AN IMPROVED DESIGN OF SUPERVISED DIFFERENTIAL RELAY FOR POWER TRANSFORMER WITH REDUCED MALFUNCTIONING

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ABSTRACT *This paper proposes an improved design of Supervised Differential relay for power transformer protection by eradicating the malfunctioning due to the sympathetic inrush during parallel transformer bank energization phase, and magnetizing inrush currents during transformer excitation. The proposed strategy distinguishes among the internal and external faults, sympathetic inrush, and magnetizing inrush situations based on the harmonic contents and magnitude of the current. The convergence of the suggested algorithm is achieved by constraining it into a non-random mode. The algorithm has been simulated in MATLAB and validated using compatible hardware Tiva C Series TM4C123G LaunchPad. The results are additionally 2.5% more sensitive to faults, 4% operationally fast, and 6.5% better control in the relay malfunctioning over the conventional methods.*

Index Terms — Power Transformer, Differential Relay, Sympathetic Inrush, Magnetizing Inrush, Internal faults, Malfunctioning

I. INTRODUCTION

The existence of faults is inevitable in power system generation, transmission, and distribution. Protection devices are designed to overcome these unavoidable conditions. Transformer is one of the utmost significant and costly equipment in the power system. It is used to increase the reliability of the system and is the major component of power system that is used to increase or decrease the voltage levels so that transmission line losses might be reduced. Transformers are used at power generating stations to step up the voltage levels for the transmission purposes over long distances. At substations, transformers step down the voltage levels up to the extent that transmission lines can pass through the populated areas without the induction phenomenon [1]. Finally, distribution transformers are used to step-down the voltage levels for the load end usage. The inadvertent outage of a power transformer is expensive for utilities and hence requires suitable protection [2]. Transformers of rating above 10 MVA are usually protected with differential relay (DR) [3]. Differential protection is the primary protection for large power transformers. It is used for the unit protection of transformer. The DR is used most widely for the internal faults protection of transformer [4]. When a fault occurs in the power system, the transformer must be taken out of service so that its damage can be avoided. The costs of repairing an impaired transformer are usually very high. DR protects the transformer from internal faults and its boundaries are high voltage (HV) current transformer (CT) and low voltage (LV) current transformer. The power transformer is most widely protected from internal faults using a DR which is a precise and quick fault clearing procedure [5]. It works on the fact that the differential current will be high only when a fault occurs in between the boundaries of high voltage (HV) and low voltage (LV) current transformers. During a fault, the transformer must be isolated as soon as possible to prevent its damaging [6]. A differential protection is assumed to respond only to internal faults and avoid from tripping on magnetizing inrush, sympathetic inrush and external faults [7]. It takes the phasor current difference of HV and LV currents after referring secondary side of the transformer to primary side. If the difference is approximately equal to zero, then there is no fault in the system and no trip signal is given to the circuit breaker. However, if the difference exceeds a threshold value, a trip signal is given to open the circuit breaker (CB) on both sides of the transformer. Mathematically, differential current can be written as [8].

$$I_d = |\overrightarrow{Iw1} + \overrightarrow{Iw2}| \qquad (1)$$

Where I_d is differential current, I_{w1} is primary current and I_{w2} is secondary current. In ideal case, I_d is zero for the external faults and its value exists only for internal faults. The reason is that in case of external faults, the same current flows through the primary and secondary of CTs and so difference is zero. The differentiation between internal and external faults during transformer protection is shown in Fig. 1.

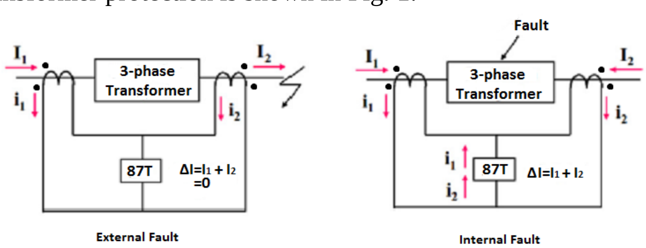

Fig. 1: Transformer Protection Schematic

Percentage differential relay has been used to protect the transformer in faulty conditions only, hence not regarding the conditions of inrush and overexcitation fault. Percentage differential relay uses the restraint current to determine whether there is a fault or not in power system. Mathematically, the restraint current I_{RT} can be written as [9].

$$I_{RT} = k\,|\overrightarrow{Iw1}\,\overrightarrow{Iw2}| \qquad (2)$$

Where, k is compensation factor and its value can be 0.5 or 1. A trip indication is given to the CB if I_d is greater than a particular percentage of restraining current I_{RT} [9].

$$I_d > SLP \times I_{RT} \quad (3)$$

Where, SLP represents the slope of the characteristics of DR. Percentage DRs perform well for internal faults i.e. inter-turn faults, bushing faults, single phase to ground faults, double line to ground faults, etc. However, false differential currents flow due to magnetizing inrush, and sympathetic inrush, etc. During sympathetic inrush and magnetizing inrush currents, the DR should not operate [8]. The conventional percentage DR operates and gives the signal to the circuit breaker. This is due to the false differential currents that appear during magnetizing inrush and sympathetic inrush conditions. Therefore, it is essential to determine these false differential currents and the differential relay should not give the trip signal to a circuit breaker on their basis because these are not the fault currents. These false currents are rich in harmonics. There are certain solutions to prevent the incorrect tripping of DRs. The first solution is to introduce an intended time delay in DR starting [10]. The second solution is to inactivate the DR for specific period; it is the time in which the inrush current is prominent. Nevertheless, these are not efficient techniques.

Ahmed [6] used Simulink to design the DR. Gupta [7] Used FPGA (Field Programmable Gate Arrays) based simulation of DR. Guzman, Zocholl, and Benmouyal [15] described harmonic blocking method based on wave shape recognition technique. These authors did not consider the sympathetic inrush problem. This paper proposes an effective solution for sympathetic inrush and magnetizing inrush condition.

This paper proposes an improved method to avoid the malfunctioning of DR due to sympathetic inrush, and magnetizing inrush currents for power transformer protection. We have devised an algorithm that decreases the malfunctioning. In addition, it increases the operational speed in comparison to conventional DR. Moreover, the algorithm is simple yet robust and the computation time is of the order of 2.8 μs, thus, it can be easily implemented using a conventional microcontroller.

II. BACKGROUND THEORY

A. Magnetizing Inrush Current

Magnetizing Inrush Currents are the maximum instantaneous input currents drawn by an electrical equipment when energized. The inrush current magnitude is almost (10-15) times of the nominal peak current [11]. The magnetizing inrush current is the consequence of sudden variation in the magnetizing flux. It has a DC component [12]. It happens only for a few cycles of the input waveform. Inrush current is rich in second harmonic [13]. The decision between the inrush and internal fault currents can be made on the basis of second harmonic component [11]. Inrush current increases with the size of transformer [14]. It gives rise to harmonics, insulation failure, and fast aging due to heating up of windings.

If the second harmonic component existing in the waveform is greater than a threshold value (standard thresholds are in-between 15 and 30% of the fundamental frequency), the differential protection is blocked [15]. Magnetizing inrush is shown in Fig. 2.

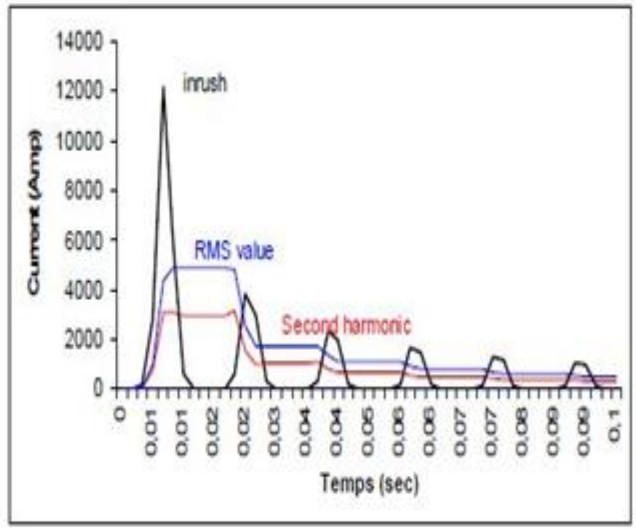

Fig. 2: Magnetizing Inrush current characteristics [9]

B. Sympathetic Inrush

Sympathetic Inrush is a phenomenon that occurs when a parallel transformer bank is energized which produces inrush current and it streams in a formerly excited transformer. The block diagram representation of sympathetic inrush is shown in Fig. 3 and 4 [12]. When CB of transformer T2 is closed then magnetizing inrush current streams in the primary winding of transformer 2, it is DC in nature and it flows through the transmission line and the voltage of bus-bar A gains a negative DC element. Thus, the inrush current flows in previously energized transformer 1 and sympathetic inrush phenomenon takes place. Therefore, the conventional differential relay used for the protection of T1 mal-functions. Like inrush current, it also has second harmonic component [1]. The sympathetic inrush contains 2nd harmonic component that is about 35-40% of fundamental component [16].

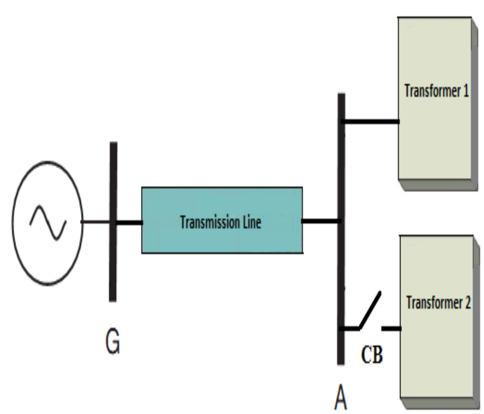

Fig. 3: Parallel transformer bank

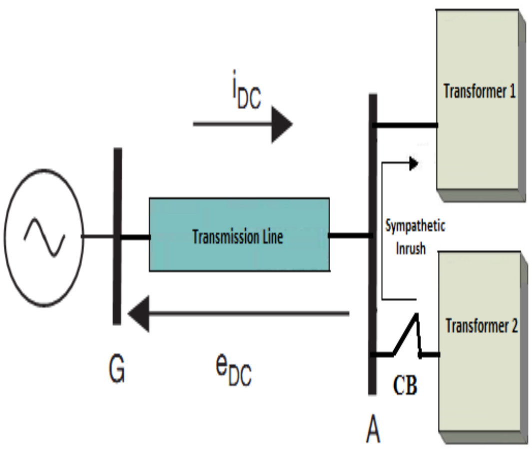

Fig. 4: Sympathetic Inrush current

III. DESIGN DESCRIPTION

The proposed algorithm makes decisions on the basis of primary and secondary side currents of transformer. First, the primary and secondary side currents are measured using the current transformer. Different ratings of current transformers are available in the market e.g. 25/5A, 50/5A, etc. It depends upon the specific requirement for which current transformer is to be used. Then the secondary side is referred to the primary side by using the turn ratio. It is due to the reason that the transformer steps down or steps up the voltage level. In this way, the current also increases or decreases respectively. To make both primary and secondary current equal, the current of secondary side is referred to the primary side. After that the secondary side current is delayed to equalize the phase change concerning the primary and secondary sides. To compensate on behalf of core loss, a multiplication factor is applied on the secondary [1]. Then the difference of the magnitudes of resulting values is calculated. In the normal case, the difference between the two currents is zero if CTs have the same turn ratio. During a fault, the difference is not equal to zero and if it is larger than pickup value of relay then the harmonic

content of the differential current is checked. For that purpose, fundamental, and 2nd harmonic components are measured and a comparison is made between fundamental and 2nd harmonic. If the 2nd harmonic component is more than the threshold limits for magnetizing inrush and sympathetic inrush, then these situations occur in the system. Hence, the algorithm does not give trip signal to circuit breaker in these cases. However, when 2nd harmonic component is less than the threshold limits and differential current is greater than the onset value then there is an internal fault between primary and secondary CTs and the algorithm gives trip signal to the circuit breaker to detach the power transformer from the power system. On the other hand, when there is no such fault conditions, the proposed algorithm repeats its cycle again and again until such fault is detected. Thus, the proposed algorithm is a cyclic process that continues to check that whether difference of current is greater than or less than the threshold limit. The flow diagram is shown in Fig. 5.

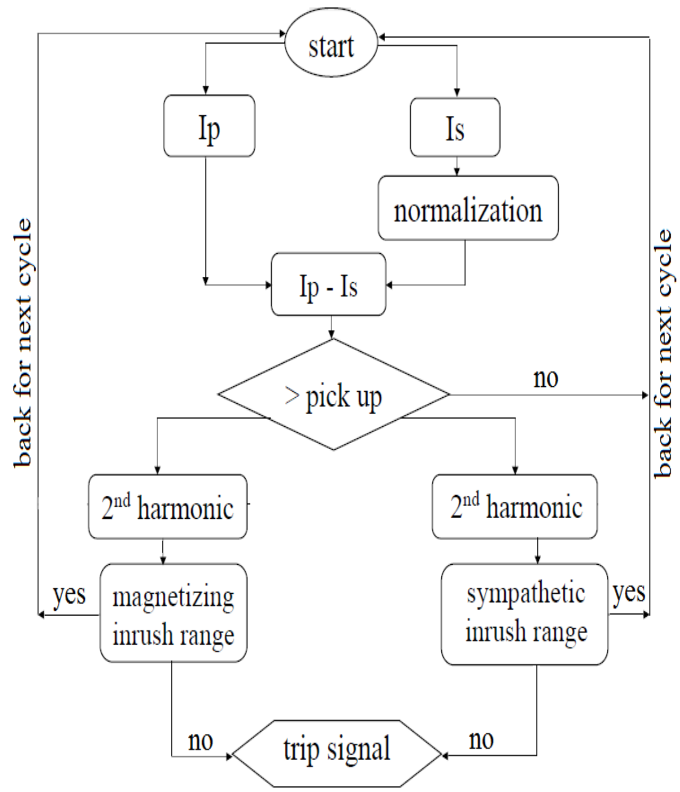

Fig. 5: Flow diagram of Supervised DR

IV. MODELING AND SIMULATION

The transformer under consideration for protection has the following specifications.

Table 1: Specifications of transformer under study

Manufacturer	ABB Company
Rating	20/26 MVA, 11/33 kV
Frequency	50 Hz
Cooling	ONAN/ONAF, 75/100%
Vector Group	YNd11
% Impedance	10%

The one-line diagram of power system simulated in Simulink is shown in Fig. 6.

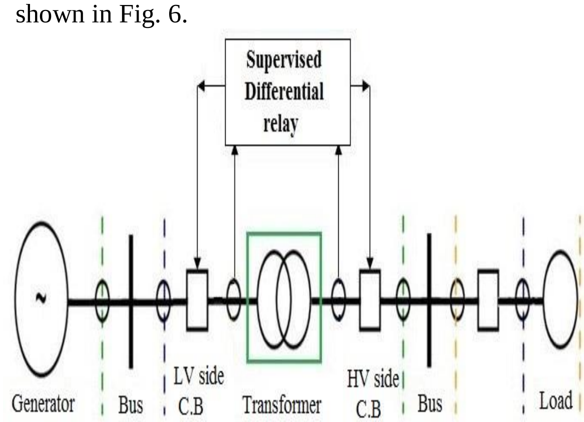

Fig.6: One-line diagram of MATLAB-Simulink model

V. RESULTS AND DISCUSSION

A. Case of No Fault

The three phase voltage measurements on the primary and secondary side during normal operation in power system are shown in Fig. 7 and 8 respectively. The magnetizing inrush current initially occurs for about 2.5 cycles and it is due to the energizing of the transformer. During this time, the algorithm detects the inrush current and does not give the trip signal to the circuit breaker.

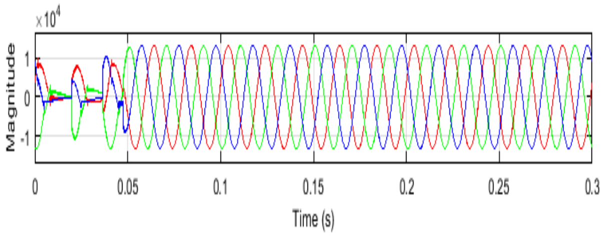

Fig. 7: LV side 3-Phase Voltages

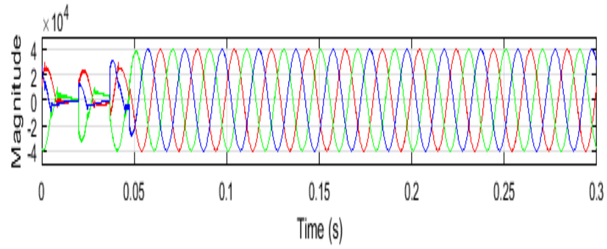

Fig. 8: HV side 3-Phase Voltages

B. Case of External Fault

When an external fault beyond the LV and HV 3-phase V-I measurement blocks is added from 0.1–0.2 seconds, the following results are obtained for phase A as shown in Fig. 9, 10, 11, and 12. A fault is an external fault when it occurs beyond the primary and secondary CT boundaries. When it occurs, the magnitude of voltages at that point approach zero and current increases to a large value. During an external fault, the magnitude of difference between currents of HV and LV sides is zero due to same increase in current on both sides of transformer. Due to the magnitude of difference less than the threshold limit, the differential relay does not operate for external faults.

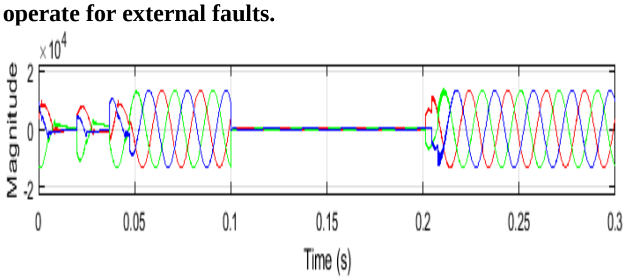

Fig. 9: LV side 3-Phase Voltages

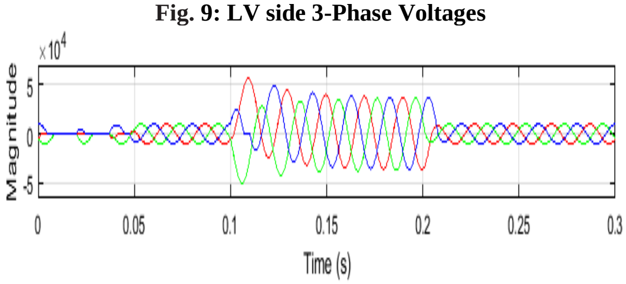

Fig. 10: LV side 3-Phase Currents

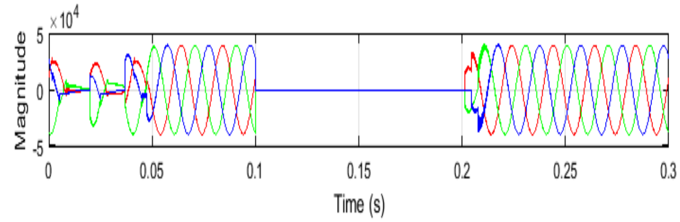

Fig. 11: HV side 3-Phase Voltages

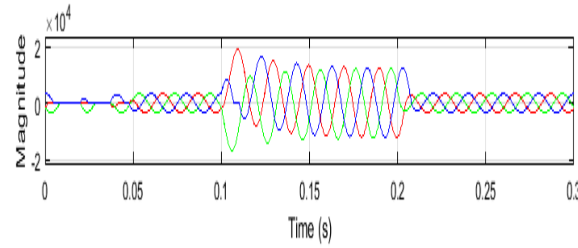

Fig. 12: HV side 3-Phase Currents

It can be observed that currents and voltages returned to the normal values after the fault has been acquitted via timer blocks. The same situation can be noticed for phases B and C.

C. Case of Internal Fault

When an internal fault between LV and HV V-I measurement blocks was added from time 0.05 – 0.1 seconds via timer block, the following results were obtained as shown in figures 13, 14, 15, and 16.

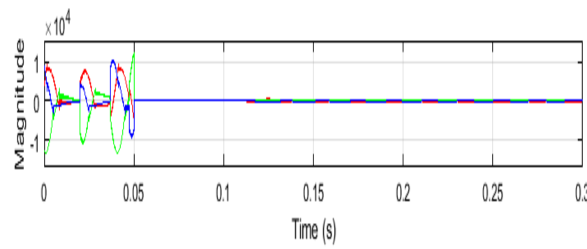

Fig. 13: LV side 3-Phase Voltages

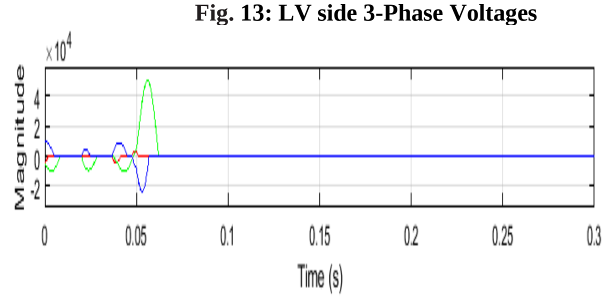

Fig. 14: LV side 3-Phase Currents

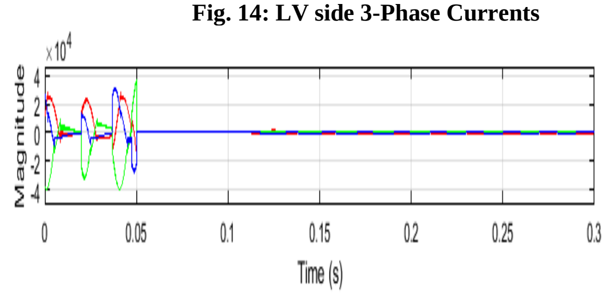

Fig. 15: HV side 3-Phase Voltages

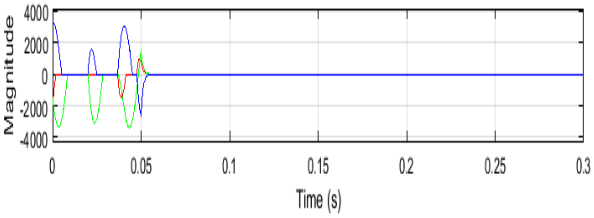

Fig. 16: HV side 3-Phase Currents

It can be seen that during internal fault, it took approximately half cycle for the algorithm to detect the fault and after half cycle, the trip signal was given to CB to open its terminal for the isolation of transformer from the system. Therefore, the voltages and currents became zero after half cycle of the occurrence of a fault. In this way, the transformer was protected from the internal fault.

D. Case of Magnetizing Inrush Current

When the transformer is energized, inrush current is produced. The RMS of the differential current waveform during inrush current is shown in Fig. 17.

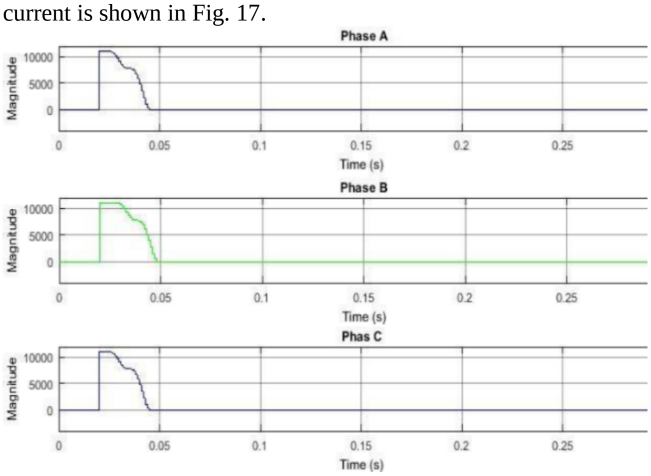

Fig. 17: Magnetizing Inrush Current

The spectrum for phase A inrush current is shown in figure 18.

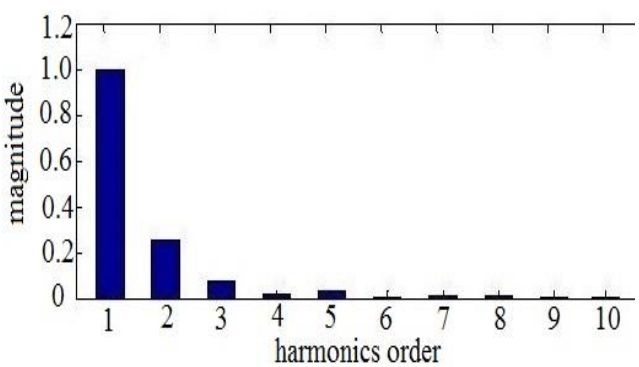

Fig. 18: Phase A primary current spectrum

It can be perceived that the second harmonic component is above the threshold value i.e. 20% of the fundamental. The algorithm detects it and no action is taken against this inrush current. Therefore, the proposed algorithm does not provide malfunctioning in the operation of differential relay. The spectrum shows that the 5^{th} harmonic component is only 5% that is below the threshold limit for overexcitation and so there is no overexcitation current.

E. Case of Sympathetic Inrush

In this case, the transformer T1 is already energized. When a transformer T2 parallel to transformer T1 is invigorated at 0.15 seconds, the sympathetic inrush current flows from in T1 from 0.15-0.2 seconds. The following figure shows the result.

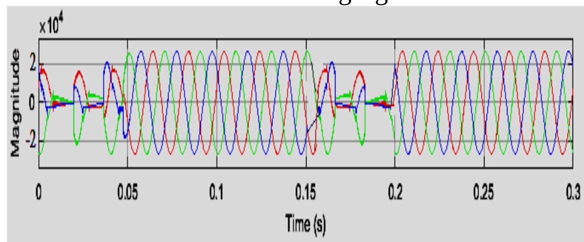

Fig. 19: LV side 3-Phase Currents

The RMS of I_d during sympathetic inrush is shown in Fig. 20. During sympathetic inrush, differential current rises very rapidly and then decreases to its normal value.

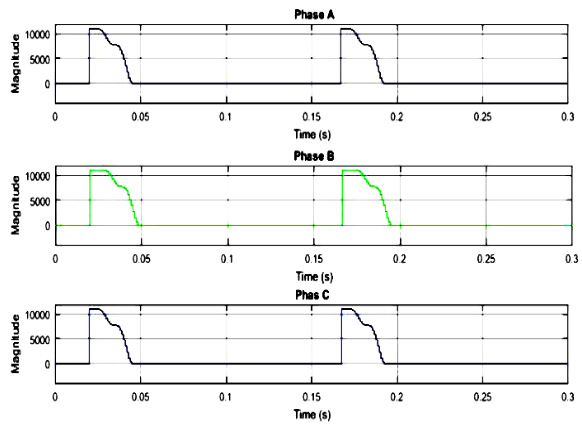

Fig. 20: RMS of differential current during sympathetic inrush

The algorithm detects the sympathetic inrush current based on threshold of 2^{nd} harmonic and prevents the malfunctioning of differential relay. Therefore, the system remains in service when a parallel bank transformer is energized. The results summary of proposed design is shown below.

Table 2: Results summary

Cases	Nature of Fault	Action Performed
Case A	No fault	No Action
Case B	External fault	No Action
Case C	Internal fault	Trip signal to CB
Case D	Magnetizing Inrush current/ Sympathetic inrush current	Malfunctioning of supervised DR was prevented

The obtained results are also validated using hardware as shown in the Fig. 21. The experiment is performed under the same conditions and limitations as previously described for simulation. The experimental results match precisely with the simulation. From both simulation and experiment, the dominance of proposed algorithm is approved by 2.5% increase in sensitivity, 4% increase in operation speed, and 6.5% better control in malfunctioning of DR over conventional designs.

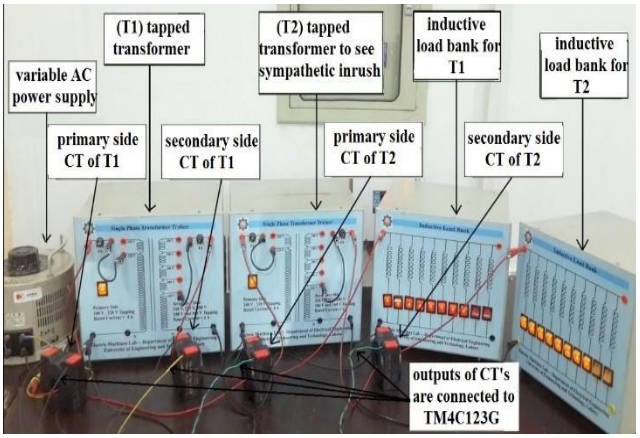

Fig. 21: Experimental set-up of proposed method

VI. CONCLUSION

In this paper, an improved design to avoid the malfunctioning of DR is proposed and implemented. It is shown that the proposed method works efficiently and effectively for reducing the malfunctioning by simulating the design in MATLAB and validating using TM4C123G LaunchPad. The results demonstrate that the proposed algorithm outperforms the conventional differential protection methods by having 4% faster decision capability, 2.5% increased sensitivity to faults and 6.5% better control in relay malfunctioning. It is envisioned that the proposed method can be very useful in the practical design of supervised differential relay.

VII. ACKNOWLEDGMENT

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