

Investigation of Residential Customer Safety- Line, Neutral and Earth Integrity

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Abstract-- Reverse polarity and neutral failures can produce potentially dangerous voltage levels within electrical consumer's premises. While earthing at the consumers premises is normally good during the installation, it may degrade over time. Existing conventional electromechanical energy meters do not detect such conditions at the consumer premises. Hence, an accurate detection of conditions such as reverse polarity, earthing and neutral failure and degradation is essential for safe and reliable operation of a household electrical system. It is highly desirable that a protection system is designed such that it should detect such conditions accurately and it should not be oversensitive, as this could lead to an unnecessarily unacceptable high level of "nuisance" operation. In addition, such a solution should have to be reliable, economical and easily adoptable into existing premises without any major modification to the installation. This paper is intended to derive various necessary indices to detect neutral and earthing failure or degradation and reverse polarity conditions at the electrical consumer's premises. The simulation is carried out with the MATLAB® – SIMULINK® software with SimPowerSystems™ toolbox. These indices can be integrated into a smart meter or similar device to accurately detect earthing and neutral failure or degradation and reverse polarity conditions at consumer premises.

I. INTRODUCTION

IN a Multiple Earthed Neutral (MEN) system, both neutral and earth are connected together. In addition, earthing is bonded together with gas/water pipes in order to improve overall earthing in a household electrical system. The main purpose of a grounded electrical system is to provide human or animal safety by facilitating fault current to flow safely through ground in the event of a fault. In addition, earthing is used for the correct operation of an electrical system, overall economy of the system and stabilisation of voltage and limitation of lightning and other surges [1]-[3]. During neutral failure and reverse polarity conditions, high current flows through earthing and it can create potentially dangerous voltage levels within a consumers installation. Other conditions such as earthing failure or degradation are not detected by conventional electromechanical meters and it is not easily recognised by electrical consumers. Such conditions prevail for a longer duration without detection. It is essential to immediately detect and isolate power supplies to prevent any electrical accident within electrical consumers premises

upon occurrence of such events.

Nowadays, tamperproof smart meters are available to record energy that can detect various fault conditions such as reverse polarity, neutral failure, earth fault etc. [4][5].

In a conventional electromechanical meter, energy recording depends upon both line and neutral currents. If neutral current is bypassed totally or partially through ground, the energy recording in the electro mechanical meter can be reduced or stopped. Instead, smart meters continuously monitor neutral and line current separately. The analog meter device ADE7761 consists of a programmed chip that immediately detects mismatch between line and neutral current more than 6.25% in the event of tampering and continues billing taking the larger of the two currents into consideration [4]. Similarly, other smart meters use a different index (e.g. ADE7751 uses 12.5% mismatch between neutral and active current) to detect tampering conditions [4]. However, the operation of a smart meter is limited to a revenue purpose.

During various fault conditions such as reverse polarity, neutral failure, earthing failure, neutral and earthing degradation at residential consumer premises, the neutral and the line currents change. In addition, the potential between neutral and line rises during reverse polarity and neutral failure. It is possible to detect various fault conditions within consumers premises by continuous monitoring of the currents. This paper investigates various fault conditions within a household electrical system by deriving various indices based on the measurements of active and neutral currents. These indices can be incorporated into a smart meter or a similar device to accurately detect various fault conditions.

II. BACKGROUND THEORY

A. Reverse Polarity

In a reverse polarity condition, line and neutral conductors are interchanged and are thus connected in the opposite polarity. During reverse polarity, very high current flows from neutral (which is connected to line phase instead) to earth and smaller currents return to the source through line (connected to neutral). This high current flow through the ground results in a high voltage drop between the neutral and ground, there is also a potential of neutral rise with reference to ground.

B. Neutral Integrity

The probability of an electrical accident due to neutral failure at a consumer premises is low as compared to other faults, which occur at consumer installations as it requires occurrence of many events simultaneously. [1] The neutral

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conductor carries an unbalanced current in the distribution system. The potential of the neutral point continuously fluctuates depending upon the unbalance in the system. In addition, neutral current flows from load points toward the source and a potential drop appears across neutral conductor depending upon the neutral impedance. In a Multiple Earthed Neutral (MEN) system, the neutral conductor is grounded at an equal interval to maintain neutral potential nearer to the ground potential. A break in the neutral conductor can vary phase to neutral voltage from zero to phase to phase voltage depending upon the unbalance. [2]

The connection of the neutral to the ground at a consumers service entrance allows the current to flow through ground uncontrolled in a multigrounded neutral system [6]. The connection to the neutral at the consumer service is made through splices, where corrosion and other environmental effects increase the neutral impedance over time and more current returns through ground as a low impedance path available for current to return to the source through ground. In addition, weather conditions or foreign objects may break the neutral conductor. [1] When a break in the neutral occurs, neutral current takes another path (i.e. Ground) in order to return to the source. This increase in the ground current eventually results in a potential rise of neutral from almost ground potential. Hence, the continuous monitoring of the neutral potential can be used to detect a neutral failure. The change in neutral current with respect to the active current can also be used to detect neutral degradation and failure at the consumer premises.

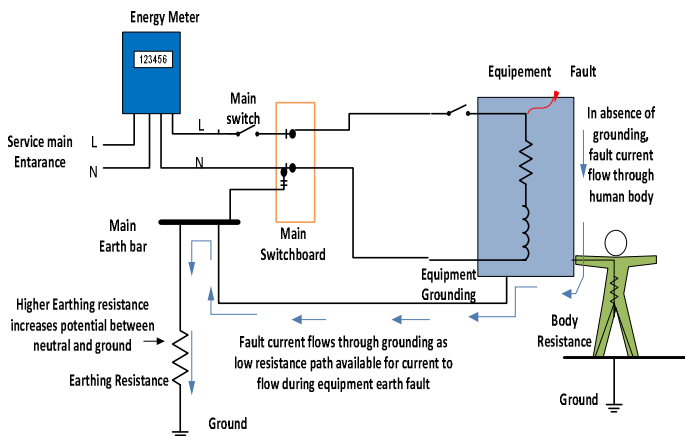


Fig 1. The ground path shunts fault current to flow safely through ground

C. Earthing Integrity

The grounded electrical system offers safety and is also beneficial for the correct operation of the electrical system, it maintains power quality/harmonics and limits power surges [1]-[3]. These advantages come with a major drawback, if earthing resistance is too high or earthing continuity is not maintained. All conductive parts of electrical equipment are connected to the ground. If a fault occurs in the wiring or if insulation of equipment fails and the conductive part of equipment comes in contact with an active conductor, current flows safely through ground as shown in Fig 1

During an earthing failure, a person can get an electrical shock as no other alternative path is available for the current to flow through ground; it is necessary to isolate the power supply during an earth fault to prevent a person from getting a shock. A current higher than 30 mA for 240 ms is considered as dangerous [6] and therefore it is desired to isolate the power supply in less than this time period when an earth fault exists.

The neutral to earth voltage depends upon the earthing resistance. The earthing resistance may increase over time due to corrosion of electrodes, moisture, other environment effects, change in soil conditions or defects in the joints. The higher earthing resistance increases voltage drop between neutral and earth. The minimum value of neutral to earth voltage is required especially when earthing is bonded with gas/water pipes accessible to public. It is essential to periodically inspect the condition of earthing. Australian - New Zealand standard AS 3000:2007 suggests performing various electrical tests to measure earthing continuity and earthing resistance at certain intervals to confirm earthing integrity [7]. However, these tests are time consuming, expensive and a level of expertise is needed to perform such tests. In addition, presence of harmonics in a distribution network makes measurement of line impedance difficult [8, 9].

As mentioned earlier, in a Multiple Earthed Neutral (MEN) system, changes in the active and neutral currents take place during various fault conditions. In addition, the neutral to earth voltage level changes during these fault events. The method proposed in this paper is based on continuous monitoring of power at consumer's installation.

III. SIMULATED MODEL

A test system is modelled and simulated using MATLAB[®] – SIMULINK[®] software with SimPowerSystems[™] toolbox. A test model includes a small three phase four wire distribution system that distributes power to single phase and three phase loads as shown in Fig. 2. Currents for line, neutral and earthing conductors are measured separately for each of the fault conditions at a consumers premises. In addition, voltage between neutral and earth is also measured. There are two different single phase load points selected for this study.

Load 1 is connected between phase c and the neutral and load 2 is connected between phase b and the neutral. Load 2 is taken nearer to the source (transformer) compared to load 1. In total 20 different loads are applied for the test of the system. The load values connected to each phase are different and unbalanced current is returned through neutral and partial current through ground to the source.

The line conductor chosen for the test system is 336,400 26/7 ACSR having a resistance = 0.19 Ω /km and the neutral conductor is 4/0 6/1 ACSR, Resistance = 0.35 Ω /km as suggested in the IEEE radial distribution test feeders given in ref [10]. The earthing resistance at the customer premises depends upon the soil conditions, type of electrodes and depth of electrodes. National Electrical code (NFPA) Article 250.52

demands connecting electrodes in parallel when a single electrode has a resistance more than 25 Ω . It is a reasonable estimate to achieve earthing resistance in the range of 1 – 4 Ω by connecting electrodes in parallel and bonding with gas/water pipes as per estimated in ref [1]. In the test system, different earthing resistance values are selected at different consumer premises in the range of 1 - 4 Ω . The earthing resistance at load point 1 is selected as 1.5 Ω and 2 Ω at load point 2. Earthing and neutral failure conditions in the simulation are implemented by inserting a time operating switch in series with neutral and earthing. It is initially closed and is opened after a certain predefined time interval to achieve neutral or earthing failure as shown in Fig. 3.

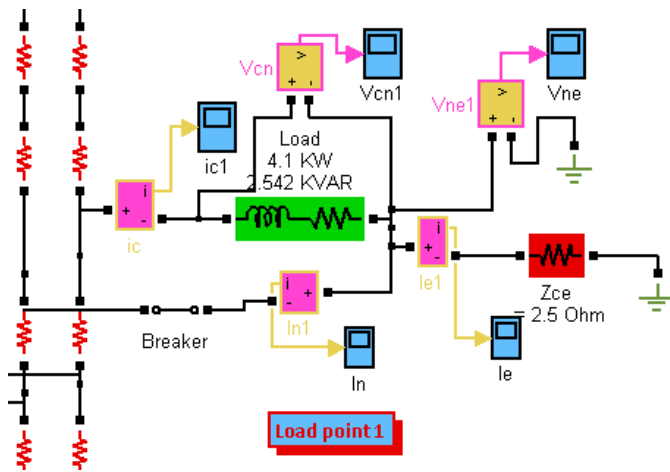


Fig 3 Breaker connected in series with the neutral conductor

IV. SIMULATION RESULTS

A. Reverse Polarity

During a reverse polarity condition at test point 1, line and neutral are interchanged and line is directly connected to the earth instead of neutral, as shown in Fig 4. As a result, a very high current flows through the line and most of the current returns to ground instead of neutral. In a simulation, very high current (83 amp) flows through the neutral conductor during reverse polarity. Most of this neutral current (70 amp) flows through ground, as it provides a low impedance path for current to return to the source (transformer) and very little current (13.10 amp) flows through the line conductor. In addition, phase angle of the line and neutral currents are measured and it is observed that line and neutral have phase angles of 12.84° and 12.46° during normal conditions. Direction of current flows changes during reverse polarity and phase angle changes to -167.42° and -141.66° for line and neutral currents respectively. It is observed and expected that around 180° changes occur in a line current during a reverse polarity. Further, while earthing resistance is 2 Ω , voltage between neutral and earth is increased to 140 V.

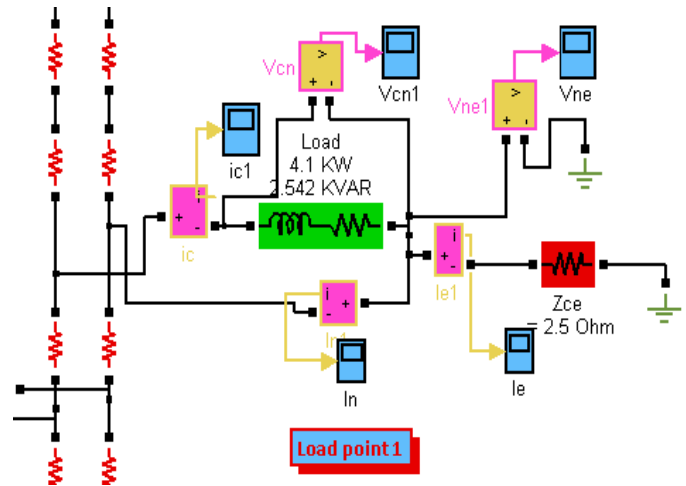


Fig 4 Reverse polarity condition at consumers premise

While the reverse polarity condition occurs at test point 2, neutral current (78.62 amp) flows and returns through the line (11.91 amp) and earth (65 amp). The earthing resistance at the consumer premises is taken as 1.5 Ω . The voltage between neutral and earth appears around 100 V. Similar to load point 1, the phase angle of line and neutral (131.82° and 130.97°) changes to -46.98° and -24.99° respectively.

From the above simulation results, the following indices are derived to detect reverse polarity condition.

- Neutral to active current ratio (I_n/I_a) = 83.39/13.10 = 3.36 >1
- Voltage between earth and neutral >50 V
- Change in phase angle of line current = $\Phi \pm 180^\circ$

B. Earthing Integrity

The earthing resistance and continuity of the earthing connection at the consumer premises can be confirmed by conducting various tests at the consumer premises. These tests are time consuming, expensive and require expertise. In addition, these tests do not guarantee earthing conditions are maintained between two tests performed. Earthing degradation and earthing failure can be accurately detected by the continuous monitoring of active and neutral currents.

1. Earthing Degradation

The earthing at the consumer premises may degrade over time. Possible causes include corrosion of electrodes, defects in joints or other weather conditions. The earthing resistance is increased from 0 Ω to 6 Ω in steps of 0.1 Ω and both active and neutral currents are measured. The neutral to active ratio is plotted against earthing resistance as shown in Fig. 5. It can be observed that the neutral to active ratio increases with the increase in the earthing resistance at test point 1.

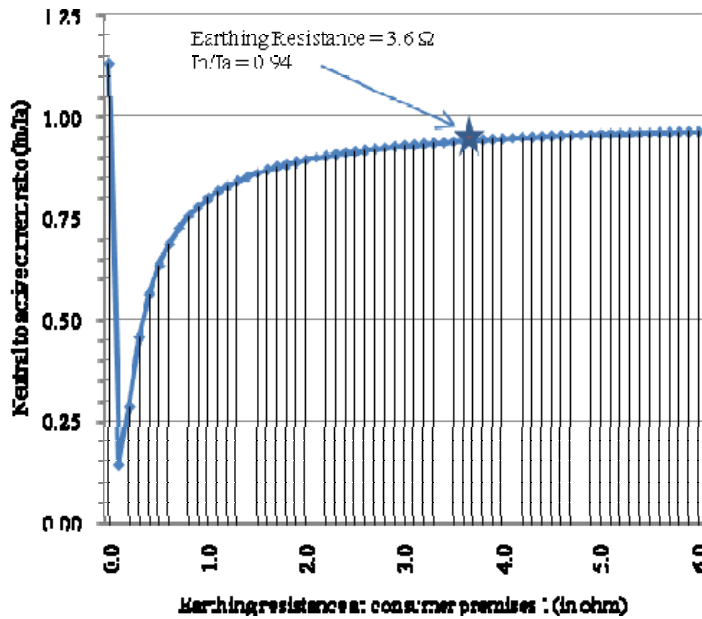


Fig 5 Neutral to active current ratio against earthing resistance

The neutral to active current ratio becomes 0.94 when earthing resistance is 3.6Ω for load point 1. Any further increase in the earthing resistance will increase this ratio from 0.94. For load point 2, the ratio becomes 0.94, when earthing resistance is 2.7Ω . The difference in the two results is due to the facts that load point 1 is farther away from the source compared to load point 2. The overall neutral resistance at load point 1 is higher than load point 2.

Proposed index:

- Neutral to active current ratio (I_n/I_a) > 0.94

2. Earthing Failure

During normal operation, the active current is returned to the source through the neutral and little current returns through the ground. The earthing at the consumers premises can become open circuit due to foreign object causing damage, weather conditions or a break in the earthing conductor. Under an earthing failure condition, all line current returns to the source through the neutral and earth current becomes zero. The ratio of the neutral to active current (I_n/I_a) becomes equal to 1.

Proposed index:

- Neutral to active current ratio (I_n/I_a) = 1

C. Neutral Integrity

The line conductors return path in the consumer premises to the source is through the neutral conductor. It is essential to maintain neutral integrity to avoid current taking another path (i.e. ground) to return to the source. The neutral resistance accounts for the earth loop fault impedance. An increase in the neutral resistance increases overall earth fault loop impedance.

1. Neutral Failure

During neutral failure, line current returns through the earth and neutral current becomes zero. The failure of the

neutral suddenly increases the voltage between the neutral and earth to a potentially dangerous level depending upon the earth resistance value. The ratio of the neutral to active current becomes 0 during a neutral failure. In a simulation, time operating switch is connected in series with the neutral conductor and initially placed closed as shown in Fig 3. After 0.2 sec delay, switch opens to achieve neutral failure. It is seen from the Fig 6 that small voltage appears between neutral and earth while switch is closed. During neutral failure, around 60 V appears between the neutral and earth at both load points as shown in Fig 6.

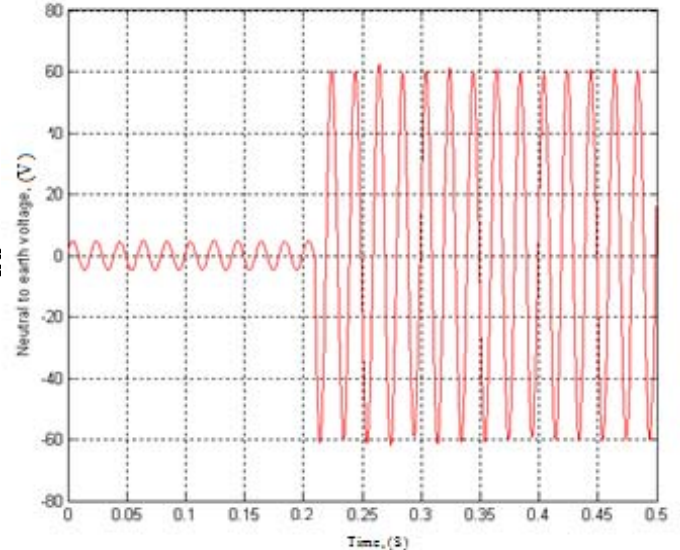


Fig 6 Neutral to Earth voltage

Proposed Indices:

- Neutral to active current ratio (I_n/I_a) = 0
- Voltage between neutral and earth > 50 V

2. Neutral Degradation

The neutral is connected through splices and weather effects can increase the neutral resistance over time. The increase in the neutral resistance in the simulation is achieved by connecting resistance in series with the neutral and neutral resistance is increased from 0Ω to 0.6Ω in steps of 0.01Ω . The active and neutral currents are measured and the ratio of the neutral to active current is plotted against neutral resistance as shown in Fig 7. It is observed from the simulated results that the neutral to active current ratio becomes 0.8 while neutral resistance is 0.34Ω at load point 1. Any further increase in the neutral resistance reduces the neutral to active current ratio from 0.8.

The neutral to active current becomes 0.8 when neutral resistance is 0.17Ω at consumer load point 2. The earthing resistance value for load point 1 and 2 is taken as 2.5Ω and 1.5Ω respectively. It is seen that an increase in the neutral resistance from 0.34Ω for load point 1 and 0.17Ω for load point 2 can be accurately detected when the neutral to active current ratio becomes less than 0.8.

Proposed index:

- Neutral to active current ratio (I_n/I_a) < 0.80

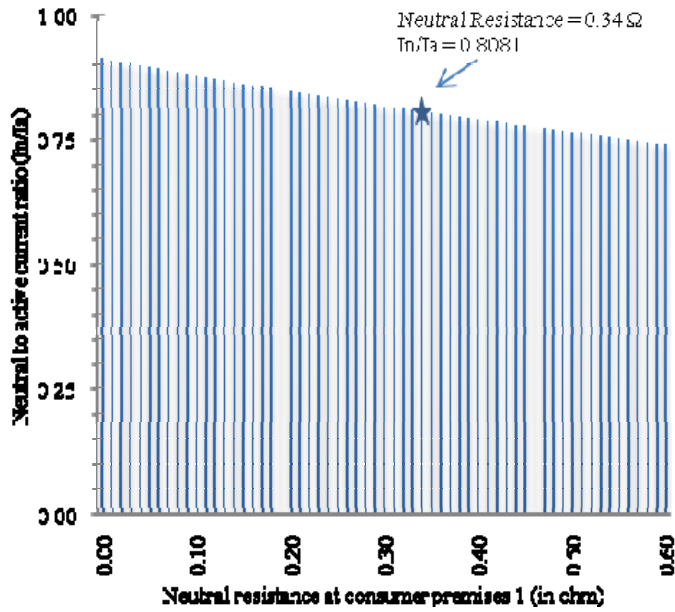


Fig 7 Neutral to active current ratio against neutral resistance

Table I summarises various indices proposed in this paper. It can be seen from the results that reverse polarity and neutral failure can produce potentially dangerous voltage levels within consumer premises. The proposed method to continuously monitor currents to detect various fault conditions offers a cost effective and accurate solution for the protection system.

TABLE I
PROPOSED INDICES TO DETECT VARIOUS FAULT
CONDITIONS WITHIN CONSUMER PREMISES

Situation	Proposed indices
Normal Condition	$0.94 < I_n/I_a < 0.80$ During normal operating conditions, the neutral to active ratio falls between these two limits. It is desired to operate the electrical system within this limit for correct operation and safety of the personnel and property within the consumer premises.
Reverse Polarity	$I_n/I_a > 1$ $V_{ne} > 50V$ Change in phase angle of line current: $\Phi \pm 180^\circ$ In the reverse polarity situation, neutral current becomes higher than line current and the I_n/I_a ratio becomes greater than 1. Load point 1 $I_n/I_a = 3.36$, $V_{ne} = 140$ V, $R_e = 2 \Omega$ Load point 2 $I_n/I_a = 7.02$, $V_{ne} = 100$ V, $R_e = 1.5 \Omega$
Earthing Degradation	$I_n/I_a > 0.94$ Under normal conditions, the neutral to active current ratio should be less than 0.94. If this ratio increases from 0.94, it indicates degradation in the earthing system. Load Point 1 $R_n > 3.6 \Omega$ (indicates degradation) Load Point 2 $R_n > 2.7 \Omega$ (indicates degradation)
Earthing Failure	$I_n/I_a = 1$ During an earthing failure, earthing current becomes zero and the neutral to active current ratio becomes $I_n/I_a = 1$.

Neutral Degradation	$I_n/I_a < 0.80$ The ratio of neutral to active current being less than 0.80 indicates neutral degradation. Load Point 1 $R_n > 0.34 \Omega$ (indicates degradation) Load Point 2 $R_n > 0.17 \Omega$ (indicates degradation)
Neutral Failure	$I_n/I_a = 0$ $V_{ne} > 50$ V ($V_{ne} \approx 60$ V both load points) $R_e = 2.5 \Omega$ (Load point 1) $R_e = 1.5 \Omega$ (Load point 2) During a neutral failure, the neutral current becomes zero and the ratio of neutral to active current becomes zero.

Earthing resistance in the range of 2 – 4 Ω can be maintained with the proposed techniques. In addition, these indices can be incorporated such that the user can easily adjust to the desired level. If the proposed index at load point 1 is adjusted from 0.94 to 0.93, the earthing resistance value above 3 Ω can be detected instead of 3.7 Ω . Similarly a neutral resistance value of less than 0.5 Ω can be maintained with the proposed method. During reverse polarity and neutral failure, the circuit breaker can operate in accordance with the smart meter settings to isolate the power supply immediately upon occurrence of such a situation.

V. ADVANTAGES OF PROPOSED METHOD

This proposed technique to detect fault conditions at consumer premises offers several advantages compared to conventional protection techniques. The advantages are:

- 1) **Reliability:** The proposed method continuously monitors active and neutral currents and accurately detects various fault conditions. It is possible to detect fault conditions with the proposed method at a consumer's premises immediately upon its occurrence.
- 2) **Economical:** This method does not require expensive hardware or any costly circuitry. Nowadays smart meters are available that continuously monitor active and neutral current. The proposed indices can be easily integrated into a smart meter with further design modification.
- 3) **Compact:** The proposed method can detect various conditions such as reverse polarity, earthing failure, earthing degradation, neutral failure and neutral degradation. The conventional protection device can provide protection against a single fault event. For example, a residual current device (RCD) cannot detect a reverse polarity, earthing degradation condition. Today, several devices are required to provide protection against these fault conditions. It is possible to detect various fault conditions from a single device with the proposed method.
- 4) This method does not require any extra modification in the installation and it can be easily implemented into existing premises without extra modifications.
- 5) It is possible to control and maintain line and earth integrity from a remote place with this method. The smart meter comes with a feature that allows the supplier to monitor power at consumer premises from a remote place. With this proposed method, the supplier of a

remote place can easily monitor line and earth integrity of the user's installation.

VI. CONCLUSIONS

Various indices are proposed in this paper to accurately detect various fault conditions within an electrical consumer's installation. These indices can be easily incorporated into a smart meter to detect a number of fault conditions in addition to energy recording. Alternatively, other devices can be designed and these indices can be integrated to detect fault conditions. In this proposed method, separate measurement of active and neutral current is required. This device can work in association with a circuit breaker to isolate the power supply in the event of a fault condition such as neutral failure, reverse polarity to prevent an electrical accident. Future works shall work towards the design and implementation of the above proposed indices into a smart meter or other similar device after validating the results.

VII. REFERENCES

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VIII. BIOGRAPHIES



Raj B. Jadav has completed Master of electrical engineering from the, University of Queensland, Brisbane, Australia in 2008. Earlier he received a Bachelor of engineering degree from Nirma Institute of Technology, Ahmadabad, India in 2003. During 2004 to 2006, he worked for an electrical distribution company, P.G.V.C.L (Paschim Gujarat Vij Company Limited), Gujarat, India and he worked for Sardar Sarovar Hydro Power project, Gujarat, India in 2007.

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