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ORIGINAL ARTICLES

# Improved differential relay for bus bar protection scheme with saturated current transformers based on second order harmonics

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**KEYWORDS**

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**Abstract** Differential relays security to the external faults is affected by the saturation of branches' current transformers (CTs). In this paper, a simple scheme is proposed to enhance the security of differential numerical relay by extracting the 2nd order harmonic using Fast Fourier Transform (FFT) to produce a restraint signal to inhibit the relay operation during external faults. The operation signal of differential relay is produced by comparing the vector addition of secondary currents of branches' CTs (differential current) with pre-set value; the restraint signal is produced by comparing the algebraic sum of 2nd order harmonic of individual secondary currents with the 2nd order harmonic of differential current. The proposed scheme is investigated using PSCAD/EMTDC simulation and tested during internal and external faults for saturated CTs. The obtained results reveal how this scheme is effective and secure to the external faults for different suggested scenarios. The proposed scheme is using the simplest technique of signal processing compared to other proposed techniques.


## 1. Introduction

Bus bars are the connection points for a number of transmission lines and many electrical apparatus, so differential relays are used for bus bar protection as shown in Fig. 1. Bus bar protection is considered as the most important part of power system protection because if any incorrect operation occurs, it will lead to disconnecting healthy circuits connected to the bus bar.

The principle operation of differential bus bar protection depends on the Kirchhoff current law, which states that the sum of currents that enter the bus equals the sum of currents that leave bus; on the other hand, it can be expressed as the vector sum of all currents entering and leaving the bus bar equals zero as in (1):

$$\sum \bar{I}_j = 0. \tag{1}$$

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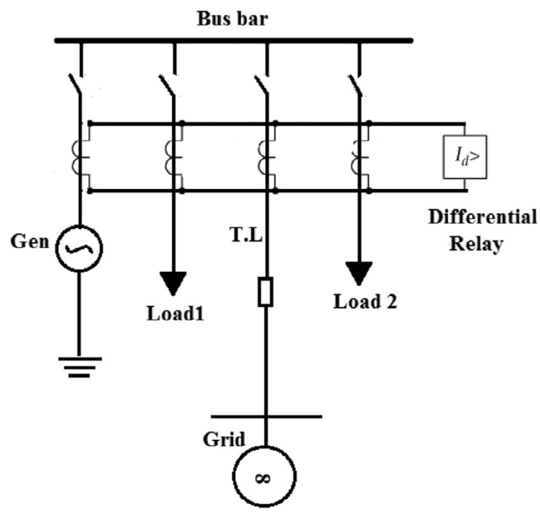


**Figure 1** Differential bus bar protection.

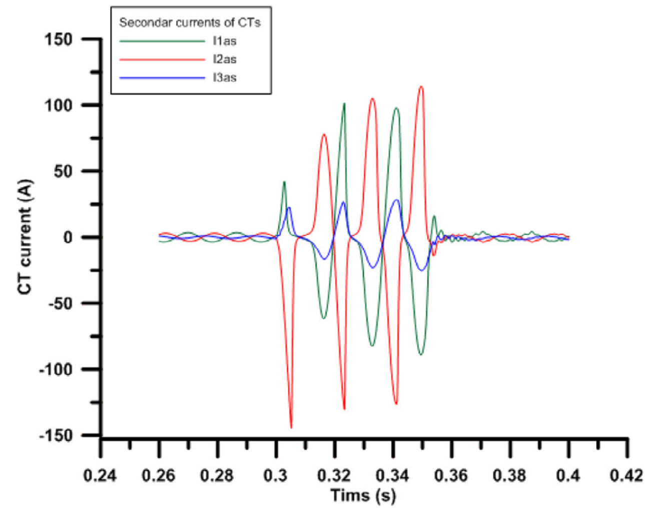


**Figure 3** Secondary currents of saturated branches' CTs.

where $j$ is the branch connected to bus bar, $\bar{I}_j$ is the vector current of $j$ branch which is measured by current transformer CT as in Fig. 2(a). If an internal fault is incepted in the bus bar as shown in Fig. 2(b), then the vector sum of all branches' currents will equal the fault current as in (2):

$$\sum \bar{I}_j = I_f \tag{2}$$

where $I_f$ is the fault current. If the fault is located out of the protection zone of the differential protection of the bus bar as shown in Fig. 2(c), which is called external fault, then the vector sum of all branches' currents should equal zero as in (1).

The major problem with bus protection is unequal core saturation of branches' CTs during external faults as shown in Fig. 3.

The basic requirement is that the total scheme must provide the degree of selectivity necessary to differentiate between an internal and an external fault (Kang et al., 2008). For electromechanical relays, the harmonic component current as restraint was used to prevent incorrect operation of differential relays in the presence of unbalanced currents due to various causes such as CT saturation (Kennedy and Hayward, 1938).

In recent differential numerical relays, signal processing techniques are used to enhance the performance of differential relays such as a wavelet transform to detect bus bar faults and discriminate them from external faults (Eissa, 2014, 2013, 2004; Fernandez, 2001; Kang et al., 2008).

Adaptive digital band pass filter is used to extract the fundamental frequency components of differential and through current signals (Basha et al., 1996). Measuring the power system source impedance at the relay location is used to detect CT saturation (Fernandez, 2001), which requires current and bus voltage measurements.

Positive and negative sequence of measured currents and voltages at bus bar location are used to detect the CT saturation and ratio mismatch (Sachdev et al., 2000). A graph theory is used for selecting the bus protection zones in microprocessor relays (Qin et al., 2000).

In this paper, Fast Fourier Transform (FFT) technique is used to extract the 2nd order harmonics of secondary currents of individual branches' CTs and differential current signal. FFT is the most widely used technique in signal processing which makes this proposed scheme simple and robust.

## 2. Proposed scheme for bus bar protection

The proposed scheme shown in Fig. 4 is producing two signals to enhance the performance of differential relay: first signal is the operating signal which is produced by calculating the dif-

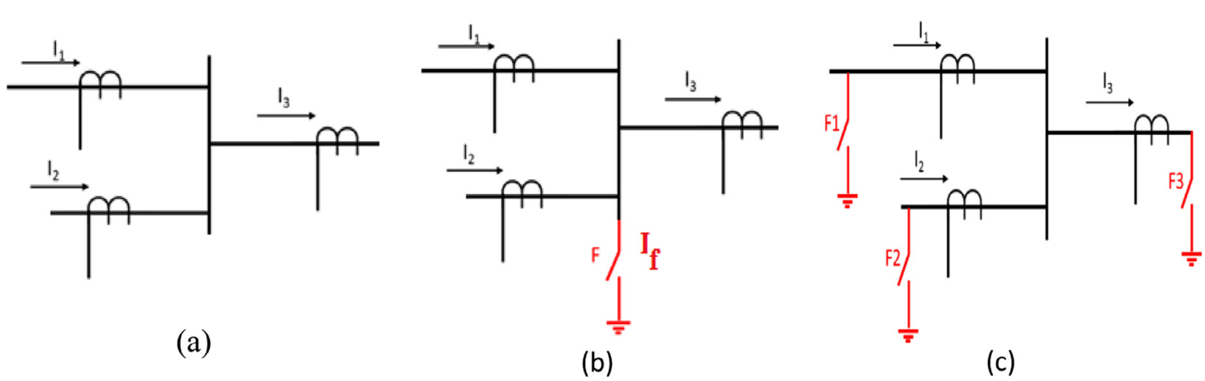


**Figure 2** (a) No fault; (b) internal fault; (c) external fault.

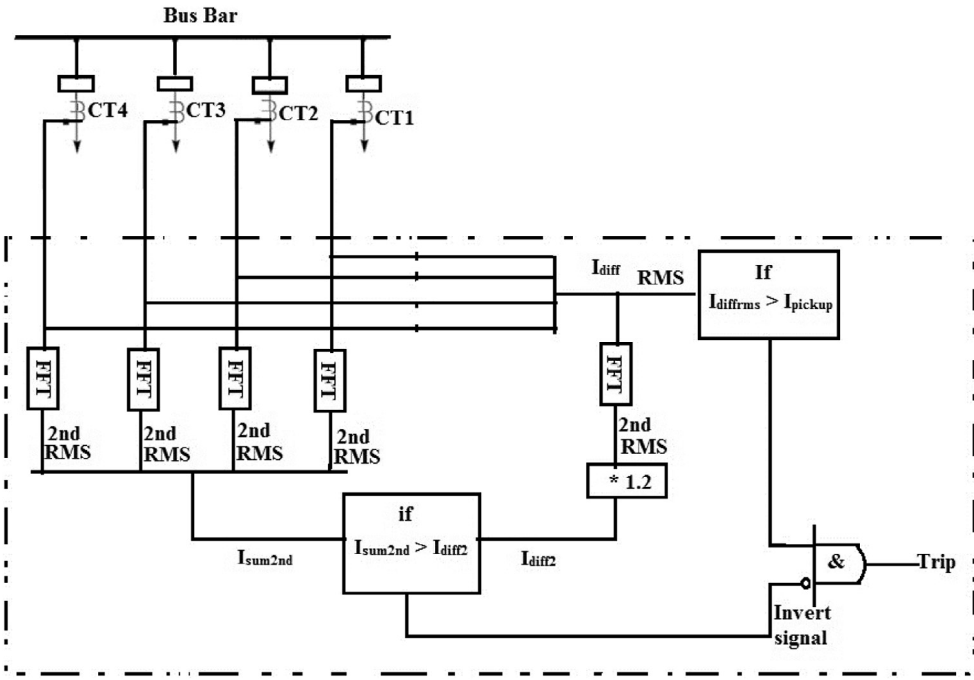

**Figure 4** Block diagram of proposed algorithm.

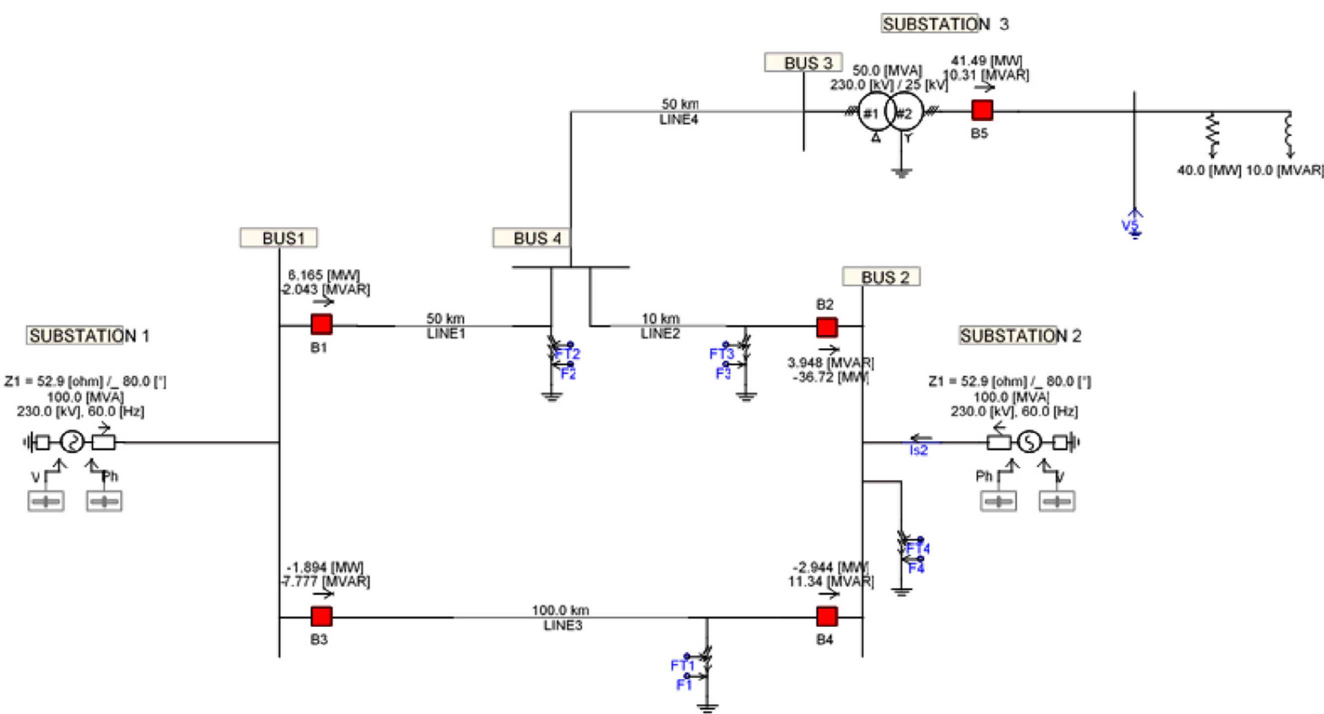

**Figure 5** Single-line diagram of power system case study.

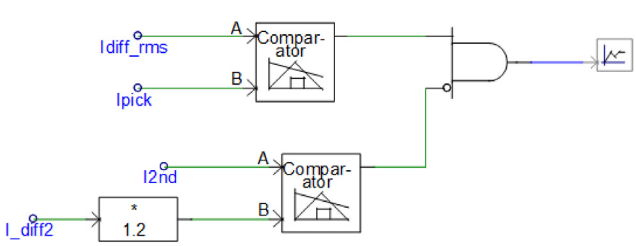

**Figure 6** Simulation of proposed scheme.

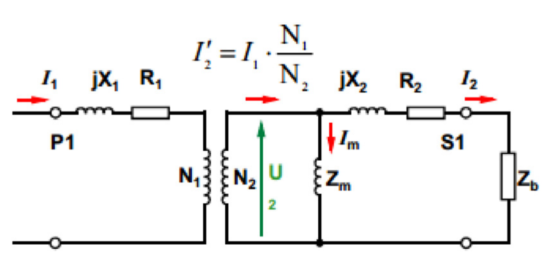

**Figure 7** Equivalent circuit of current transformer.

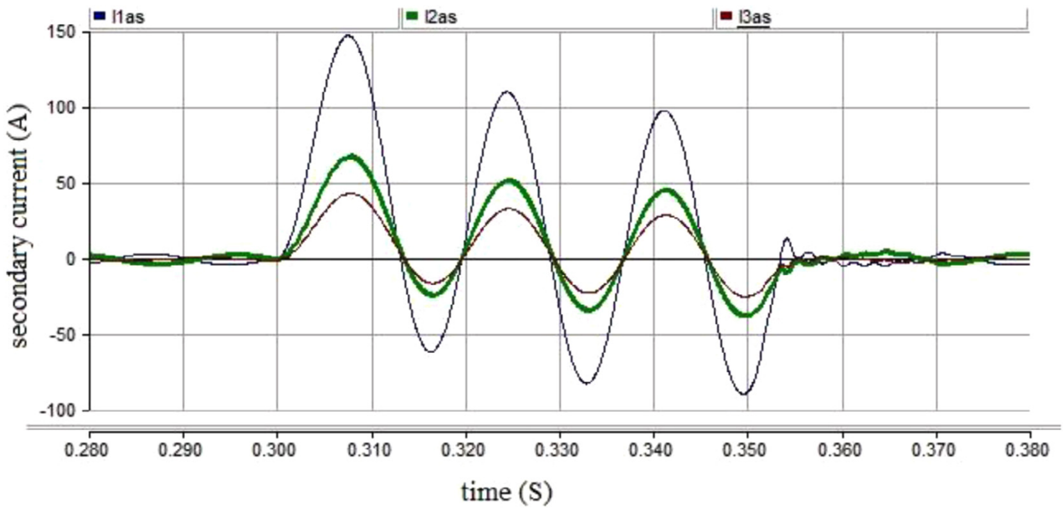


**Figure 8** Secondary currents during internal fault (burden impedance 0.5 Ω without remnant flux).

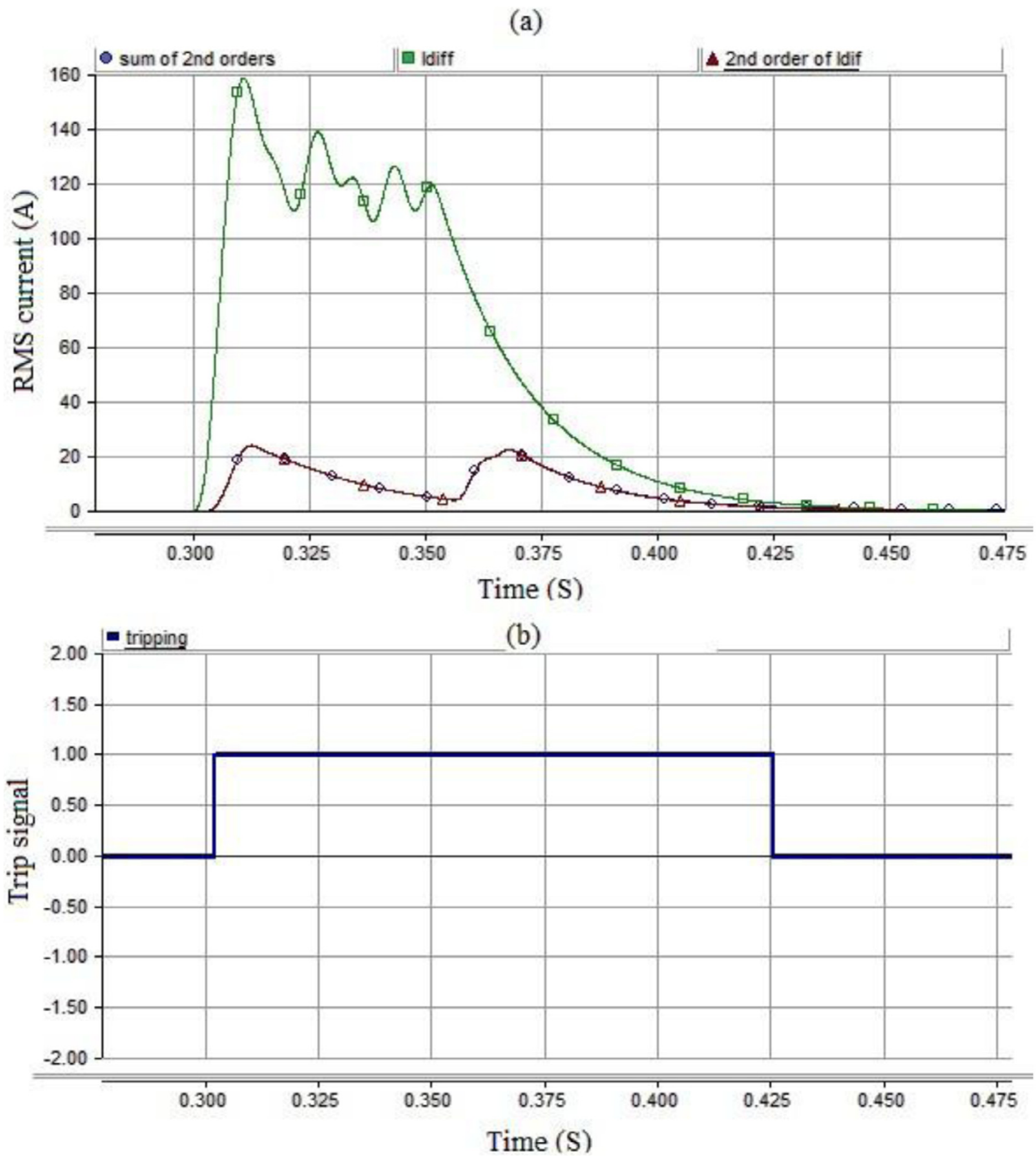


**Figure 9** (a) RMS currents; (b) trip signal during internal fault with low fault resistance and unsaturated CTs.

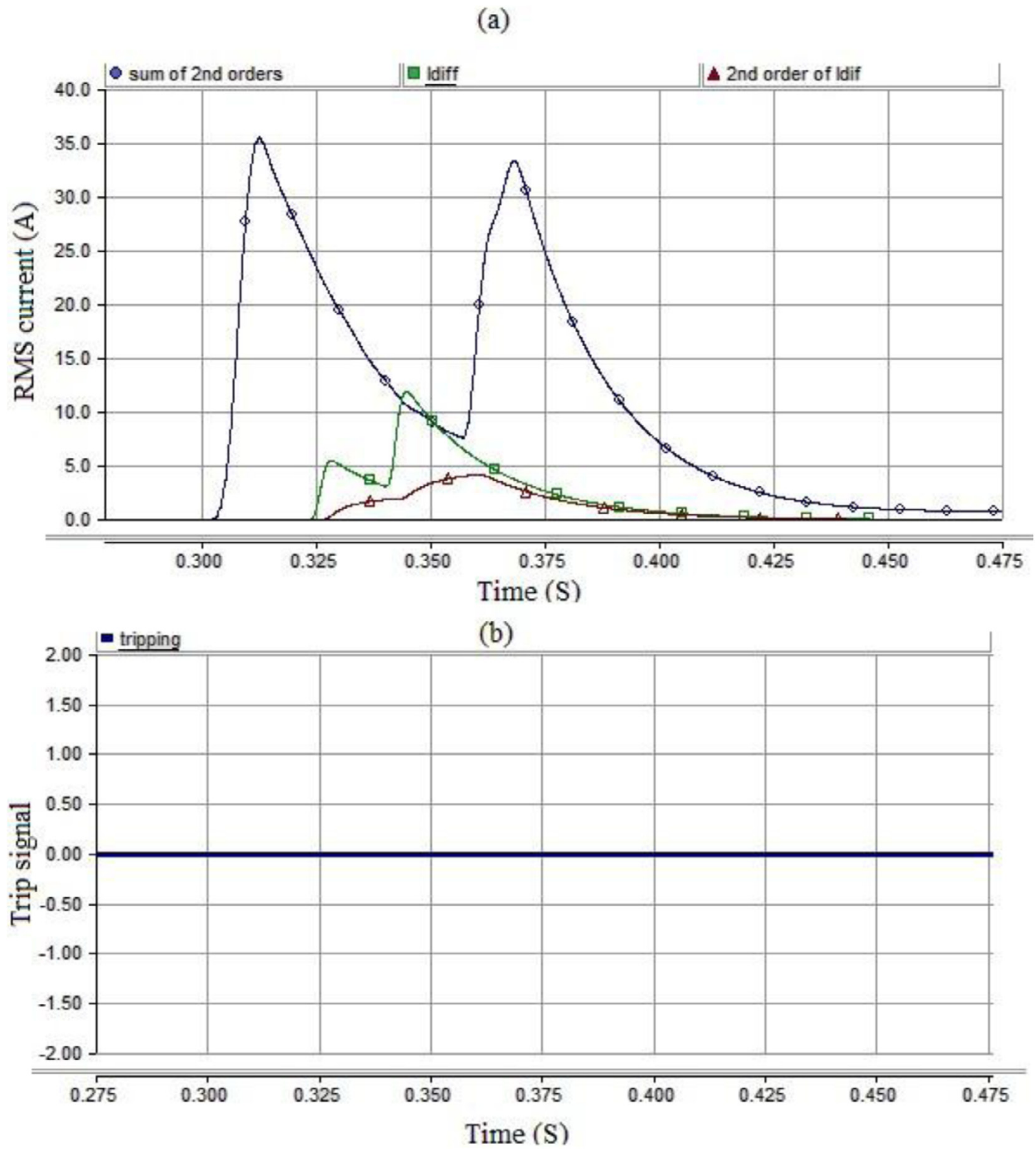


**Figure 10** (a) RMS currents; (b) trip signal during external fault, with low fault resistance and unsaturated CTs.

ferential current from the vector sum of secondary currents of branches' CTs as in (3):

$$\sum \bar{I}_j = I_{diff} \tag{3}$$

where $I_{diff}$ is the differential current and $I_j$ is the secondary current of CT placed in $j$ branch. $I_{diff} \approx 0$ for normal operation and unsaturated CTs, and for normal operation and saturated CTs the differential current is compared with pickup current value $I_{pickup}$ as in (4)

$$I_{diff} > I_{pickup} \tag{4}$$

Second signal is a restraint signal which calculated to inhibit the incorrect operation of differential relay. The restraint signal is produced in the proposed scheme by comparing the algebraic sum of 2nd order harmonic of secondary currents of branches' CTs ($I_{sum2nd}$) with the 2nd order harmonic of differential current $I^{2nd}_{diff}$ as in (5) and (6)

$$I_1^{2nd} + I_2^{2nd} + I_3^{2nd} = I_{sum2nd} \tag{5}$$

$$I_{sum2nd} > 1.2 \, * \, I^{2nd}_{diff} \tag{6}$$

The external fault can happen at any branch of bus bar either $F_1$, $F_2$ or $F_3$ as in Fig. 2(c). If the external fault occurs and (4) is true due to the CTs saturation then (6) will block the differential relay from operation during external faults.

## 3. Methodology simulation

Single line diagram of power system shown in Fig. 5 is used to investigate the proposed differential relay scheme, where data for the studied system are given in Appendix I. The proposed differential relay scheme is simulated using PSCAD/EMTDC as shown in Fig. 6. Bus 2 is protected by proposed differential relay scheme, so the faults (FT1, FT2, and FT3) are considered

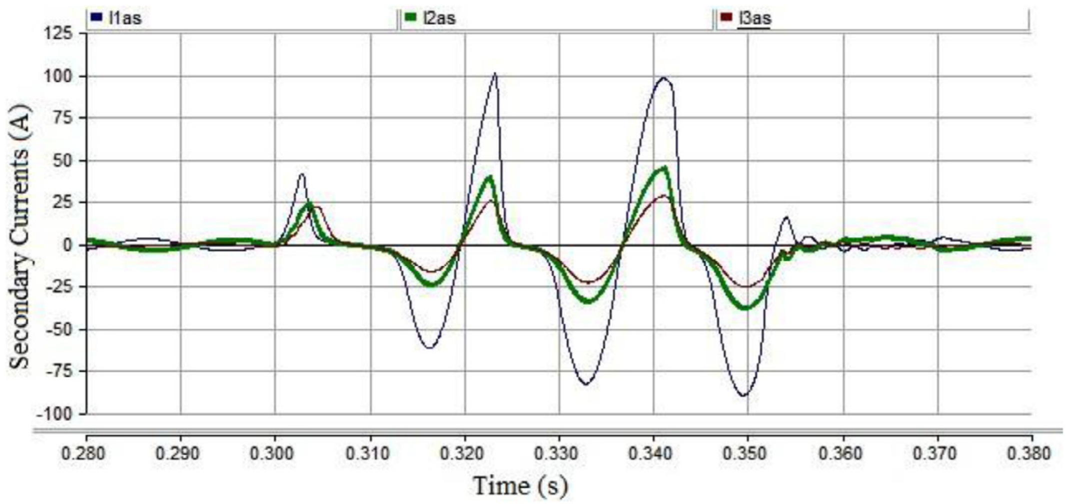


**Figure 11** Saturated secondary currents during internal fault (burden impedance 5 Ω and remnant flux 1.5 *Tesla*).

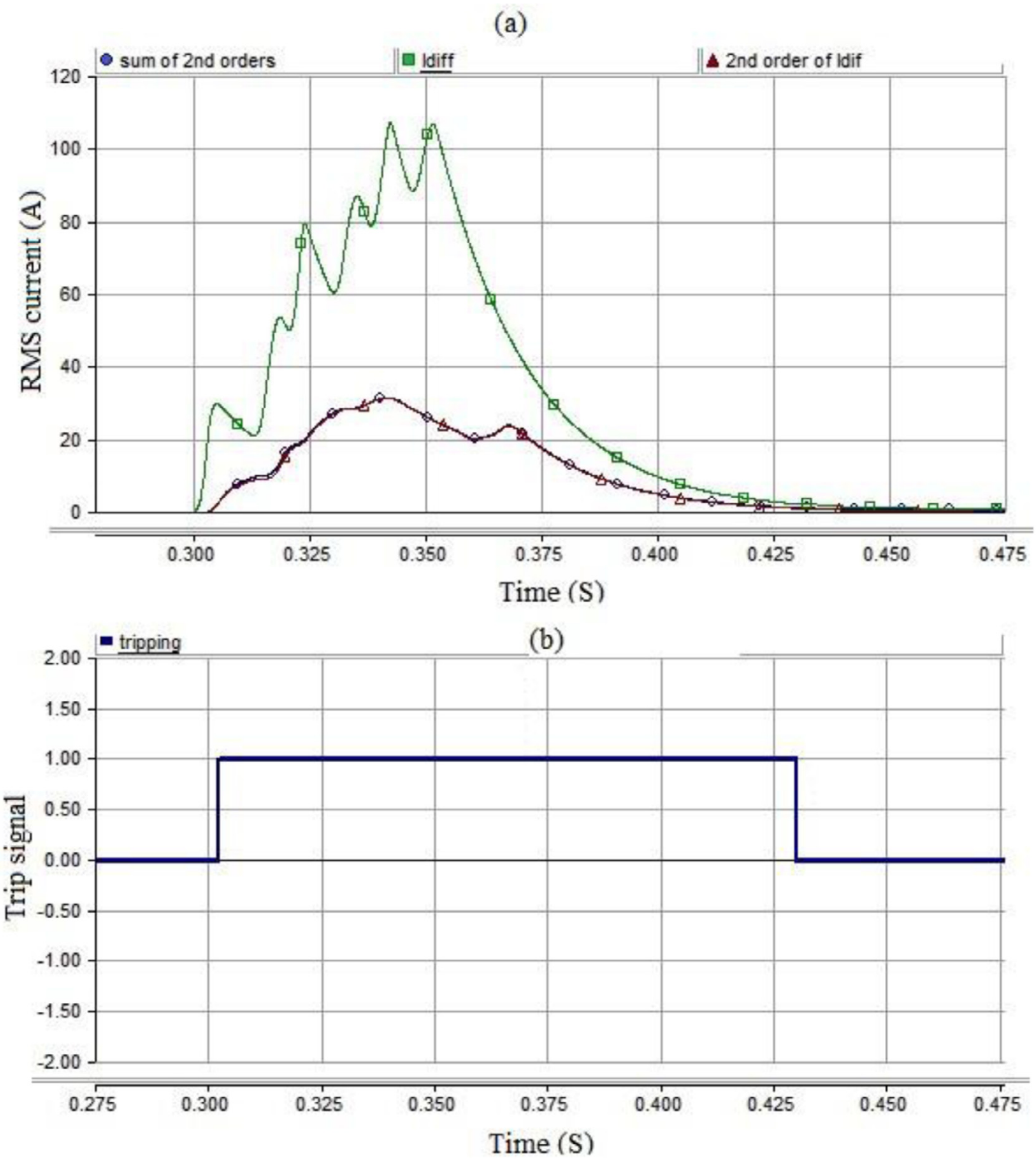


**Figure 12** (a) RMS currents; (b) trip signal, during internal fault, with low fault resistance and saturated CTs.

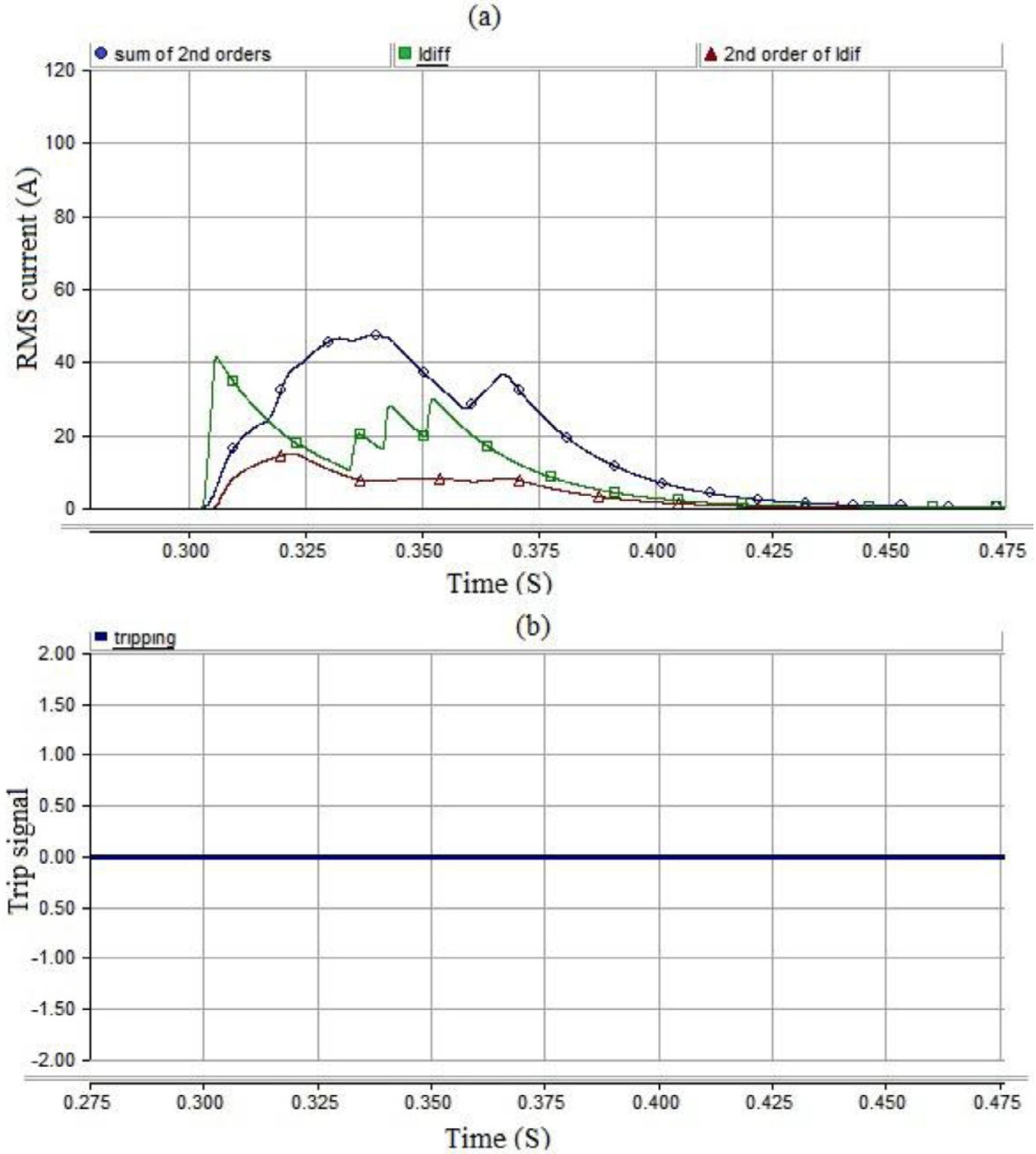


**Figure 13** (a) RMS currents; (b) trip signal during external fault, with low fault resistance and saturated CTs.

as external faults to bus 2 and fault (FT4) is considered as internal fault as shown in Fig. 5.

The equivalent circuit of CT is shown in Fig. 7, where the secondary side voltage $U_2$ can be calculated as in (7)

$$U_2 = Z_m \times I_m = I_2 \times (R_2 + jX_2 + Z_b) \tag{7}$$

where $Z_m$ is magnetizing impedance, $I_m$ is magnetizing current, $R_2$ is resistance of secondary winding, $X_2$ is the leakage reactance of secondary windings, and $Z_b$ is the burden impedance. Secondary voltage of CTs $U_2$ should be very small value to avoid CT saturation.

CT Saturation is achieved in PSCAD by controlling burden impedance $Z_b$, Remnant flux which affects $Z_m$, and fault current $I_1$ by controlling the fault resistance $R_F$.

## 4. Results

### *4.1. Low fault resistance and unsaturated CTs*

Under the condition of low fault resistance $R_F = 0.001\ \Omega$ and unsaturated or unstressed CTs ($Z_b = 0.5\ \Omega$ and remnant flux 0 *Tesla*), the fault is incepted at 0.3 s, and the duration of the fault is 0.05 s. The secondary currents of the three CTs during the internal fault are shown in Fig. 8.

During the internal fault (at location FT4), the protective relay should send a trip signal to the CBs to isolate the protected bus 2. Fig. 9(a) shows that the RMS differential current is very high during the internal fault when the pickup current is set to 0.2A and that the second-order harmonic of the differential current is almost equal to the sum of all three second-order harmonics of the phase currents in the three branches, as shown in Fig. 9(a). Then the protective relay will send a trip signal to isolate the faulted bus 2, as shown in Fig. 9(b).

On the other hand, during an external fault (at FT3, located close to CB2), it is clear that the differential current is not zero because the current that passes through CT2 is the sum of the currents passing through CT1 and CT3, leading to unequal saturation between CTs. It is clear that the sum of all second-order secondary currents in the CTs is very high at the beginning of the external fault and that the second-order differential current is very low, as shown in Fig. 10(a). Once the external fault has been detected, the protective relay is blocked, and no trip signal is generated, as shown in Fig. 10(b).

### 4.2. Low fault resistance and saturated CTs

Under the condition of low fault resistance $R_F$ = 0.001 Ω and saturated or stressed CTs ($Z_b$ = 5 Ω and remnant flux 1.5 *Tesla*), higher stress is applied to the CTs, where the CT secondary currents are as shown in Fig. 11. It is clear that all CTs are saturated and that the measured currents are distorted.

Fig. 12(a) shows that the RMS differential current is very high during the internal fault, with the pickup current still set to 0.2A. The second-order harmonic of the differential current is almost equal to the sum of all three second-order harmonics of the phase currents in the three branches. Then the protective relay will send a trip signal, as shown in Fig. 12(b).

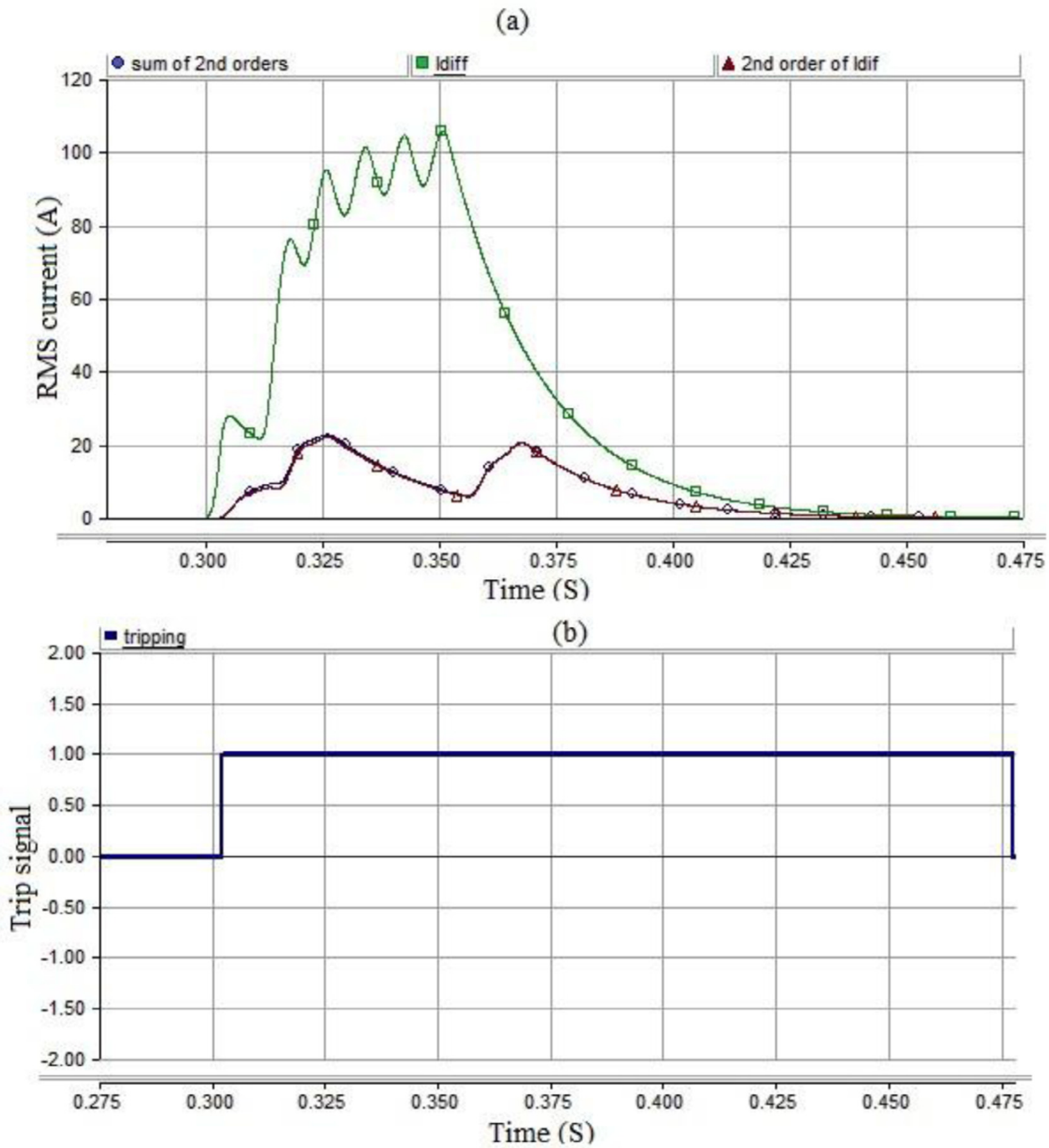


**Figure 14** (a) RMS currents; (b) trip signal during internal fault, with high fault resistance and saturated CTs.

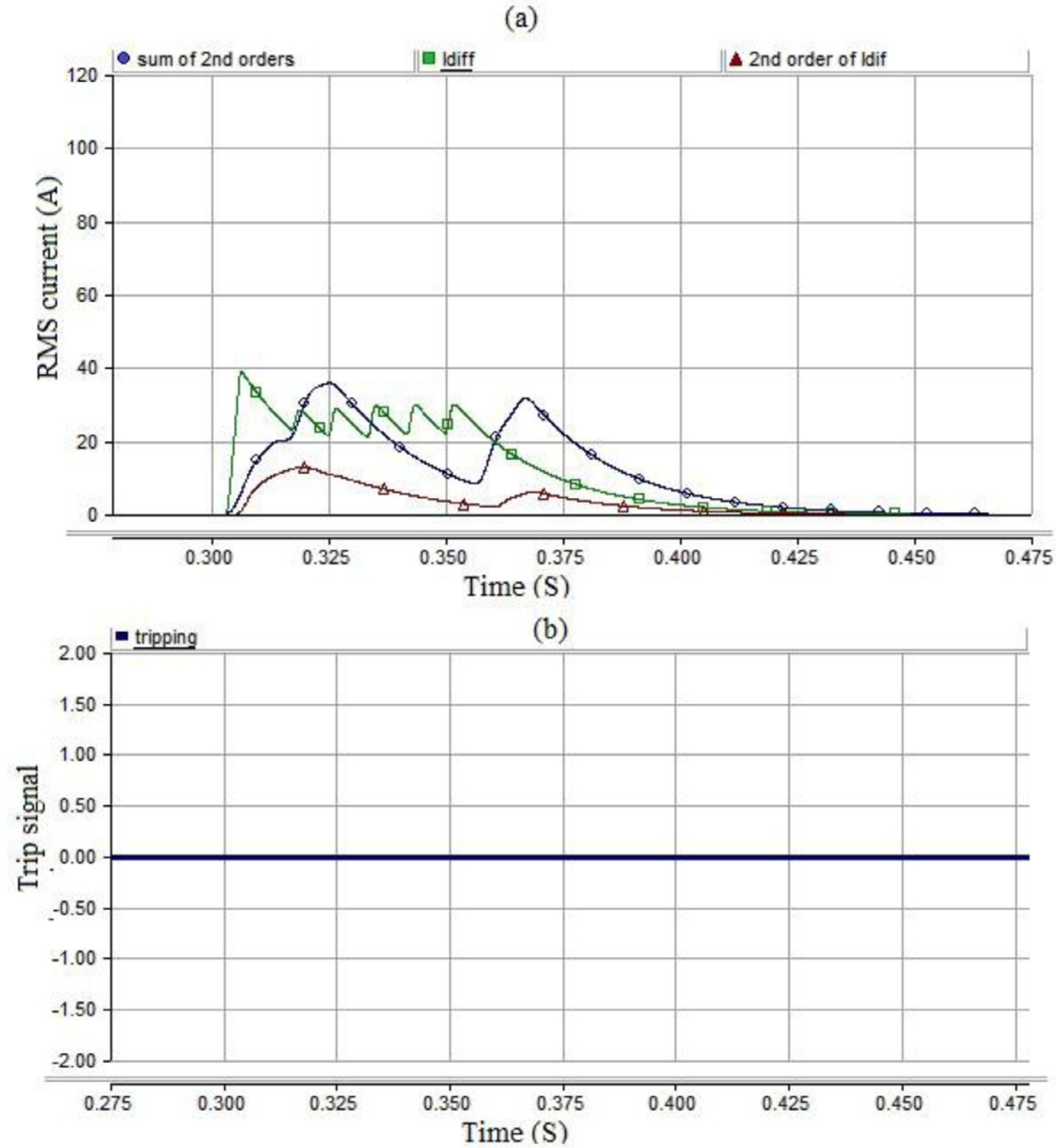


**Figure 15** (a) RMS currents; (b) trip signal during external fault, with high fault resistance and saturated CTs.

In contrast, during an external fault (at location FT3, close to CB2), it is clear from Fig. 13(a) that the differential current is larger than the pickup current, but the protective relay will not send a trip signal, as shown in Fig. 13(b).

### *4.3. High fault resistance and saturated CTs*

In this section, the fault resistance is assumed to be high, $R_F = 10\,\Omega$. The fault begins at 0.3 s and lasts for 0.05 s. For high fault resistance, it is sufficient to test the proposed algorithm under stressed CT operating conditions at burden impedance $Z_b = 5\,\Omega$ and remnant flux 1.5 *Tesla*.

Fig. 14(a) shows that the RMS differential current is very high during the internal fault (located at FT4) with the pickup current set to 0.2A and that the second-order harmonic of the differential current is almost equal to the sum of all three second-order harmonics of the phase currents in the three branches. Fig. 14(b) shows that the protective relay sends a trip signal during the internal fault.

During an external fault (at location FT3, close to CB2), Fig. 15(a) shows that the differential current is larger than the pickup current, but the protective relay will not send a trip signal, as shown in Fig. 15(b).

## 5. Conclusion

Bus bars are a critical part of a power system because they are the connection point of many circuits, and therefore any incorrect operation of a differential protective relay will lead to tripping healthy circuits. In this paper, a new numerical differential relay scheme is proposed to protect the bus bars. Fast Fourier Transform (FFT) technique is used to extract the 2nd order harmonic of secondary currents of branches' CTs and differential current. The proposed scheme produces two signals: operating signal by comparing differential current with pickup current, and restraint signal by comparing the algebraic sum of 2nd order harmonic of secondary currents of CTs with 2nd order harmonic of differential current. The proposed scheme is simulated and tested using PSCAD. Saturation of branches' CTs is achieved by controlling burden impedance, remnant flux, and fault resistance. The obtained results reveal that the proposed scheme has very fast response to the internal faults and highly secure to the external faults. The proposed scheme is simple and robust compared to other proposed scheme because it uses simple and wide spread technique for signal processing which is FFT.

## Appendix I

The load current at bus 2 in the system shown in Fig. 2 can be calculated as follows: load + losses = 50 MVA; then 120% * 50 = 60 MVA, so the current = 60 MVA/($\sqrt{3}$ * 230 kV) = 150.61 A. The CT ratio is selected as 200/5 A. The Jiles-Atherton type of CT was used in this research. The secondary resistance and inductance of CTs were 0.021 Ω and 0.8 mH respectively. The area and path length of the iron core were $2.601e^{-3}$ $mm^2$ and 0.6377 m, respectively.

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