K_1 which is the desired condition of a protection system. Hence, further attention is not required in this case.

Figure 4 shows primary and secondary side current waveforms on CT secondary of the considered transformer. The External fault is initiated at 0.2 s, as can be seen from Fig. 4 where the magnitude of both primary and secondary side current increases after inception of external fault condition. However, the rise in magnitude of primary and secondary side currents is equal and opposite which will cancel out rising impact of each other and resultant differential current will remain the same (i.e. ≈ 0). Hence, during external fault or normal condition, the transformer protective scheme remains inoperative.

4.2. Performance of the Proposed Technique during Internal Fault Condition of the Transformer

From Fig. 5, it can be noted that during internal fault condition, the I_{diff}/I_{bias} trajectory (red line of Fig. 5) immediately crosses the defined blocking limits and enter into the operating region. This will activate the differential relay to trip the circuit breakers. Although this is the desired condition for the protection engineer as per the algorithm (Fig. 2) of the proposed technique, the condition of the over-flux will be checked as per the Eq. (3). Further, if the over-flux is less than the defined threshold (25 %), then only the relay will decide it as an internal fault condition and successfully issue a trip signal. On the other hand, if the estimation of over-flux as per Eq. (3) exceeds the predefined threshold, it will activate the V/f protection of the transformer and simultaneously will prevent differential relay maloperation by shifting the basic setting of the characteristic which is further elaborated in subsequent section.

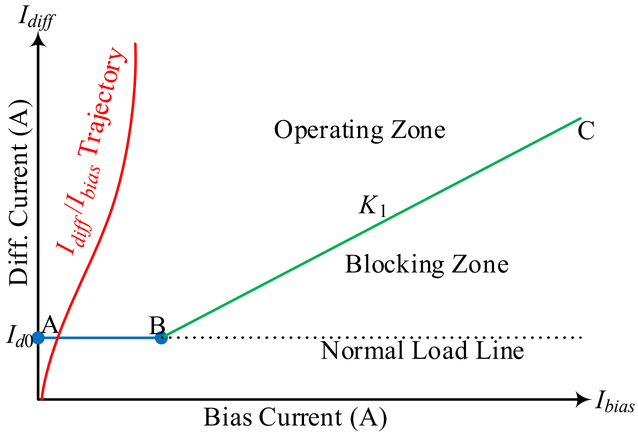

Fig. 5: I_{diff}/I_{bias} trajectory during internal fault condition.

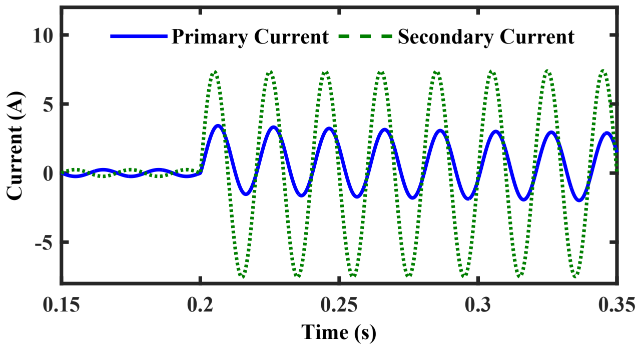

Fig. 6: Primary and secondary side current waveforms during internal fault condition of the transformer.

4.3. Performance of the Proposed Technique during Over-Fluxing Condition of the Transformer

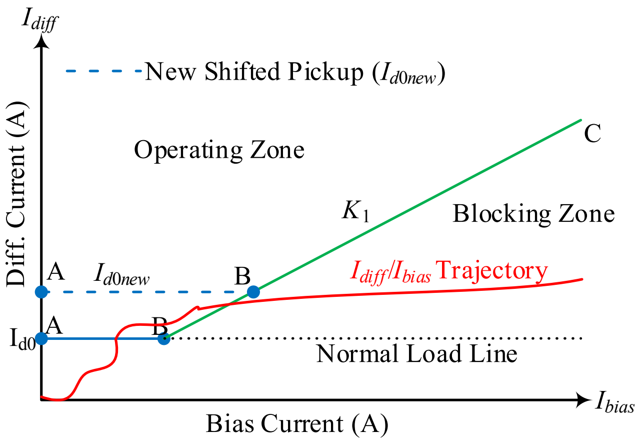

Fig. 7: I_{diff}/I_{bias} trajectory during over-fluxing condition.

If the transformer encounters over-fluxing due to increase in voltage or decrease in frequency, then the proposed algorithm will prevent immediate maloperation of the differential relay by adaptively modifying the basic pick up setting of the differential relay.

As shown in Fig. 7, when over-excitation is detected by the proposed algorithm as per Eq. (3), then the technique will adaptively change the basic pick up setting of the differential relay as per the Eq. (5). During over-excitation condition, the I_{diff}/I_{bias} trajectory (red line in Fig. 7) crosses the old basic pickup setting (continuous blue line AB at I_{d0} in Fig. 7). This escorts maloperation of the differential relay which is an undesired condition in the protection system. Hence, during over-fluxing condition of the transformer, the proposed technique will adaptively modify the basic pickup setting of the differential relay (dotted blue line A'B' at I_{d0new} in Fig. 7) and prevents relay maloperation. Further, this technique simultaneously activates the V/f protection and hence, if the over-flux persists for a longer duration, then the necessary action will be taken by V/f relay. The proposed technique only prevents maloperation against immediate tripping of the differential relay during short time rise of core flux.

Figure 8 shows primary and secondary side current waveforms of the considered transformer during over-fluxing condition as implemented on primary side. The over-fluxing is applied at 0.1 s by applying a sudden rise in primary side voltage. As a result, the magnitude of primary side current and secondary side current is not balanced. This type of situation is interpreted as an internal fault condition by the simple differential protection scheme of the transformer and results in the isolation of the transformer. The situation is actually not an internal fault and can be bearable by the equipment up to some extent. The severity of the over-flux is measured in the proposed article and corresponding actions are also mentioned in the proposed algorithm.

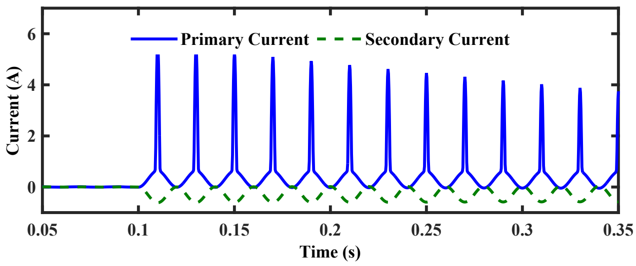

Fig. 8: Primary and secondary side current waveforms during over-fluxing condition of the transformer.

5. Hardware Setup and Its Results Discussion

A single-phase transformer having capacity 1000 VA, 220/110 V, multi tapping on both sides is considered. The hardware prototype is developed in laboratory as displayed in Fig. 9 and Fig. 10. Various controlling and measuring equipment like voltage variac, contactor as circuit breaker, digital ampere meter, Digital Storage Oscilloscope (DSO), current sensors etc. are used to measure and acquire current quantities of the considered multi tapping transformer.

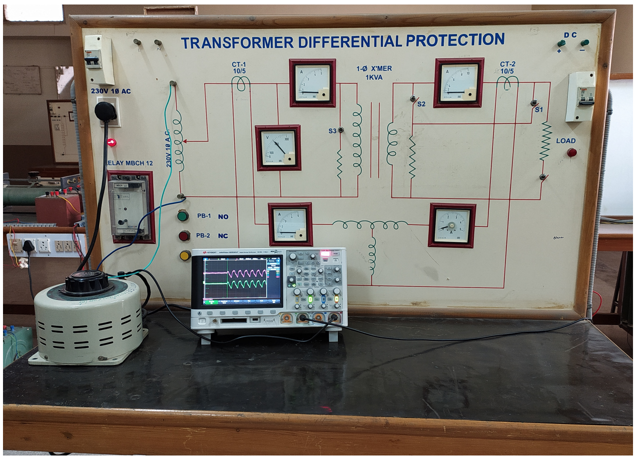

Fig. 9: Front view of the developed hardware for practical test.

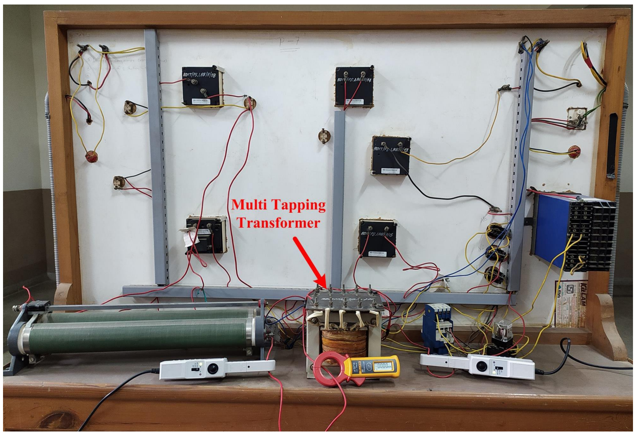

Fig. 10: Rear view of the developed hardware for practical test.

Various test cases have been implemented on the developed hardware setup and the waveforms captured in DSO have been displayed in the figures below.

5.1. Current Waveform During Internal Fault Condition of the Transformer

The internal fault is created through substantial resistance by closing switch S2 as shown in Fig. 9, i.e. on the secondary terminal of transformer. The internal faults have been created between two current sensors on the tapping provided on the transformer windings. It has been observed that the current waveforms captured in DSO are in phase during internal fault condition. The captured/sampled current data in *.CSV file of DSO is migrated and buffered into the computer memory. Later, the stored sample data of the hardware currents are utilized to validate the proposed algorithm developed in MATLAB.

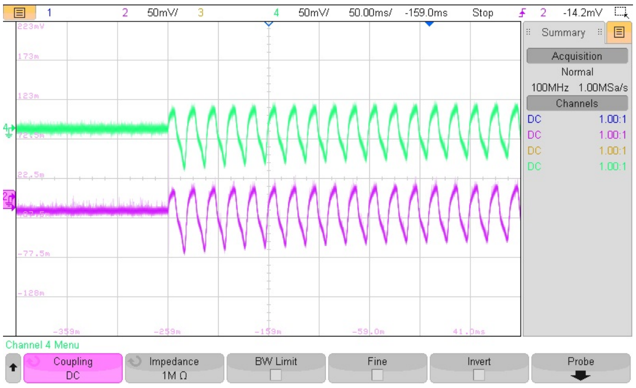

Fig. 11: DSO current waveforms during internal fault condition of the transformer.

5.2. Current Waveform during External Fault Condition of the Transformer

The external fault is created through substantial resistance by closing switch S1 as shown in Fig. 9. The external faults have been created outside the location of current sensors. As shown in Fig. 12, the captured current waveforms are equal in magnitude and out of the phase in the case of external fault condition. This condition does not satisfy the differential logic set in the proposed algorithm and the relay remains inoperative.

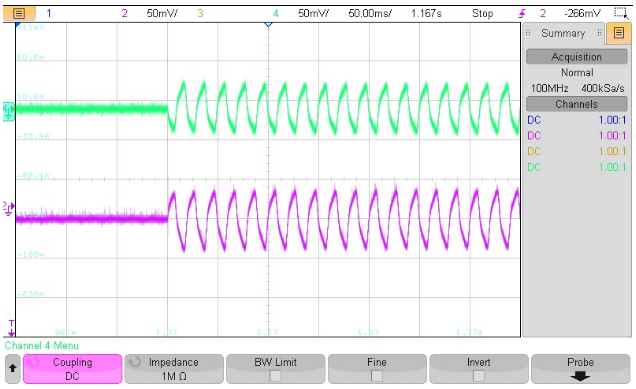

Fig. 12: DSO current waveform during external fault condition of the transformer.

5.3. Current Waveform During Continuous and Momentary Over-Fluxing Condition of the Transformer

Figure 13 shows the current waveform during over-excitation condition implemented on practical transformer. As mentioned in the article, over-excitation condition takes place only when the ratio of V/f is getting disturbed. The frequency of the power system is nearly constant to 50 Hz for Indian power system network and hence only one factor "voltage" that can affect transformer excitation condition remains. The voltage variations will change the corresponding current of the particular transformer winding.

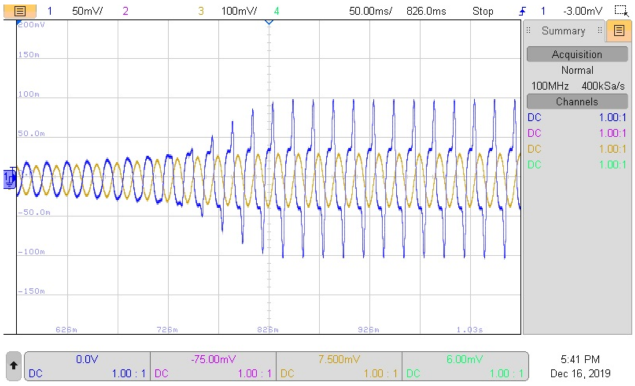

Fig. 13: DSO current waveform during continue over-fluxing condition of the transformer.

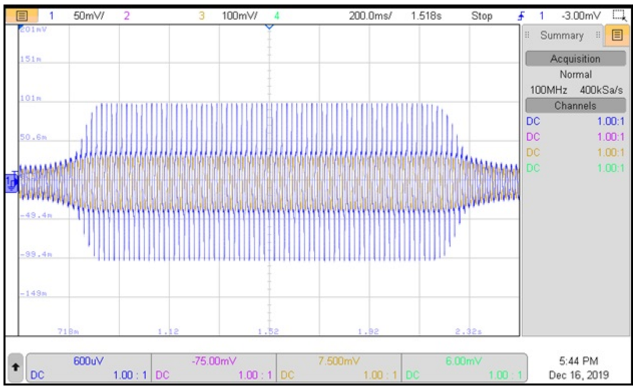

Fig. 14: DSO waveform during momentary over-fluxing condition of the transformer.

Here, by changing the applied voltage of the primary side by single-phase variac, the corresponding primary current (blue signal in Fig. 13) also increases. This increase in current will breach the balance between the primary and secondary side currents of the transformer and lead to maloperation of the differential protection of the transformer. Definitely, the V/f protection provided to the transformer will take care of this situation if over-fluxing persists for long term. But if the over-excitation condition is momentary as shown in Fig. 14, then the dedicated V/f protection will delay its operation and during that time frame simple differential relay may isolate the transformer. However, the proposed algorithm properly discriminates the over-fluxing condition and real internal fault to improve the reliability of the transformer.

The authors have proposed a preventive technique based on the fifth harmonic component of the differential current to identify the intensity of the over-excitation condition and, with the help of adaptive basic pickup setting, to retain the false tripping of the transformer.

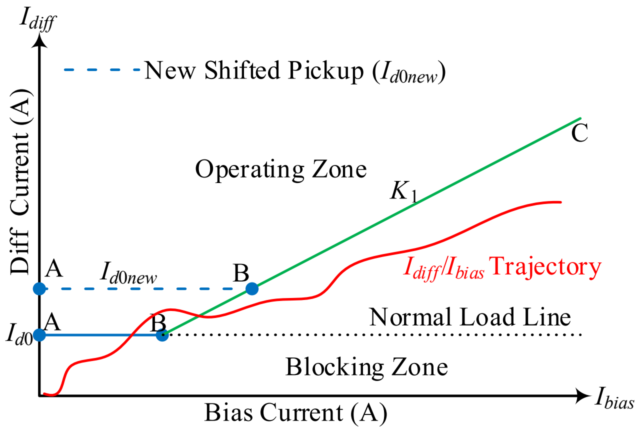

Fig. 15: I_{diff}/I_{bias} trajectory during practical over-fluxing test.

Authors have used this hardware prototype for data acquisition purpose and the acquired data are evaluated in MATLAB software to validate the proposed algorithm for transformer protection. The result of the hardware prototype for an over-fluxing condition is also captured from the MATLAB software and has been displayed below in Fig. 15. It shows the I_{diff}/I_{bias} trajectory during the over-fluxing condition of the transformer for data captured from the hardware prototype. It is obvious from Fig. 15 that the trajectory crosses the original basic pickup setting (I_{d0}) of relay characteristic. Nevertheless, the modified pickup setting (I_{d0new}) prevents the mis-operation of the differential relay during such over-fluxing situation.

The proposed scheme has the following advantages:

- Calculation of the fifth harmonic component is faster than the V/f calculation.
- The adaptive shifting of basic pickup setting is enabling quickly as and when required.

Avoiding immediate operations of differential relay during the momentary over-excitation condition and activate time-dependent committed V/f protection.

6. Conclusion

Standalone unit protection for the power transformer improves reliability, stability, and security of the entire power system. The over-fluxing in the transformer is probably occurring due to 'overvoltage' or 'under frequency'. This situation may result in an imbalance of both side currents of the transformer and rise in differential current and may lead to maloperation of the protection scheme. Therefore, the differential protection must be restricted under this short span of over-fluxing conditions to maintain the system stability and load continuity. A lot of fifth harmonics are produced in current during over-excitation and this fact is utilized in this article to stabilize the differential relay against an unwanted operation. The algorithm continuously checks the ratio of the fifth harmonic to a fundamental component of differential current to adaptively shift the basic setting of differential relay. One of the major advantages of this scheme is avoiding immediate operation of the differential relay during an over-excitation condition and activating time-dependent dedicated V/f protection. With various parameter considerations, authors have simulated a part of a power system in PSCAD™ software and the algorithm is validated in M-code (MATLAB). Normal load, over-fluxing, external faults, and internal faults are created and validated on the proposed algorithm. Moreover, the developed algorithm is tested on a single-phase transformer in a laboratory for various faults and over-fluxing conditions. It should be mentioned that the proposed technique operates within 47 ms in case of in-zone fault and within 50 ms to activate the V/f protection to safeguard the transformer. Thus, it provides an effective solution to prevent the mal-operation and discriminate an over-fluxing phenomenon contrast to faulted situation in the power transformer.

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