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A novel approach to transformer differential protection using sequence component based algorithm

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This paper presents a new unit type protection for power transformer by combining differential protection and phase angle comparison of sequence components of currents. The simple differential protection scheme alone may ma-operation during current transformer (CT) saturation and high resistance internal fault conditions. Hence, the sequence component based phase angle comparison technique is combined with percentage biased differential protection scheme. Discrete Fourier Transform (DFT) is used to calculate the phase angles of sequence components and harmonics of primary and secondary current signals of transformer. Low pass butter worth filter is used to correct the current signals before passing it to DFT. During internal fault, the phase angle difference of primary and secondary current is very low whereas large angle difference observed during external fault/other conditions. The performance of the proposed algorithm has been evaluated by considering various transformer and system parameters. Numerous simulations are carried out on three phase power transformer using PSCAD/EMTDC™ software to validate the technique. The proposed algorithm perfectly distinguishes internal fault and external fault condition. Moreover, various situations such as magnetizing inrush current, high resistance internal fault and CT saturation conditions are also tested for validation.

Keywords: *Transformer fault, Discrete Fourier Transform (DFT), Sequence components (SCs), phasor calculation, differential relay.*

1.0 INTRODUCTION

A power transformer is very precious equipment in power system so far as concern with power reliability and continuity of supply. However, the protection schemes of power transformer is very complicated due to magnetizing effect, different voltage ratio and phase angle difference between primary and secondary side of a power transformer. In past many number of schemes are suggested by researcher for the protection of power transformers. Some of them are based on discrimination of internal fault with other conditions such as inrush current, heavy load changes, presence of decaying DC component in fault, the transient nature of fault current [1].

Hosny *et al*. [2] presented transformer differential protection with phase angle difference between primary and secondary side currents however high resistance fault using sequence component remain unclassified. Wagh *et al*. proposed extraction of DC component and harmonic analysis for protection of power transformer [3]. The limitation of this research work is that, various cases have not been considered for validation. Madzikanda and Negnevitsky shows practical look at harmonics in power, transformer differential protection [4],

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however considerable variation in the harmonic content can lead maloperation of transformer differential scheme. Ali Hooshyar *et al.* suggested a new algorithm to identify magnetizing inrush conditions based on instantaneous frequency of differential power signal [5] and algorithm also capable to find magnetising inrush condition with minimum time approximately quarter of the cycle after disturbance. Guzman *et al.* [6, 7] have explained current based solution for transformer differential protection with restraining and blocking harmonics derived from current. Even though this methodology is now a day out of dated due to maloperation in various faulty condition like CT saturation and magnetic inrush. B A I-Fakhri [8] described a differential relay depends on the vector difference of a restraint quantity, while keeping the vector sum as a differential quantity, but the scheme is tested for only few abnormal conditions. K. Narendra *et al.* [9] elaborated phase angle comparison and differential rate of change methods used for differential protection of busbar and transformer. However, this scheme was not tested with high resistance in-zone fault. Furthermore, the scheme may maloperate during close-in external fault as it depends on rate of change of differential current. Khan *et al.* [10] presented a protection technique based on directional comparison approach but additional cost of voltage transformer will increase overall cost. Mohammad Ahmadi *et al.* [11] deal with a method for discrimination between magnetizing inrush and internal fault currents in three-phase transformers based on sine-wave curve fitting. Hamilton [12] analyzed inrush current & compare harmonic restraint in transformer protection. However in above two schemes, various test conditions like high resistance, percentage faulty winding, fault location, fault inception angle are not considered. Jettanasen *et al.* [13] proposed a scheme which discriminate external fault and internal fault in power transformer with the spectrum comparison technique of DWT. In this scheme LV winding ground fault efficiency is 94.44% and in internal faults 83.33% which is very less. Z. Moravej *et al.* [14] presented an algorithm based on time-frequency analysis of differential current in comparison with DFT based analysis. Meshal Al-Shaher and Mohamed Saied [15] analyzed the faults using the input impedance with consideration only turn to turn and turn to ground faults. Manoj Tripathy *et al.* [16] have proposed review paper with advising for utilization of recent techniques like artificial neural network and fuzzy logic concepts. However, neural network and fuzzy logic based methods may fail under some typical practical situations and leads mal-operation of digital relays. Fani *et al.* [17] proposed transformer differential protection using waveform feature monitoring scheme, the ratio of the second harmonic to the fundamental component give major effect in protective scheme so it must be properly utilized.

This article presents a combined method of differential principle and phase angle comparison method. This covers the comparison of positive, negative and zero sequence current of primary and secondary current of the transformer to identify internal and external fault conditions. In order to validate the proposed method, various test cases of internal fault, external faults, magnetic inrush, CT saturation and other conditions are simulated in PSCAD/EMTDC™ software [18]. In section II, problem description and possible solution with proposed algorithm is given. Section III describes system modeling and section IV shows simulation results for suggested scheme of transformer protection.

The proposed scheme perfectly operates during all internal fault conditions and even during high resistance internal fault. On the other hand, it remains stable during external fault, magnetizing inrush, CT saturation conditions and thus provides satisfactory performance.

2.0 PROPOSED TRANSFORMER DIFFERENTIAL PROTECTION TECHNIQUE

2.1 Problem Description and Solution

The scheme based on computation of pre/post fault current and voltage, transient reactances, presence of harmonic content and noise work well upto certain extent. However, they fail to protect transformer in some situation or may mal-operate during CT saturation and close-in external fault condition. Moreover, the methods based on simple differential principal which compare only current magnitude may fail during high resistance internal fault.

Many scheme proposed in past depends on measurement of voltage and current quantity suffer from high computation, complexity in implementation, increase in cost and inappropriate discrimination between internal and external faults. The solution to the aforementioned problems is presented in this paper by proposing new transformer fault distinguishing scheme using sequence components of current and phasor comparison. The solution to the aforementioned problem is describes here.

The symmetrical components of primary as well as secondary side current of a transformer like positive, negative and zero sequence components (SCs) are computed by equation (1), (2) [19].

For primary current, sequence components are:

$$\begin{bmatrix} I_{0p} \\ I_{1p} \\ I_{2p} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_{ap} \\ I_{bp} \\ I_{cp} \end{bmatrix} \quad ....(1)$$

For secondary current, sequence components are:

$$\begin{bmatrix} I_{0s} \\ I_{1s} \\ I_{2s} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_{as} \\ I_{bs} \\ I_{cs} \end{bmatrix} \quad ....(2)$$

Where, $a = 1\angle 120^0 = e^{j2\pi/3}$

As shown in Figure 1(a) and (e), the transformer is connected in interconnected network and represented in one line diagram of internal and external fault respectively. The algorithm receives CT secondary current I_x and I_y from the primary and secondary side of the transformer respectively. Remaining section of Figure 1(b), (c), (d) and Figure 1(f), (g), (h) illustrate behavior of phase angle of all positive, negative and zero sequence components (SCs) during internal and external faults respectively.

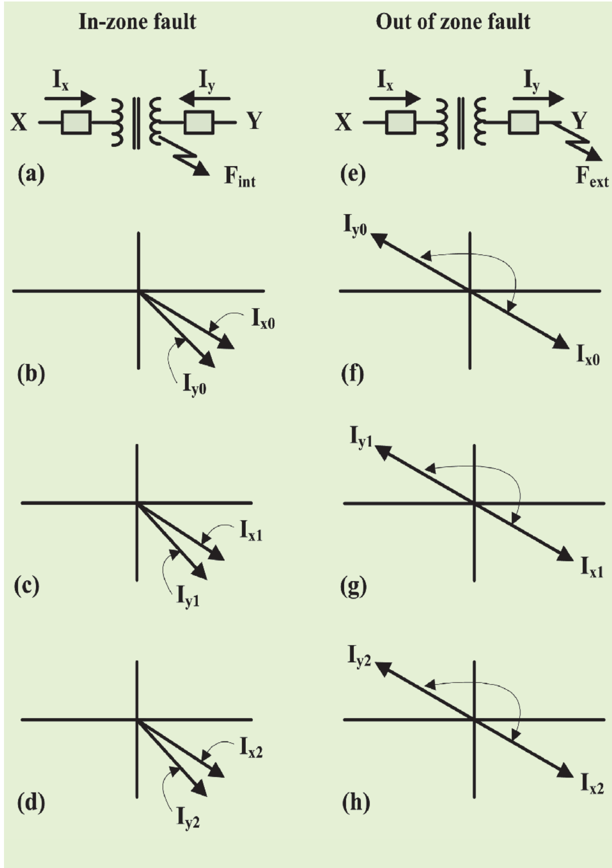


FIG. 1 PHASOR OF SYMMETRICAL COMPONENTS OF FAULT CURRENT DURING INTERNAL AND EXTERNAL FAULT CONDITIONS

It is to be noted that relative phase angle difference of positive, negative and zero sequence components during an internal faults is less and fall within a cone of 90^0. For Y-Y configuration it is near about 0^0 and for Δ-Y or Y-Δ it is around 30^0. Whereas during an external fault for any configuration of transformer the phase angle difference of sequence component is greater than 90^0 [20].

If only one sequence component out of three is utilized to discriminate, the scheme fail for particular fault type. Hence, phase angle of all sequential component (+Ve, -Ve and zero) of primary and secondary current are utilized to distinguish internal and external fault of transformer. It is also observed that pure phase angle comparison based scheme is not guaranteed during some phenomenon such as magnetizing inrush and turn to turn fault. Thus for dedicated protective scheme, a percentage biased differential scheme along with second harmonic restrained is used in parallel to symmetrical components (SCs) based algorithm.

2.2 Proposed Algorithm

In this paper author has proposed new methodology to discriminate internal fault and other external situations of a power transformer. In this method, phasor value (magnitude and phase angle) of CT secondary current as well as harmonic components are calculated using DFT filter. At initial stage, the algorithm utilizes to discriminate faulty and inrush condition based on harmonic level. The calculations of symmetrical components of current from the derived phasor are done to compare the phase angle of primary and secondary current. On the base of comparative analysis of all phase angle components of primary and secondary current, it discriminate internal fault and other situation. Figure 2 describes proposed algorithm for the fault identification in transformer. Sampling frequency of 4 kHz i. e. 80 samples/cycle with 50 Hz operating frequency is utilized in this proposed scheme.

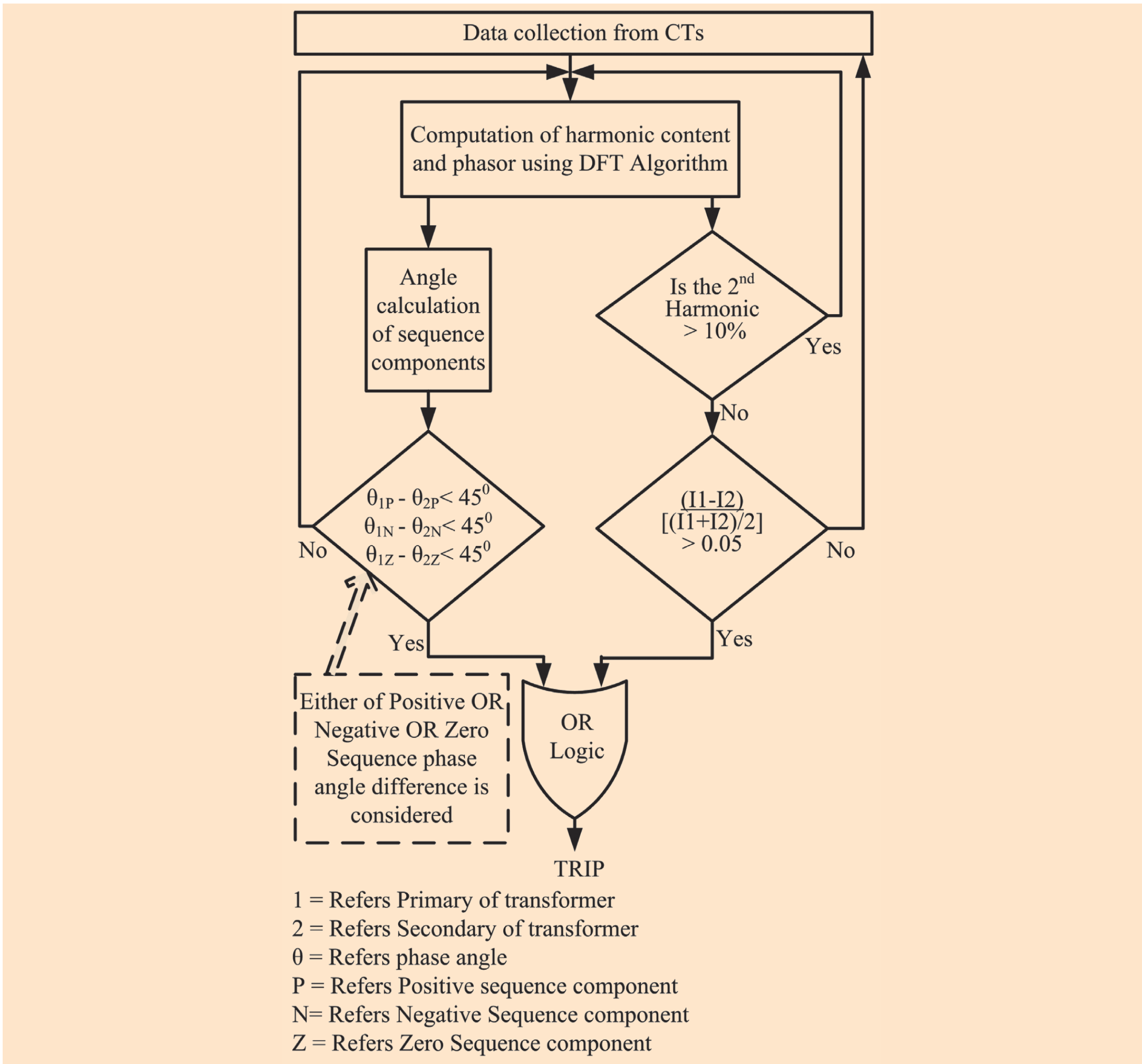


FIG. 2 TRANSFORMER FAULT ZONE IDENTIFICATION ALGORITHM

Initially, data acquisition system acquires primary and secondary current data through CTs located on both side of transformer. Whenever fault detector unit detects faulty condition, samples of one cycle post fault data are given to Discrete Fourier Transform (DFT) for phasor estimation. The DFT calculates phasor values and harmonics of the given current signals. As per algorithm each phase angle comparison unit compares either of positive (P) or negative (N) or zero (Z) sequence phase angle difference. This unit generates an output value as 1 (trip) if comparative phasor values are lying within 45^0 or otherwise 0 (return to further calculation).

Successively, biased percentage differential protection in conjunction with 2nd harmonic restrain scheme is evaluated by algorithm to detect magnetizing inrush and internal fault condition. The level of second harmonic components is set greater than 10% of the fundamental component to detect the magnetising inrush condition. The threshold of the biased differential scheme depends on the normal/overload condition of the transformer which is 0.05 A in this case. Hence, the output contact status of phase angle based fault discrimination scheme and biased differential based scheme are connected in parallel i.e. OR logic is used.

3.0 SYSTEM MODELING

The PSCAD/EMTDC™ software has a standard three phase power transformer component in its library. However, to simulate exact internal faults in transformers, a model having tapping from different location of winding is required. PSCAD/EMTDC™ software provides facility to design a user define device using the component wizard. The new component in PSCAD represents a model which allows input parameters and performs pre-calculation on input data. An internal code with FORTRAN and dialog box is designed to fix the transformer parameters to represent new device. The script file of designed power transformer required to fix various parameters such as system frequency, transformer MVA rating, and nominal voltage of each sub coil, tapping position and leakage reactance of each sub coil. Three single phase transformers are modeled with tap changing facilities to simulate internal fault.

Figure 3 shows a single line diagram of a portion of Indian power system. Three phase, 50 Hz, 350 MVA, 400/220 kV power transformer model is developed in PSCAD/EMTDC™ using three single phase transformers [18]. In this simulation model, a three phase voltage source (230 kV) is connected through CT and breaker to one side of three phase power transformer. The other side of transformer is connected to infinite bus system.

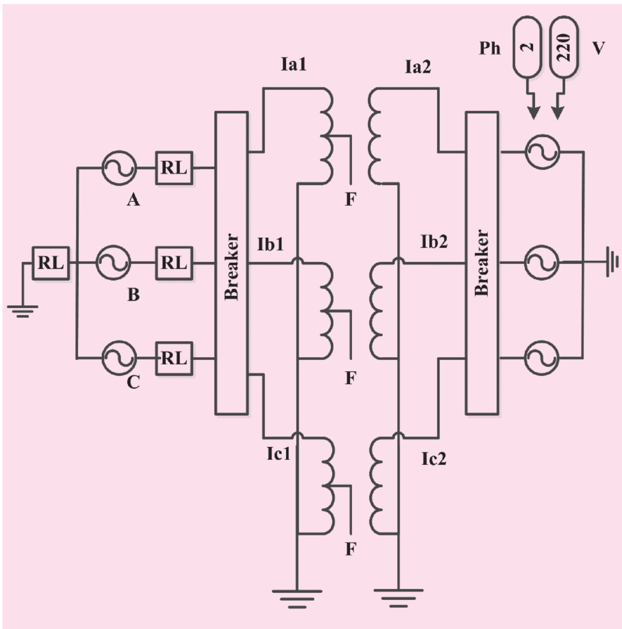


FIG. 3 SINGLE LINE DIAGRAM OF POWER SYSTEM MODEL

For normal/healthy operating state, simulations have been carried out for different loading conditions from no load to full load. Internal faults (phase-to-ground, phase-to-phase and phase-to-phase-to-ground) are applied at various percentage of winding from the terminal of the transformer including terminal faults. Moreover, different external faults have been simulated with various fault and system conditions.

Furthermore, the effectiveness of the proposed algorithm is tested by considering magnetizing inrush, high resistance internal fault, CT saturation conditions with close-in external fault, variation in load angle, fault resistance, Fault Inception Angle (FIA), Fault types (F_{type}) and fault locations. All the data related to transformer and simulation is given in Appendix A.

4.0 SIMULATION RESULTS AND DISCUSSION

For testing of the proposed algorithm, various test cases are simulated on Y-Y and Δ-Y connected transformer. Different types of fault and system parameters are considered during the simulation for validation. Table 1 shows the fault/system parameters considered and numbers of data generated for testing of the algorithm.

As per Table 1, a total of 1080 and 360 numbers of internal faults in transformer winding and external faults are simulated, respectively in PSCAD software. However, due to space limited few cases are represented in this section. The results for the above mentioned cases are shown in next sub-section.

4.1 Internal and External Fault Conditions

Various internal faults have been simulated on primary and secondary side of transformer at different percentage of winding including terminal. From Table 2, it has been observed that the phase angle difference of like sequence components of primary and secondary current is very low. It means that the angle difference of positive sequence component from both side current is 4.5^0 for LL-g fault which is lower than set threshold (45^0). Whereas during external fault condition this difference is approximately 180^0 as shown in Table 3.

TABLE 1

VARIOUS FAULT AND SYSTEM PARAMETER VALUES CONSIDERED

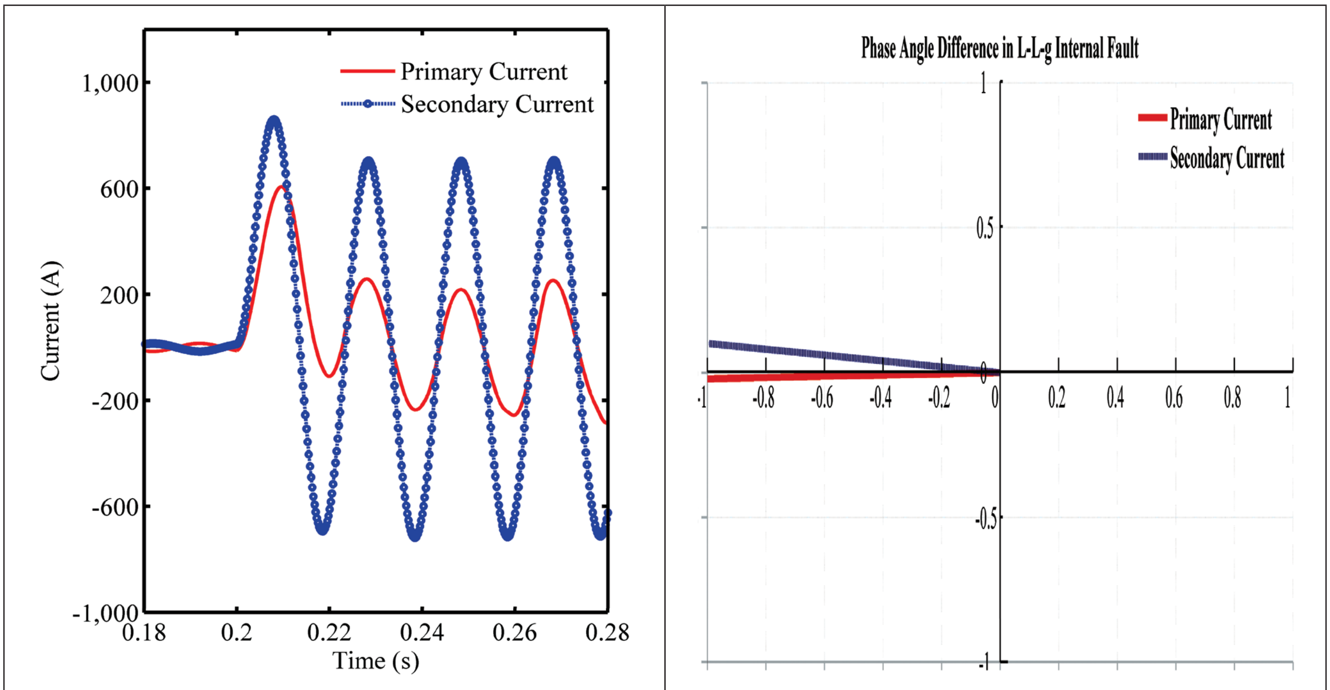
Fault	FL (% of winding from Terminal)	R_f (ohm)	Fault type (F_{type})	FIA (deg.)	Load angle δ (deg.)
Internal fault in winding (**1080**)	0%, 25% & 50% of winding (primary side) **(3)**	0, 5 & 10 Three values **(3)**	L-G (3 No.) L-L (3 No.) L-L-G (3 No.) L-L-L-G (1 No.) Ten types of Fault **(10)**	0^0, 25^0, 45^0 & 90^0 Four values **(4)**	0^0, 5^0 & 10^0 Three values **(3)**
External to transformer **(360)**	Not Applicable	0, 10 & 20 Three values **(3)**			

Among all the test cases, LL-G internal fault and LL external fault condition is considered for the analysis, and applied at 0.2 sec. The graphical representation of simulated internal fault at 50 % of winding on primary side is shown in Figure 4. Figure 5 illustrates the waveform during external fault condition. The phasors of sequence component for primary and secondary current are represented in Figure 4(b) and Figure 5(b) for internal and external fault respectively.

TABLE 2

PHASE ANGLE VALUES OF SCS DURING IN INTERNAL FAULTS

	SCs	Internal Fault				
		R-g	**RY**	**RY-g**	**RYB**	**RYB-g**
Primary	Z	179.7	-	62.4	-	-
	P	179.1	-178.4	**-178.7**	-178.9	-178.9
	N	179.7	-66.1	-60.1	-	-
Secondary	Z	-177.6	-	56.8	-	-
	P	-179.8	175.1	**174.2**	174.3	174.1
	N	-177.0	-72.3	-66.4	-	-



(a) (b)

FIG. 4 LL-G INTERNAL FAULT (A) PRIMARY AND SECONDARY CURRENT WAVEFORM (B) PHASE ANGLE COMPARISON FOR SCS

TABLE 3

PHASE ANGLE VALUES OF SCS DURING EXTERNAL FAULTS

	SCs	External Fault				
		R-g	RY	RY-g	RYB	RYB-g
Primary	Z	-179.9	-	129.2	-	-
	P	179.9	**-178.0**	-179.9	-179.8	-179.8
	N	179.9	-128.3	-128.8	-	-
Secondary	Z	0.060	-	-52.1	-	-
	P	-0.049	**1.640**	0.078	0.104	0.104
	N	-0.022	52.65	52.4	-	-

Successively for the same fault, Table 4 shows the calculation of bias percentage differential current for internal as well as external fault condition. It is to be noted that during internal fault the differential current magnitude (I_1-I_2) turn out to be more comparing to (I_1+I_2)/2. On the other hand, during external fault biased value of current is more than the differential current. Hence, the proposed scheme issue trip signal in case of any internal fault and remain stable during external fault situation.

TABLE 4

PERCENTAGE RESTRAINED CURRENT FOR VARIOUS INTERNAL AND EXTERNAL FAULTS

	Type of fault		I_1	I_2	I_1-I_2	(I_1+I_2)/2	$\frac{I_1-I_2}{(I_1+I_2)/2}$
1	L-g	INTERNAL FAULT	2.3	0.4	1.83	1.38	1.319545
2	L-L		4.0	0.14	3.90	2.09	1.865361
3	LL-g		2.7	0.04	2.74	1.41	1.94123
4	LLL		5.7	0.11	5.60	2.91	1.921744
5	LLL-g		2.9	0.09	2.84	1.52	1.873139
1	L-g	EXTERNAL FAULT	24.6	24.1	0.42	24.40	0.017305
2	L-L		19.5	19.2	0.33	19.42	0.017392
3	LL-g		24.7	24.2	0.42	24.5	0.017306
4	LLL		26.4	26.0	0.45	26.26	0.017284
5	LLL-g		24.7	24.3	0.42	24.57	0.017304

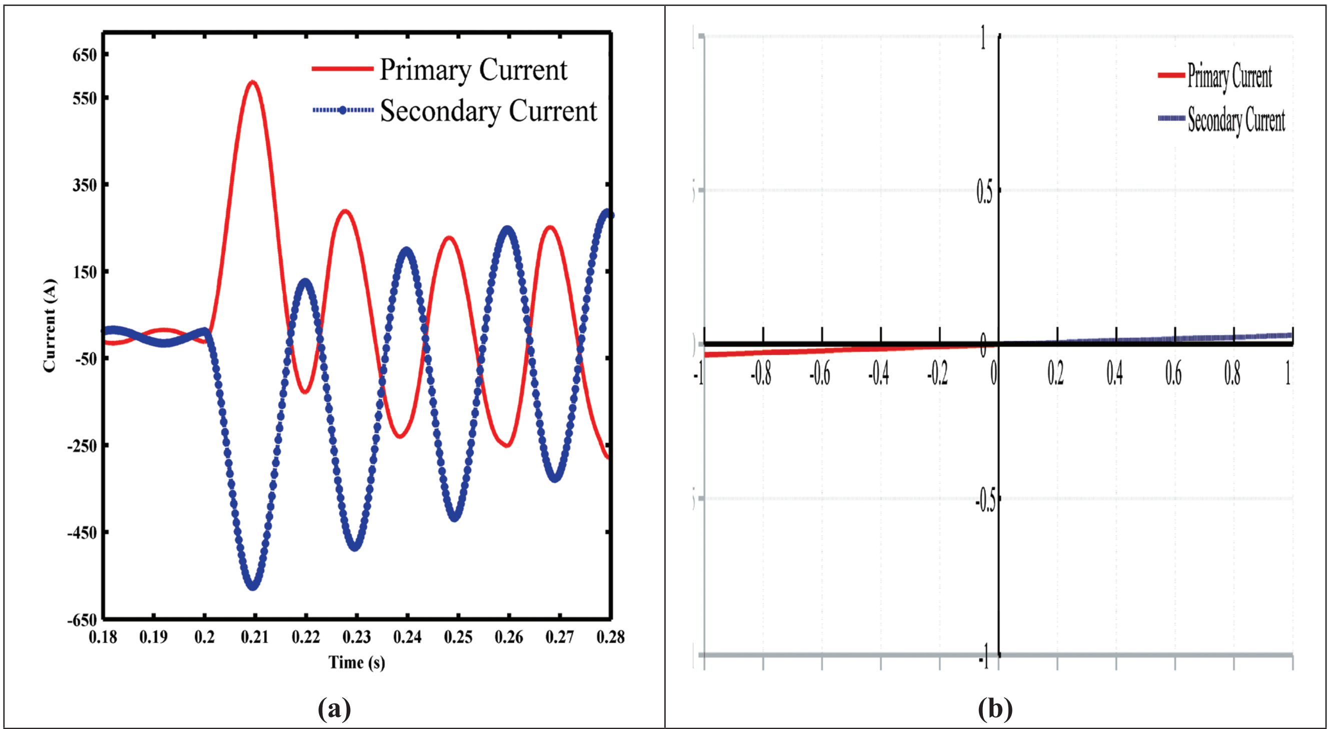


FIG. 5 L-L EXTERNAL FAULT (A) PRIMARY AND SECONDARY CURRENT WAVEFORM (B) PHASE ANGLE COMPARISON FOR SCS

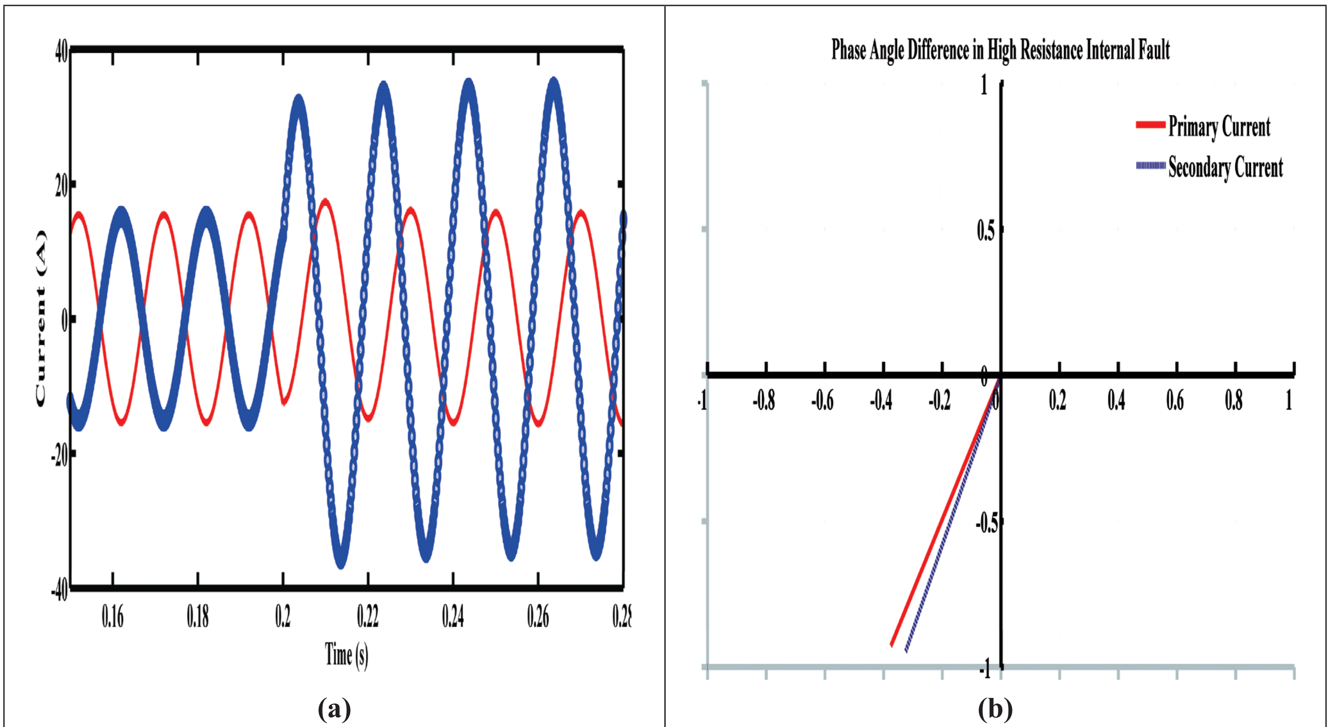


FIG. 6 L-G HIGH RESISTANCE INTERNAL FAULT (A) PRIMARY AND SECONDARY CURRENT WAVEFORM (B) PHASE ANGLE COMPARISON FOR SCS

4.2 High Resistance Internal Faults

It is worth to check the feasibility of the proposed algorithm for high resistance internal fault condition. To conduct high resistance internal fault on YY connected transformer, deliberately 20 Ω resistance is inserted in the L-g fault path. The fault is being subjected at 10% of transformer primary winding from terminal side. Difference between primary and secondary current magnitude is slightly lower than solid grounded fault. However, the phasor difference of like sequence current component fall within the given threshold limit. Figure 6 demonstrate the waveform of current during high resistance fault and phasor comparison. Table 5 shows the calculated phase angles for the said high resistance fault condition. Thus, in both the cases the proposed algorithm successfully operates and issues trip signal.

4.3 CT Saturation Conditions

The transformer protection is affected during CT saturation phenomenon which occurs mainly during heavy through fault condition. The protection scheme must remain stable during external fault as well as during CT saturation phenomenon. The CT saturation is obtained by CT model block available in PSCAD/EMTDC. By changing the CT secondary burden resistance, different degrees of CT saturation can be obtained.

The performance of the proposed scheme during CT saturation is carried out by simulating different close-in external faults on secondary side of star-star transformer just behind CT location. A bolted LLL fault is simulated with CT secondary burden resistance of 8 Ω. Figure 7(a) shows the CT secondary current (one phase) during the said CT saturation condition. As shown in Figure 7(a), profound saturation of CT starts just after the point of fault inception (0.2 s), and it results into slightly lower value of I_1-I_2. But, it is higher than preset threshold. Hence, during such CT saturation condition, only circulating differential based protection scheme may mal-operate and leads to unnecessary tripping of transformer (external fault). On the other hand, percentage biased differential protection scheme tackle the said situation as the calculated differential current (I_1-I_2) remain above the restrain current (I_1+I_2/2). Moreover, the SC based phasor comparison scheme work well and by maintaining the phase angle difference (124.3^0) above the set threshold. Figure 7(b) along with Table 5 exemplify that the phase angle difference of similar SCs is higher than 45^0 so the relay does not operate.

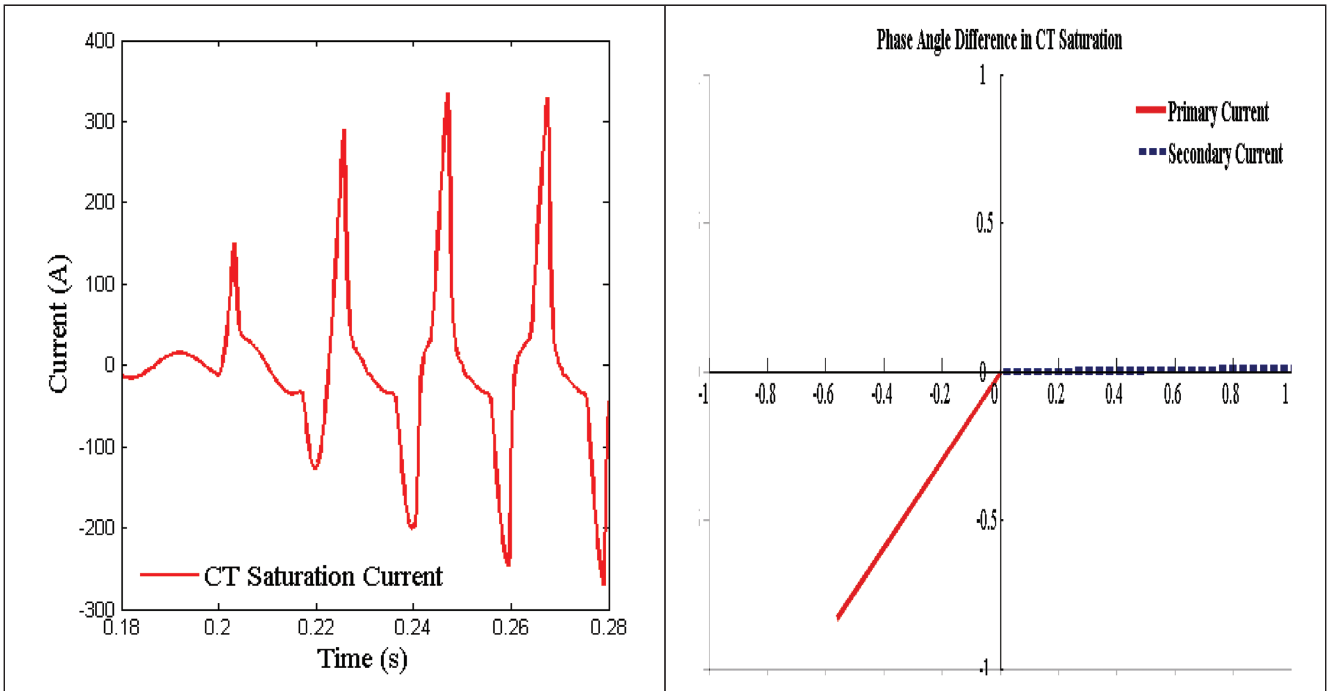


FIG. 7 CT SATURATION CONDITION (A) SECONDARY CURRENT WAVEFORM (B) PHASE ANGLE COMPARISON FOR SCS

TABLE 5				
PHASE ANGLE VALUES OF SCS DURING VARIOUS ABNORMALITIES				
	SCs	High resistance internal fault (L-g)	CT saturation (external fault)	Load variation (10% over load)
Primary	0	-111.9	-110.6	126.9
	1	-116.9	**-124.0**	**125.4**
	2	**-112.0**	-113.3	126.8
Secondary	0	-112.2	0.395	-53.07
	1	-111.74	**0.3338**	**-54.65**
	2	**-108.9**	0.3352	-53.17

4.4 Magnetizing inrush condition

Magnetizing inrush is a condition when the transformer draws a very large current from the supply while the load current is either zero or of nominal magnitude. The nature and magnitude of inrush current will be decided by the direction & magnitude of the residual magnetization flux in the core and switching instant. On harmonics analysis, it is found that during inrush situation flux consists of a significant amount of higher order harmonics out of which second harmonics is predominant. Generally the range of second harmonic is in the order of 15–20% of the fundamental frequency component [21]. In the proposed method, DFT algorithm computes level of second harmonic contents and decides whether it is fault current or magnetising inrush current. Figure 8(a) shows magnetizing inrush wave form while energizing the transformer during no-load condition. Figure 8(b) shows the level of 2nd harmonics component compare to fundamental which is higher than the set threshold (10%) in algorithm.

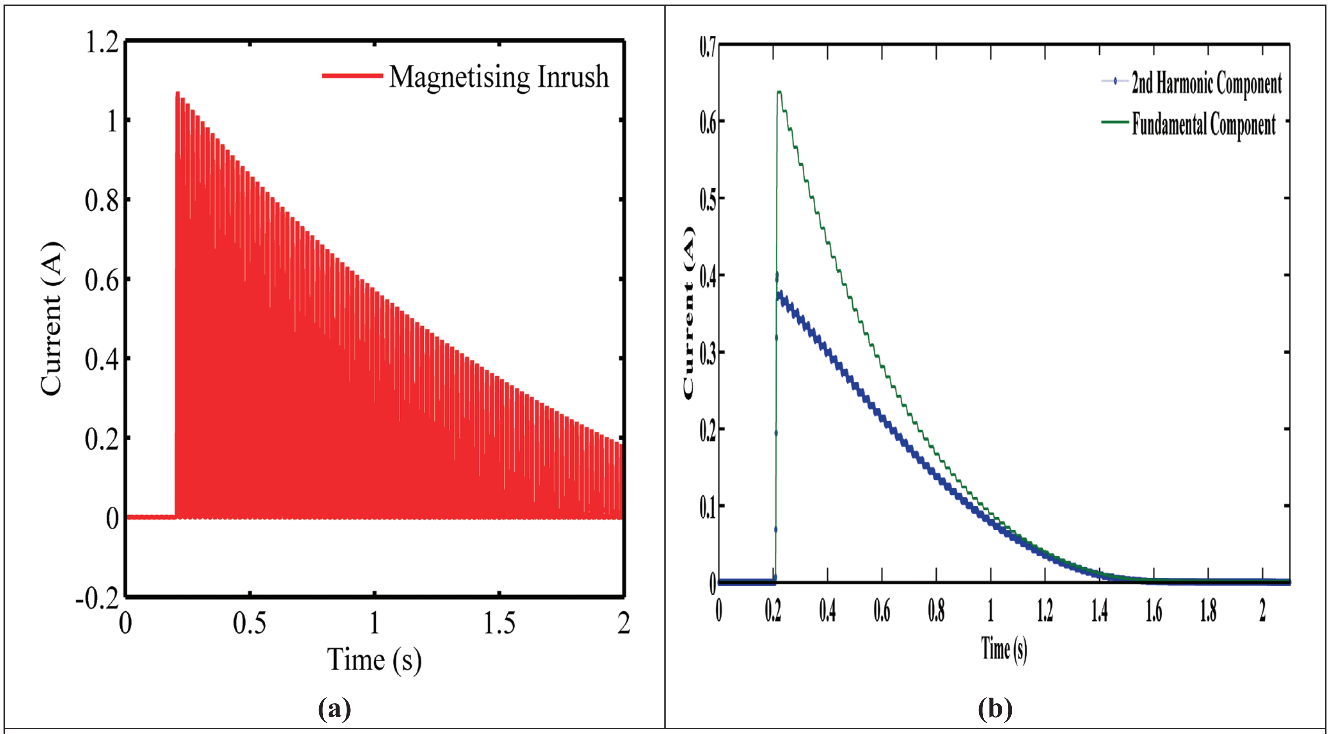


FIG. 8 (A) MAGNETIZING INRUSH CURRENT WAVEFORM (B) FUNDAMENTAL AND SECOND HARMONIC COMPONENTS

4.5 Effect of Variation in load

The proposed scheme is tested for the variation of load on secondary side of transformer. The 3-phase active and reactive load (power) is varied from no-load condition (magnetizing inrush) to full load as well as 10% over load condition with respect to the power transfer capacity of transformer. This is simulated by changing the load angle (δ^0) of generator (infinite bus) connected on secondary side of transformer. During sudden change from light load to heavy overload condition, the primary and secondary current abruptly varied. This result momentarily changes in differential and biased current at relaying point. However, the magnitude of restrain current remains well above the calculated biased current. Moreover, the phase angle difference of same sequence components are almost out of phase during load variation as shown in Figure 9(b). Thus, the proposed relaying scheme remains inoperative during variation of minimum to maximum load condition.

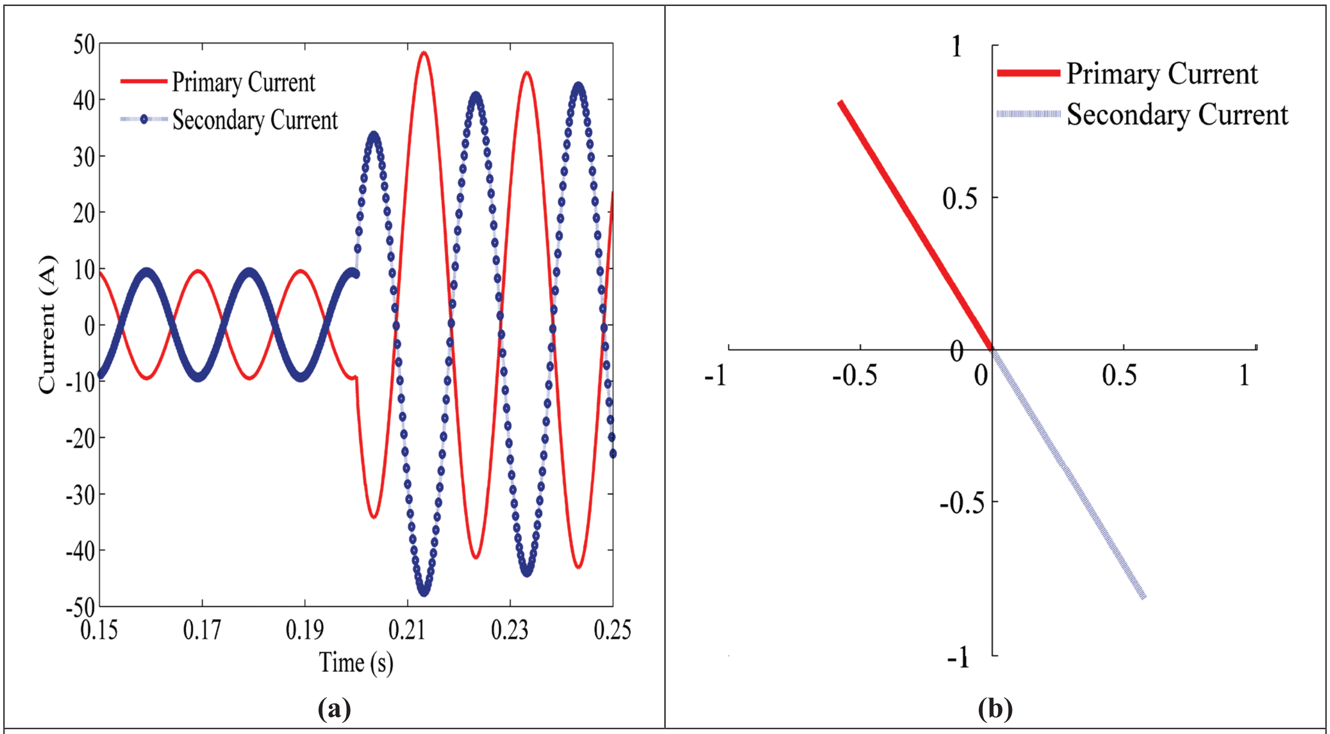


FIG. 9 (A) CURRENT WAVEFORM DURING 10% OVERLOAD (B) PHASE ANGLE COMPARISON FOR SCS

5.0 CONCLUSION

This paper presents a new scheme for the transformer protection based on phase angle difference of sequence component of current to discriminate internal fault with external fault/ other situations. At the same time the proposed scheme presents percentage biased differential protection scheme including detection of magnetizing inrush current. DFT algorithm is used to derive the required parameters and harmonic contents by eliminating decaying DC components and noise present in current signals. Different fault conditions with varying system parameters are simulated in PSCAD for the validation of the proposed algorithm. The proposed algorithm depends on minimum numerical calculation, which can easily apply to relay programming and hence, highest speed of operation is achieved. Various internal faults, external faults, magnetizing inrush condition, CT saturation phenomenon and high resistance internal faults are tested with the proposed algorithm. Simulation results demonstrate that the algorithm is able to distinguish internal fault with external fault & various conditions perfectly.

APPENDIX A

Three phase voltage source-1		
1	Phase to phase rms voltage	400 kV
2	Frequency	50 Hz
3	+Ve sequence impedance	1.0 ohms and 85 Degree
4	Zero sequence impedance	2.0 ohms and 85 Degree
Three phase voltage source-2 is modeled as infinite bus system.		

Three phase transformer parameter (YY connected)		
1	Normal power	350 MVA
2	Frequency	50 Hz
3	Leakage Reactance	0.1 pu
4	Magnetizing current	4%
5	Voltage (primary/ secondary)	400/220 kV
Current Transformers		
1	Primary side of transformer	1200/2
2	Secondary side of transformer	2000/2

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