

# Negative Sequence Component:for Detection of Inter-Turn Fault of Transformer

Rupali Chavhan<sup>1</sup>, DR. V. A. Kulkarni<sup>2</sup>

M. E Student, Department of Electrical, Government College of Engineering Aurangabad, Maharashtra, India<sup>1</sup>

Associate Professor, Department of Electrical, Government College of Engineering Aurangabad, Maharashtra, India<sup>2</sup>

**ABSTRACT:** In this paper, Negative Sequence Component scheme for analysis of inter-turn winding fault detection at initial level has been discussed. Inter-turn faults are the most difficult types of faults to detect within the power transformer. When small percent of turns are shorted, the sensitivity of current differential protection is limited so it does not cause false tripping due to normal imbalances in current. Digital relays are capable of computing the negative sequence current on both primary and secondary sides of the transformer along with the phase difference between these two negative sequence currents. Algorithm discussed is faster and more sensitive than conventional differential protection and capable of detecting inter-turn faults occurring during transformer energization. The mathematical analysis is illustrated and compared with simulation studies performed with MATLAB/ SIMULINK.

**KEYWORDS:** Inter-turn fault, negative sequence component, transformer protection.

## NOMENCLATURE

$r_c$  - Core resistance

$r_n$  - Number of resistance

$r_T$  -Total resistance of primary winding of transformer

$r_F$  -Resistance of faulty turns

$x_m$  -Magnetizing reactance

$x_n$  -Number of reactance

$x_T$  -Total reactance of primary winding of transformer

$Z_{mH}$  -Input impedance of healthy transformer

$Z_{mF}$  -Input impedance of faulty transformer

$x_F$  -Leakage reactance of faulty turns

$x_F'$  -Leakage reactance of faulty turns referred to primary side

$a$  - ratio of primary to faulty turns of transformer

$N_1$  - Primary turns of transformer

$N_f$  Faulty turns of transformer

ITF - Inter-turn fault

NSC - Negative Sequence Component

TTF - Turn-to-Turn Fault

# International Journal of Innovative Research in Science, Engineering and Technology

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Vol. 6, Issue 7, July 2017

## I. INTRODUCTION

Transformer is a very vital part of the power system. It is a static device which works on the principle of mutual induction. In transformer whenever a fault occurs, electrical failure of transformer can be prevented by providing on-line condition monitoring. Generally, before occurrence of Turn-to-Turn (TTF) or inter-turn fault (ITF) in winding there is a development of aging-arcing. This process is known as incipient fault [1].

On histories of modern transformer breakdowns a brief analysis shows that near about 70-80% of failures are caused by inter-turn faults. There are various methods to spot turn-to-turn winding fault in transformer on the basis of terminal voltage and current. Such as V-I locus diagram, Dissolve Gas Analysis (DGA), Doernenburg Ratio Method (DRM), Frequency response Analysis (FRA), Reverse Voltage Measurement Technique (RVMT), on-load exciting current extended Park's Vector, Leakage flux, Zero Sequence Component and Negative Sequence Component etc.[2].

The Negative Sequence Component is more sensitive to sense minor ITF and its action is based on evaluating the magnitude and phase of Negative Sequence Component like current, voltage and phase angle [3].

In detection of ITF in transformer with help of NSC of Current, the calculation of system has been prepared for different operating conditions, different number of shorted turns and different connection of power transformer. It observed that even when 2% of turns are shorted, the arrangement will work properly [4]. In fuzzy logic based protective relays an application to the power transformer protection indicates the sensitivity and selectivity of self-organized relay equating with traditional methodologies [5]. Under different functioning circumstances the identification of different types of current flowing in the power transformer by using simulation results offers fast, accurate and reliable experiences of WPT algorithm [6].

The behaviour of power transformer under occurrence of inrush current and ITF of transformer winding provides reliable protection, enhanced sensitivity for 3-phase fault detection [7]. Using new approach in [8] novel flux base protection is used for the protection of transformers to find turn to turn fault by inserting several Surge Coils on core legs in order to measure flux linkage at various stage. A Novel offline to online approach for TTF detection of the transformer indicates an increase in fundamental component of current due to fault which in turn, reduces a percentage contribution of individual harmonics [9].

## II. PROTECTIVE RELAYING SCHEME FOR DETECTING TURN-TO-TURN FAULTS

Basically, a transformer ITF is functioned by conventional protection scheme. But the conventional protection scheme is bias and is not suitable for protection against ITF at incipient level. This drawback is excluded using upgraded protective relaying scheme by providing a way to confirm the presence of fault. Different method of negative sequence based relay operated area against CT saturation, magnetizing inrush etc. is implemented and all this is probable without addition of any cost as it is based on CT signals which are freely existing [10].

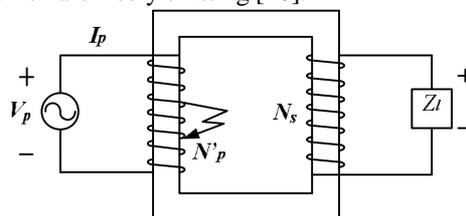


Fig.1. Turn-to-turn fault in primary side

### A. Protection of transformer using negative sequence current

This relay makes use of negative sequence percentage differential current element which is calculated by vector sum of all current incoming the protection region. The condition for fault detection is that the magnitudes of phase comparison and the magnitude of primary and secondary negative sequence current must be larger than minimum rated current ( $I_{\min \text{ rated}}$ ) [11].

### B. Negative sequence component system

Negative-sequence differential protection is excellent for protecting lines and transformer. It is an unbalance system in terms of three phase balance system. Three-phase faults do not contain negative-sequence components, so

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they require a different approach. Negative sequence network are basically equal to positive sequence network except for the absence of source and different phase shifts in some connection of the power transformer [12].

According to IEEE Standards at no load the transformer winding voltages be within 0.5% of the rated voltage. If a 0.5% imbalance is occurs in healthy system, it produces a negative-sequence voltage well below rated.

$$V_{RST} = \frac{|V_{negp} + V_{negs}|}{2} \times S \quad \text{and} \quad V_{DIFF} = |V_{negp} - V_{negs}| \times S \quad (1)$$

Where, S is transformation ratio

From equation (3) and (4) it is noticed that the primary and secondary negative sequence voltage gives restraining and differential voltage respectively. And both the primary and secondary side of NSC like current and voltage, transposed to the primary side of the transformer, which must be greater than 1% prescribed primary voltage. This prevents false tripping due to small imbalance occurs in healthy transformer. If differential current exceeds the restraining current equation a trip is assured. When transformer negative sequence current indicate that the transformer is being energized, negative sequence voltage are used to determine if transformer is experiencing a ITF or TTF [11], [13]. The following table I. gives technical specification of transformer which is require for simulation modeling.

TABLE I. TECHNICAL SPECIFICATIONS OF TRANSFORMER

Parameters	Quantity
Capacity	100 MVA
Frequency	50 Hz
Voltage	132/66 kV
Connection type	Star - Star
Resistance	R <sub>1</sub> =0.34848 Ω, R <sub>2</sub> =0.08712 Ω
Inductance	L <sub>1</sub> = 0.04437 H, L <sub>2</sub> = 0.011092 H
Turns	N <sub>1</sub> =100, N <sub>2</sub> = 50

### C. Equivalent model of transformer with mathematical equations

The mathematical results shows that for internal faults with less number of windings the equivalent impedance of faulty windings is mostly resistive [15]. For analysis of ITF an equivalent circuit is presented in Figure 2.

$$x_F = (a-1)^2 x_F' \quad , \quad a = \frac{N_1}{N_f}$$

#### 1. At Normal Condition

At normal condition there is no turns are shorted in its windings. An equivalent circuit of single phase of transformer under no-load condition on primary side is shown in Fig. 2.

$$Z_{inH} = x_m || r_c = \frac{r_c x_m^2}{r_c^2 + x_m^2} + j \frac{r_c^2 x_m}{r_c^2 + x_m^2} \quad (2)$$

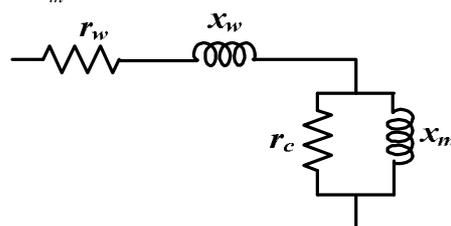


Fig.2. Equivalent circuit of healthy transformer at normal condition on primary side

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$$Z_{inH} = r_n + jx_n$$

Where,

$$r_n = \frac{r_c x_m^2}{r_c^2 + x_m^2} = x_m \left( \frac{r_c x_m}{r_c^2 + x_m^2} \right), \text{ and } x_n = \frac{r_c^2 x_m}{r_c^2 + x_m^2} = r_c \left( \frac{r_c x_m}{r_c^2 + x_m^2} \right) \quad (3)$$

$$\therefore \frac{x_n}{r_n} = \frac{r_c}{x_m} \quad (4)$$

The angle of impedance can be calculated as follows:

$$\therefore \angle Z_{inH} = \tan^{-1} \left( \frac{x_n}{r_n} = \frac{r_c}{x_m} \right) \quad (5)$$

## 2. At Fault Condition

As shown in Fig.3 the input impedance can be calculated from the equivalent circuit. The actual value of resistance and leakage inductance of shorted turns is very low, especially for less number of faulty turns. Therefore, specifications referred to primary side determines the major part of input impedance of ITF of winding,

$$Z_{inF} = (r_n + jx_n) \parallel (r_f + jx_f)$$

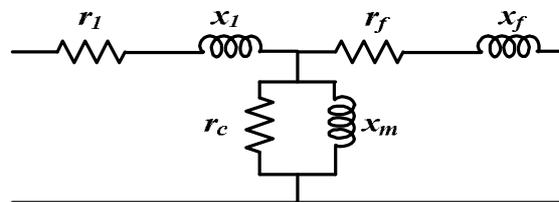


Fig.3. Equivalent circuit of transformer when turn-to-turn fault to primary side

$$= \left( \frac{r_n^2 r_f + r_f^2 r_n + x_f^2 r_n + x_n^2 r_f}{(r_{nF})^2 + (x_{nF})^2} \right) + j \left( \frac{r_n^2 x_f + r_f^2 x_n + x_n^2 x_f + x_f^2 x_n}{(r_{nF})^2 + (x_{nF})^2} \right) \quad (6)$$

$$r_{nF} = r_n + r_f \text{ And } x_{nF} = x_n + x_f \quad (7)$$

$$\therefore \angle Z_{inF} = \tan^{-1} \left( \frac{x_f}{r_f} \right) \quad (8)$$

The impedance angle depends on  $r_f$  and  $x_f$ . It is possible to find a method to detect ITF in transformer only when this dependency follows equation (11). As the number of faulted turns differs, the angle of input impedance also varies considerably.  $\angle Z_{inF}$  must be smaller than  $\angle Z_{inH}$ . And this condition is satisfied by solving equation 8<sup>th</sup> and 11<sup>th</sup> which is written in equation (12).

## D. Turn-to-turn fault detection algorithm

Current and voltage existing on primary and secondary side of transformer is consider first in this system. As on the both sides of transformer detection of the magnitude of negative sequence current is above rated value, a phase comparison is warranted.

$$\frac{x_f}{r_f} < \left( \frac{x_n}{r_n} = \frac{r_c}{x_m} \right) \quad (9)$$

If negative sequence voltage exist only on either secondary side, then secondary or primary side of transformer is being energized. In this case flowchart proceeds to negative sequence current or voltage and vice versa. When a transformer

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negative sequence current indicate that the transformer is being energized, negative sequence current or voltages are used to determine if the transformer is experiencing a ITF.

Inter-turn fault of a transformer by using sensitive technique, for one period the speed of algorithm is very fast and shall not be delayed for fault which coincides with inrush condition, but the operation is substantially delayed in case of second harmonic at period of second time [14].

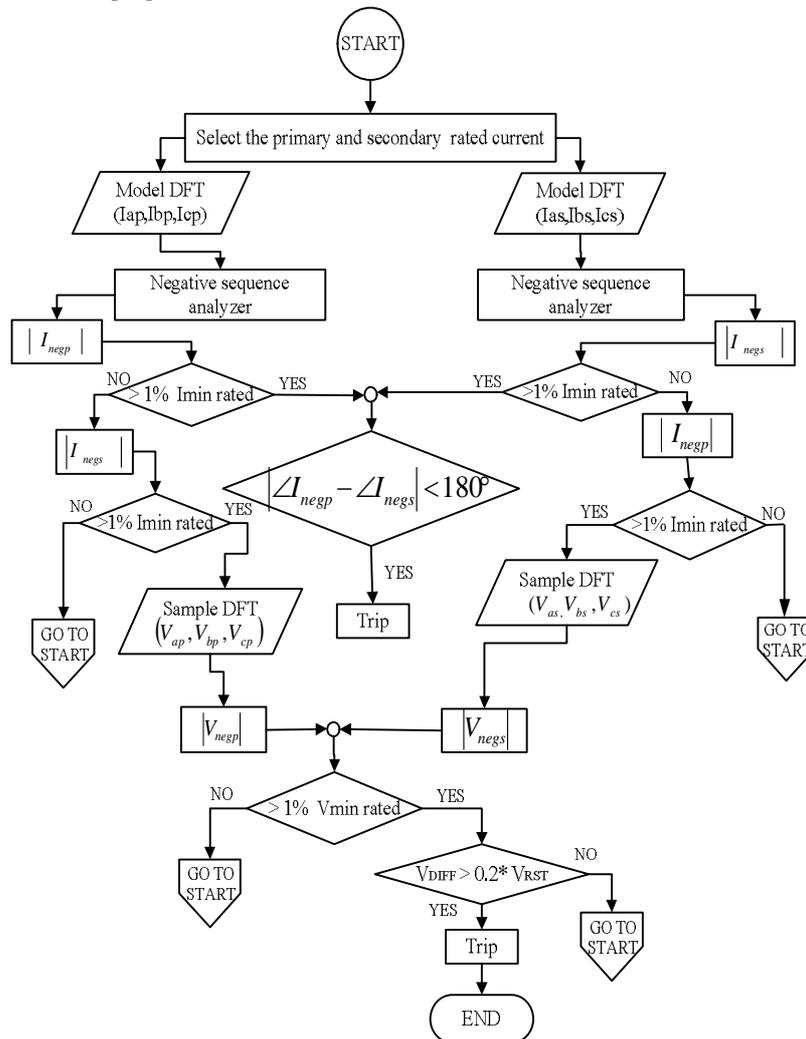


Fig.4 Flowchart of protective relaying scheme for detection of ITF

### III. SIMULATION RESULTS

In this paper, the protective relaying scheme for ITF in winding of transformer using negative sequence component system is simulated in MATLAB/SIMULINK. Results are given for unprotected system and for protection using negative sequence component system due to occurrence of 2 %, 3%, 5%, and 10% of inter-turn fault respectively.

#### A. Unprotected system

As inrush current is not a faulty state, the protection of transformer is unchanged in inrush condition. Fig. 5 shows the inrush currents in unprotected system. When primary side CB1 is closed at 0.5 sec, an inrush current flows in primary winding of transformer and no current flows through secondary side of transformer and gives a trip signal as shown in fig. 6 which received at 0.5 sec but it is not analyzed by the fault.

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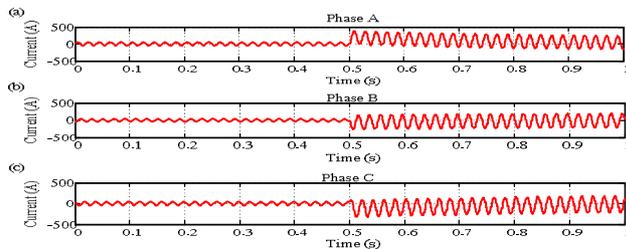


Fig. 5 Waveforms of effect of ITF on inrush current with unprotected system for (a) phase A, (b) phase B, and (c) phase respectively

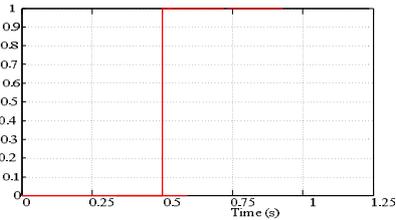


Fig.6 Trip signal with unprotected system

Fault is created and security of algorithm is tested. In fig.7 (a) significant change in primary negative sequence current takes place at 0.15 sec due 2 % of ITF inside the protected zone and fig. 7 (b) shows secondary Negative sequence current.

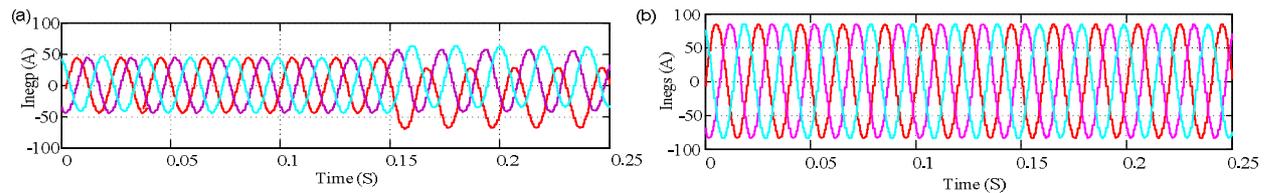


Fig.7 Simulation result for 2 % Inter-turn fault, shows (a) Negative Sequence current of primary winding (b) Negative Sequence current of secondary winding

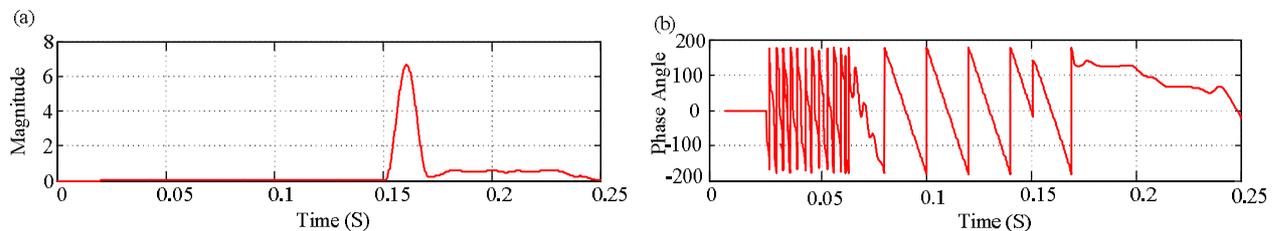


Fig. 8 Simulation results of 2% Inter-turn fault for Difference between primary and secondary negative sequence current of (a) Magnitude (b) phase angle

Fig. 8 (a) shows magnitude of comparison of primary and secondary negative sequence current and fig. (b) shows phase angle for difference between primary and secondary negative sequence current which is less than  $180^{\circ}$ .

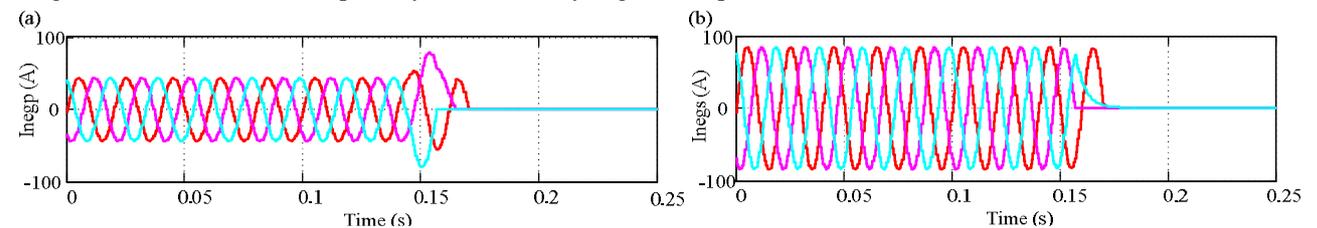


Fig.9 For 3 % Inter-turn fault, simulated result shows (a) Negative Sequence current of primary winding (b) Negative Sequence current of secondary winding

Fig. 9 (a) and (b) gives simulation result for negative sequence current of primary and secondary winding for inter-turn fault of 3% at 0.145 sec.

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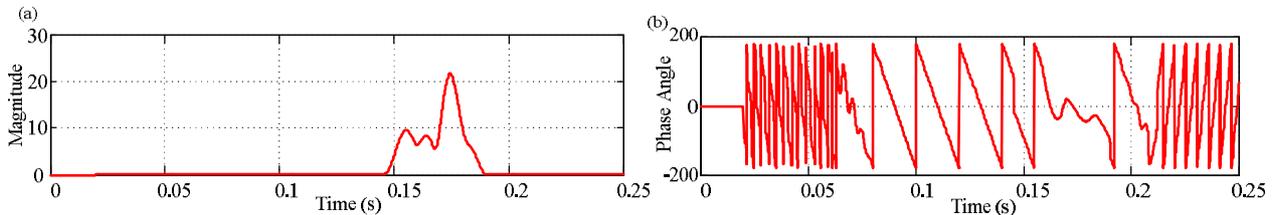


Fig.10 Simulation results of 3% Inter-turn fault for Difference between primary and secondary negative sequence current of (a) magnitude (b)phase angle

Fig 10 (a), and (b) shows magnitude and phase angle between primary and secondary negative sequence current for 3 % of ITF respectively.

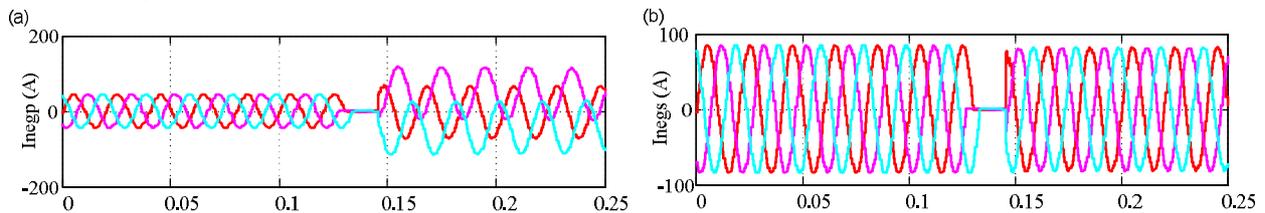


Fig.11 For 5 % Inter-turn fault, simulated result shows (a) Negative Sequence current of primary winding (b) Negative Sequence current of secondary winding

Fig.11 (a) and (b) gives simulation result for negative sequence current of primary and secondary winding respectively at 0.125 sec. for 5 % of IFT.

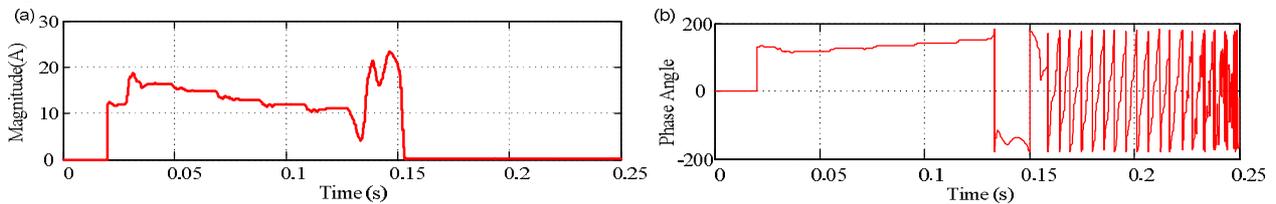


Fig. 12 Simulation results of 5% Inter-turn fault for Difference between primary and secondary negative sequence current of (a) Magnitude (b) phase angle

Fig. 12 (a) and (b) shows magnitude and phase angle between primary and secondary negative sequence current for 5 % of ITF respectively.

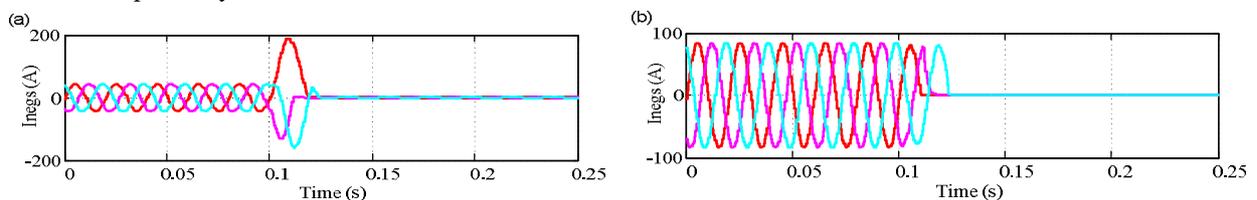


Fig.13 Simulation results of 10 % Inter-turn fault for (a) Negative Sequence current of primary winding (b) Negative Sequence current of secondary winding

Fig.13 (a) and (b) gives simulation result for negative sequence current of primary and secondary winding respectively, for 10 % of IFT at 0.10 sec.

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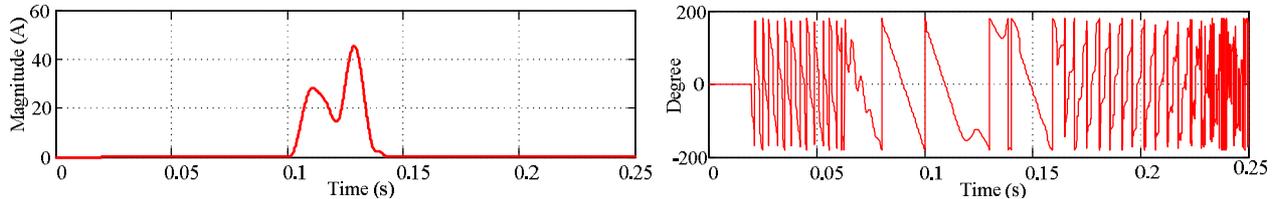


Fig. 14 Simulation results of 10% Inter-turn fault for Difference between primary and secondary negative sequence current of (a) Magnitude

Fig 14 (a) shows magnitude and phase angle between primary and secondary negative sequence current for 10% of ITF.

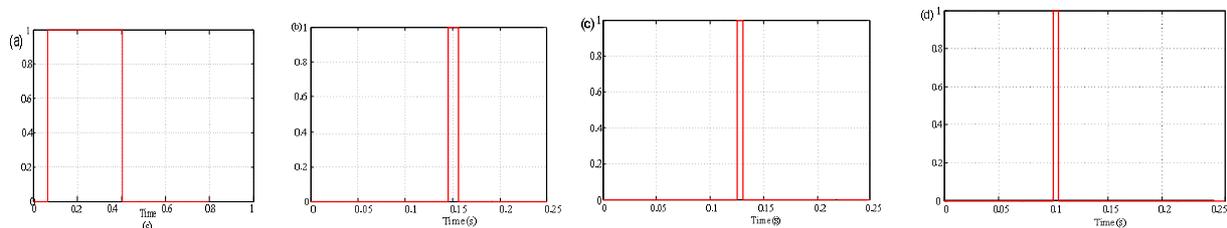


Fig.15 Simulation results of tripping signal for (a) 2%, (b) 3 %, (c) 5%, and (d) 10% of ITF respectively.

For 2% of ITF Fig. 15 (a) shows that a trip signal is received at 0.15 sec and the fault is analyzed up to 0.2. For 3% of ITF, fault is analyzed from 0.145 sec to 0.156 sec in Fig.15 (b). For 5% of ITF Fig. 15(c) a trip signal received at 0.125 sec and fault is analyzed up to 0.130 sec. For 10% of ITF fault is sensed at 0.1 sec and analyzed up to 0.132 sec as shown in fig. 15 (d).

TABLE II. COMPARISON OF MATHEMATICAL ANALYSIS AND SIMULATION RESULTS

% Turns Faulted	Mathematical Analysis		Simulation Results	
	$ I_{negp} - I_{negs} $ (A)	$ \angle I_{negp} - \angle I_{negs} $	$ I_{negp} - I_{negs} $ (A)	$ \angle I_{negp} - \angle I_{negs} $
2 %	6.25	179.8°	6.70	179.10°
3%	21.22	179.11°	21.6	179.82°
5%	25.54	176.83°	26.02	179.93°
10%	42.96	179.81°	45.25	179.30°

## IV. CONCLUSION

Simulation results for different percentages of Inter-turn Fault are discussed in this paper. It is observed that, ITF fault for various percentages as 2 % ITF, 3 % ITF, 5 % ITF, and 10 % ITF are represented and discussed in detail. The results are satisfactory for all cases. Using Negative Sequence Component, the value of current and phase angle is obtained to identify ITF on related winding. The algorithm is given in which comparison of primary and secondary current with NSC trip signal is carried out. This relaying scheme i.e. NSC is stable and very sensitive to offer better fault detection capability and that too without any addition sensor requirement.

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