



# Geomagnetically Induced Current Impact on Power Transformer and Neutral Protection Methods

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## Abstract

Geomagnetically induced current (GIC) is a geomagnetic phenomenon. Inducing this current in power grid can cause damage to the transformers by creating hot spots, increase the losses of the power system, and cause some problems in the electrical energy transmission process to the consumers. GIC can make the transformer operate in its magnetic saturation region and therefore increase the reactive power and harmonics by the transformer. This paper introduces the GIC and its impacts on the power systems and power transformers. Moreover, several methods to confront this destructive phenomenon are investigated and their merits and drawbacks are proposed using computer simulations of a power system in the presence of GIC.

**Keywords:** Sun storm, geomagnetic induced current, power transformer, saturation, neutral protection, THD.

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## 1. INTRODUCTION

Some disturbances have been observed in two recent decades due to changes in the space weather. Generally, the space weather is known as a time-variant condition in the environment which is capable to damage the human made devices in the space or on the earth and in the worst cases, losing life or health of human [1–6].

The first available documents about the impacts of space weather on human products backs to the middle of 19th century. The Telegraphy lines in Britain were completely failed by two geomagnetic storms in 1847 and 1859 [7, 8]. Following these events, many times operational disturbance of telegraph and telephone lines occurred. For example, in February 1958 [9], the communication link between Europe and North America was disconnected due to a geomagnetic storm. One of the most well-known of the events backs to 13 March 1989. Transformers of hydro power station in Quebec saturated due to the storm and then power station automatically failed. Disconnection of the power station from the network led to the voltage and frequency disturbances in the Quebec network which finally Quebec absolutely blackout 9 hours due to a series of successive events [10, 11]. Taking into account the ever increasing role of the present technologies in the human life, it is vital to have alarm systems against such natural risks [12].

The sun disturbances can be the starter of geomagnetic disturbances which ultimately leads to flow a low frequency current in power system [10, 13]. This quasi-dc current can saturate the power transformers which can cause some undesirable consequences such as probable damage of transformer, mis-operation of protective

system [14–16] and system voltage collapse. Of course, it should be noted that all these problems depend on the conditions of the power network, such as long distances and high voltage cases [13, 17, 18].

The saturation due to geomagnetic induced current (GIC) increases the demand saturated MVAR of transformer leading to the required voltage control, considerable harmonic currents generation and temperature rise of the transformer internal components. So, alarm of gas relay [17] may damage the transformer. Power transformer in electrical systems should be protected to prevent subsequent damages. It is noted that core form or shell form transformers subjecting to high level of GIC would be susceptible to significant winding overheating. The GIC leads to the power system instability because of high VARS and current harmonics [19].

This paper explores the features of GIC that causes the destruction of electrical equipment on the earth. It is necessary to find a way to protect the power grid and prevent long-term blackouts. In section 2, the GIC and its origin is introduced. In section 3, the impacts of the GIC on the power system and electrical equipment are proposed. In section 4, its impact on the power transformers and its model for the GIC is presented. Finally, wire protective methods in neutral wire are proposed and the simulation results for on-line protection and transformers are given.

## 2. GEOMAGNETIC INDUCED CURRENT

The sun flames are large loops of electrons and protons which are hurled out from the sun surface. If this explosion throws the particles toward the earth, it takes almost 2 or 3 days to reach the earth. When these particles reach the

earth (after passing the earth magnetic field) they are capable to generate a current. This current, called electrojet, induces in the electrical power transmission lines, and it can totally disturb the power network. Fig. 1 shows the sun storms in October 2012 before and after the event [20]. They were generated when the earth magnetic field receives the ionized particles carried by the sun wind [21]. The sun storm as a flowing ultrasonic plasma, magnetic and hot with a huge source of kinetic energy and different particles are distributed in the inter-planet space [21]. The charged parts are received by the earth magnetic field 20 to 30 hours after a sun explosion and it approximately takes 5 minutes to change the earth magnetic field intensively [12]. The sun activity varies quasi-periodic almost over every 11 years [22]. These phenomena particularly erupt of the sun crest toward to the earth affect satellites, communication systems, electrical power, water and weather systems [23].

Geomagnetic disturbances on the earth surface lead to the earth magnetic field variations which induces current as large as millions of Amperes flowing through ionosphere along high geographical latitude [24–26] and an after-effect dominates at middle latitudes [27]. This current has very low frequency around 0.001 to 0.1 Hz and this is the reason that it is assumed dc or quasi-dc current [28].

These currents are not regular and have continuous variations in time and position. The magnetic field causes huge currents flowing through the conducting materials such as stones in the earth layers, oceans water and any human made equipment such as long cables over oceans and power lines. The probability of the occurrence of this event differs for different geographic latitudes. For geographic latitude between 20-60 degrees this has the most probability to occur and have the most effects [18, 29]. The sudden and extensive geomagnetic storms cause GIC. These extensive variations occur in a part of the earth surface leading to the variation of the earth magnetic flux. These variations induce the electrical field on the earth surface which generates potential difference between the earthed points [30].

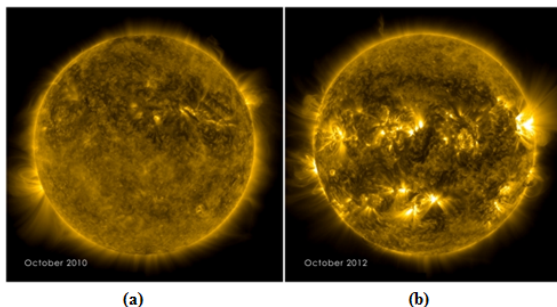


Fig. 1. Sun changes in October 2012 (a) before and (b) after solar storms [12].

### 3. IMPACTS OF GIC ON POWER SYSTEM

The GIC is related to a current in ionosphere which affects electrical power system. When this current links to the sun storms activity, it induces a current in power

system. The average value of the GIC that happens for 10 to 15 A and the peak can become over 100 A in 1 to 2 minutes [31, 32]. The GICs of up to 200 A are reported to flow in the transformers situated in Auroral regions in the United States, Canada, Finland, and Sweden when geomagnetic storms are in progress [33–35]. The first report backs to 1859 due to the failure of telegraph systems in the north of USA [8, 36] and blackout in Quebec in 1989 with a cascade breakdown started by disturbance of the reactive power compensator capacitor. In this event 6 million users had no power for 9 hours. Thousands other geomagnetic disturbances (GMDs) have been so far reported in the North of America. One of the well-known GMDs was unit transformer failure in Salem nuclear power station. One of the recent events was due to 30 October 2003. It was 20-30 minutes blackout in Malmö of Sweden which affected more than 50000 users. This event causes mal-operation of a relay due to the generated 3rd harmonic from asymmetrical magnetization of a transformer. General impacts of the GIC on power network include disconnecting local electricity, impossibility of electrical power generation and collapsing the voltage [12, 35]. During the GIC, reactive power in transformers increases and this enhances the stress on the power network. Increasing reactive power above the network capacity causes the voltage drop and network voltage collapses and blackouts [12, 18, 38, 39].

### 4. IMPACT OF GIC ON POWER TRANSFORMER

The GIC is slowly varying quasi-dc type current [10, 36]. The earth composes of different layers and each layer is a path for the GIC. Facilities of the system also are appropriate path for the GIC. If the neutral points of the transformers are known as the points of determination of these distances, according to the pattern of the Earth's layers, the resistance of the earth layers is much higher than that of the electric conductors [2]. Now, if this of the earth layers are in parallel with the transmission lines, the GMD induce a geo-electric field on the Earth's surface which generates currents in the all earthed conductive structures and the current passing through the layers of the earth is negligible, therefore, almost all inductive current flows through the power lines [2]. So, the easiest path for passing the GIC is the region between the neutral wires of power transformers. These windings have low resistance compared to the earth [12]. Neutral connections of high voltage is a better way for the GIC flow due to its lower resistance compared to the low voltage of the transformer.

The impact of the GIC depends on the transformer design. Each transformer induces a unique harmonic current spectrum. For example, single-phase transformers are more sensitive and more damageable compared to three-phase transformers. In addition, the kV rating of transformer is also an important factor. It means that by rising the rating kV under the GIC conditions, the environmental behaviors, earth demanded reactive power increases [18, 32]. The deep conductivity, limitation of the operating voltage and power network topology are some factors that intensify the GIC. But more important factor is significant increase of the GIC effects in

transformers [34]. Transformer parameters are important factors in the system behavior against GIC. This current in the transformer enters it to half cycle of saturation region. This causes harmonic currents in the power network, and the harmonic currents render the electrical system and cause over voltage [39]. Impacts of these harmonic currents are high; some of them are as follows:

1. Overheating capacitor banks.
2. Possible mal-operation of relays.
3. Sustained over-voltages on long-line energization.
4. Higher secondary arc currents during single-pole switching.
5. \High circuit breaker recovery voltage.
6. Overloading of harmonic filters of high voltage DC (HVDC) converter terminals.
7. Distortion of the AC voltage waveform that may result in loss of power [40].

These harmonic currents can lead to over-load of capacitor banks, filters and reactive power compensator, mal-operation or limited operation of relays and/or both.

Those relays that have not been designed for harmonic exhibit mal-operation in such conditions [17, 39]. The GIC flowing in transformer is the main origin of power system problems during GMD operation because it changes the AC current passing the transformer. This leads to transformer saturation and significant increase of the MVAR and in a large network can cause voltage collapse and network blackout. This is the reason for network failure in Quebec in 1989 [12, 27, 35, 36]. In some cases, intensifying the effect can increase the normal AC excitation current lower than 1 A up to 300 A which is due to the flowing GIC phase current of 25 A/phase.

A low GIC can also saturate the transformer and damage it. As shown in Fig. 2 changing the performance of the transformer AC current shifts the DC flux [42]. The core of the transformer asymmetrically saturated due to the dc magnetic flux added to the AC flux. There are two cases for system reliability in the transformer over half cycle of the saturation region:

1. Total voltage collapse of the system by rising the reactive power in transformer.
2. Increasing the destructive effects of harmonics and distortion of the AC waveform of relay and protection system [20].

Accurate evaluation of the demanded reactive power and distortion of the AC waveform in modeling transformer behavior is important and vital. In total, the GIC generates a voltage waveform which finally leads to the insulation

failure. On the other hand, magnetization impedance reduces the magnetization current leading to the increase of the no-load losses [31, 41–43]. Absorption of the reactive load can cause instability in power networks. In addition, these harmonics contribute with the system and even generate harmonics. The impact on the transformer depends upon the core permeability, and magnetization impedance decreases considerably. The losses increase due to the magnetic flux residual, eddy current and winding losses (Joule effect). In addition, there is skin effect which causes the increase of the magnetization flux. Rising the contacts and tank heat due to eddy current of the harmonics leads to the increase of the stray flux [46].

The first vibration component of harmonics in the transformer increases due to magnetic field. The residual magnetic field in the core remains fixed, even when GIC has no long presence and there will be inrush current up to end of the transient state [32].

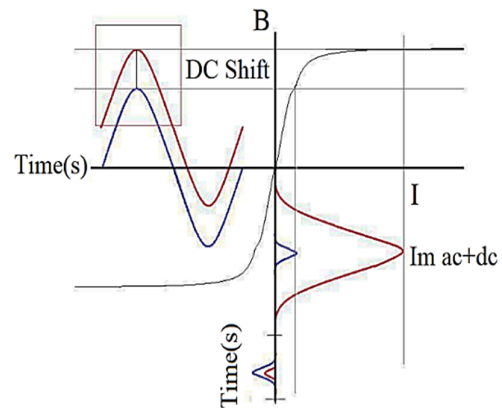


Fig. 2. Magnetic characteristic of transformer core considering GIC.

Internal connection of the power network, transmission and power flow control equipment and system voltage profile leads to higher sensitivity against GMD. GIC affects the transformer excitation characteristic by entering to the half cycle of saturation region. This distorts the excitation current having even and odd harmonics and considerable increase of the reactive power of transformer. High losses of reactive power, which may occur simultaneously, from fault point of view and/or intolerable voltage drop, is important in the system and injected harmonics causes problems for relays. In addition to the harmonic and reactive power effects for power systems, the transformer can cause extensive system stress in this operating case. Most flux exits from the core in over-saturation level.

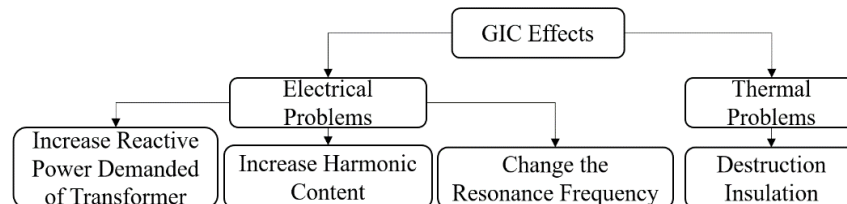


Fig. 2. Classification of GIC impacts on power transformer.

Since the core cannot provide a low reluctance path for this flux, it is considered as spatial pattern form which differs considerably from leakage flux pattern during normal non-saturated operation. This stray flux can ultimately exceed the conducting materials within the transformer and causes heat due to the eddy current. The magnetic flux penetrates in transformer tank, flux shield, braces and other structure elements and windings. Other impact of the GIC is its thermal effect on power transformers. The GIC leads to transformer temperature rise as such that hot spot temperature reaches around 175<sup>o</sup> C [20]. The thermal sensitivity depends on two factors. The first is that the single-phase unit is more sensitive to heat than that of the three-phase unit [46]. The second is that the shell type three-phase configuration is better than that of the core type [32, 46–48]. Extensive GICs can last over a period of few hours. Although a large unidirectional GIC only last a few minutes, this GIC can sequentially occur for a few days leading to the thermal effects assembling, which can damage the transformer insulation. The transformer life lose can be due to the period in which the transformer is exposed the GIC [30, 37]. On-load generator with the relevant regulations of transformer over long time has temperature rise effects upon the transformer which shortens its life span by 20% [30].

The reasons for temperature rise of the transformer include:

1. Magnetic flux leakage.
2. Magnetic flux spectrum content.
3. Magnetic flux direction considering large size of system.
4. Dimensions of system.
5. Material properties (permeability and conductivity).
6. Generated heat transfers (conduction, oil circulation).

Power transformer has a complicated structure and evaluation of its generated hotspot from the GIC saturation needs a very precise magnetic and thermal analysis. Such analysis inherently is a special case for transformer design and it is difficult to reach a comprehensive conclusion.

High saturation of transformer due to the GIC imposes abnormal performance on the system which may continue few minutes and even an hour. Such abnormal flux pattern is not generally taken into account in the transformer design process, so, it results in the shorter life or damaging risk of transformer [36]. As shown in Fig. 3, impacts of the GIC on transformers are classified into two thermal and electrical where electrical impacts are more damaging and deeper [18, 44].

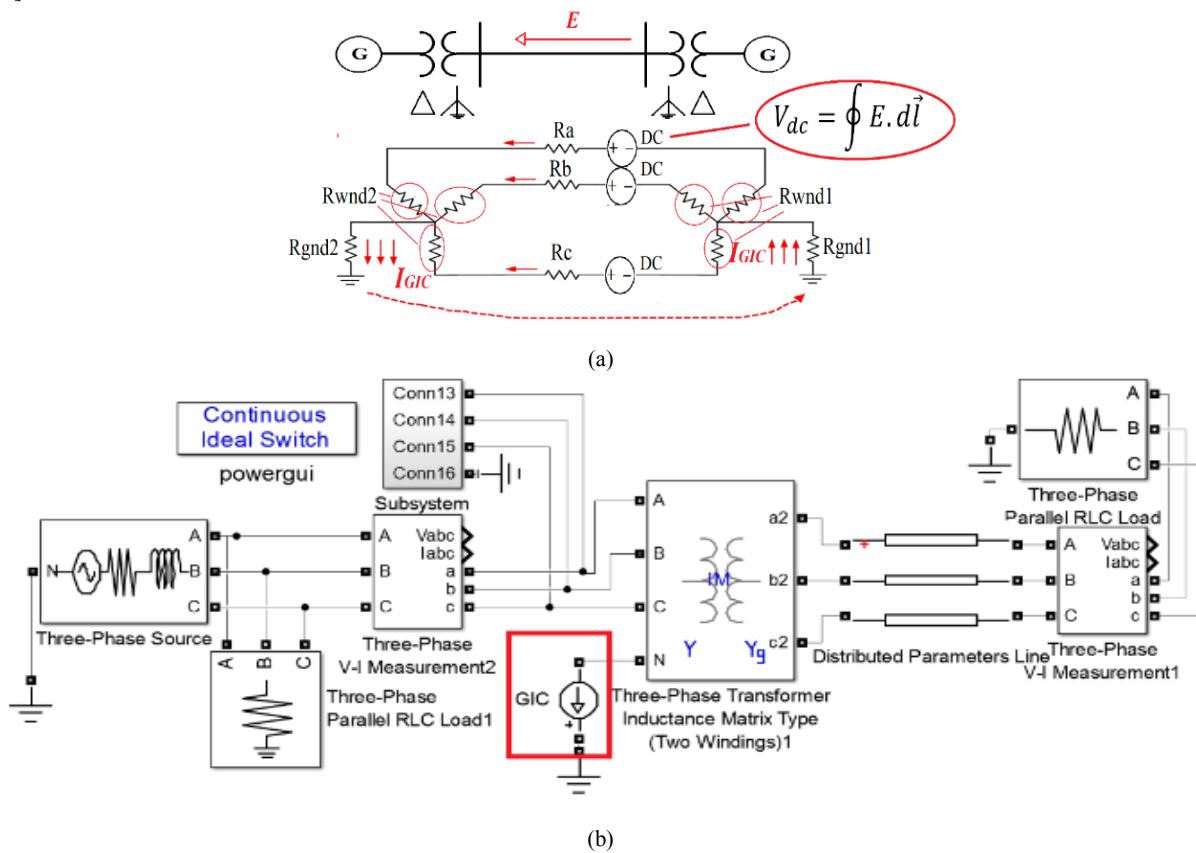


Fig. 3. (a)GIC modeling in line, (b) Schematic of system for modeling impacts of GIC on line and transformer [54].

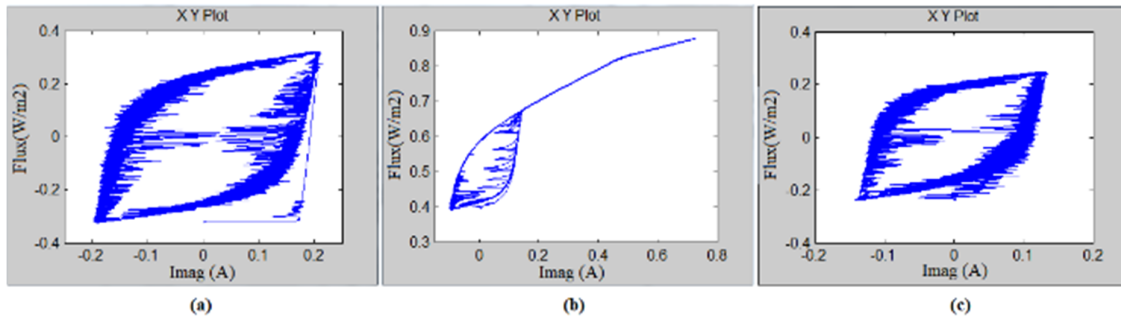


Fig. 5. Magnetization characteristic. (a). normal operation of system (no GIC), (b). with GIC, and (c). with GIC and blocker capacitance.

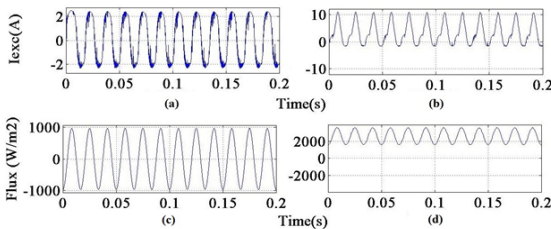


Fig. 6. Magnetic flux and excitation current: (left).normal operation of system (no GIC), (right). with GIC

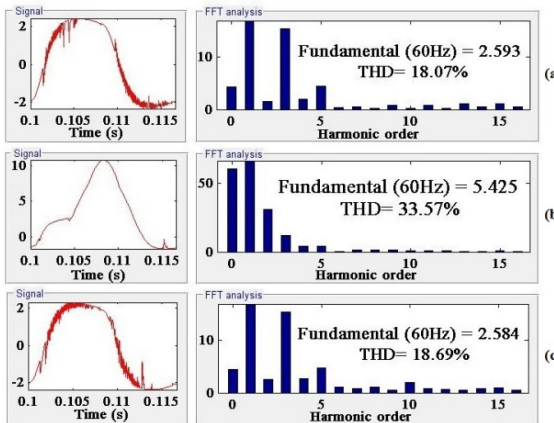


Fig. 7. Transformer excitation current.

### 5. MODELLING VOLTAGE DROP OF POWER NETWORK DUE TO GIC

Electro-jets generate the earth field variations leading to an induced current in power networks. The quasi-dc current GIC is modeled by a dc voltage source [50–52] or by current source in parallel with the line [48, 50, 51] as presented in Fig. 4a [54]. Here, impacts of the GIC on a sample line are simulated to observe precisely the fundamental components of the voltage and current and transformer core magnetization characteristic variations. The significant effects of the GIC upon transformer include variation of the hysteresis characteristic and increase of the fundamental components of the current,

voltage and excitation current of the transformer. To introduce a better perspective of the impacts of the GIC, the system is modeled and simulated (Fig. 4b). The GIC current is taken to be 25 A in the neutral and frequency 0.007 Hz. Long distances are simulated using R and X lines. Table 1 shows the specifications of the proposed transformer.

Transformer magnetization characteristic displacement in Fig. 5a and Fig 6b is evident. Presence of larger minor loops in this characteristic due to the GIC is one of the damaging effects. The dc component in voltage and current and shift of the magnetization characteristic is the other effect of the GIC on the magnetic structure of the transformer which shows the characteristic transferred to the 1st quarter of the plane. Fig. 6 indicates presence of the GIC causing the increasing 5 times of the excitation current and magnetic current 5 times, disintegrating the symmetry current, shifting flux 3 times and changes the fundamental harmonics. Fig. 7a and Fig. 7b indicate that the fundamental component of transformer excitation current has varied and 20% rise of THD indicates its high impact. The DC and fundamental component rise more than 10 times in the presence of the GIC. Since the adjustments of transformers are not ideal, excitation current has rather uniform general shape with noise. However, the presence of the GIC in power systems shifts this current and becomes asymmetrical. 15% increase of the THD of the excitation current is one of the destructive impacts of the GIC. As seen, the dc content and 2nd harmonic rises up to 15 times and 1st harmonic rises up to 3.5 times. Fig. 8 shows transformer current and its fundamental harmonic. According to Fig. 8a and b, if the dc current content flowing the transformer becomes 50 times, the 1st harmonic will be about 10 times, 2nd harmonic up to 60 times and the 3rd harmonic more than 2 times. As shown in Fig. 9a, the total THD of the transformer voltage has no significant change but the 1st harmonic will be 10 times and 3rd harmonic 2 times. Transformer voltage waveform also differs with no GIC case. The GIC destructive effects must be protected and

TABLE 1. Specifications of three-phase transformer for first simulation by MATLAB.

Symbol	Quantity	Value
$P_{nom}$	Nominal power (MVA)	450
$F_{nom}$	Frequency (Hz)	60
$V_1$	Nominal line-line rms voltage (kV)	500
$V_2$	Nominal line-line rms voltages (kV)	230
$R_1$	Winding resistances (pu)	0.01
$R_2$	Winding resistances (pu)	0.01
-	Positive-sequence no-load excitation current (% $I_{nom}$ )	2.28
-	Positive-sequence no-load losses (MW)	9
-	Positive-sequence short-circuit reactance (pu)	0.1
-	Zero-sequence no-load excitation current with Delta windings opened (% of $I_{nom}$ )	250
-	Zero-sequence no-load losses (MW) with Delta windings opened	63
-	Zero-sequence short-circuit reactance X12 (pu)	0.0914

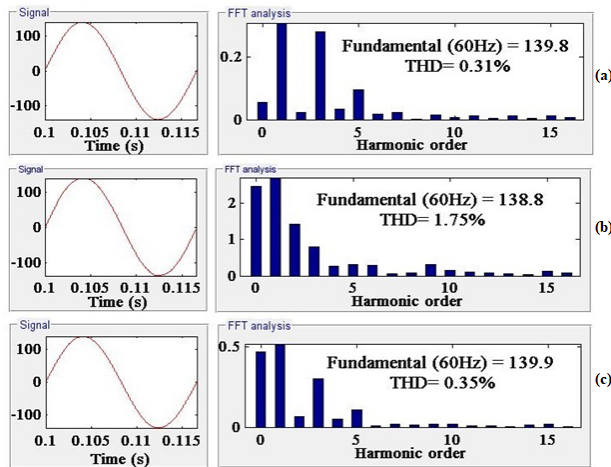


Fig. 8. Transformer current.

some preparations must be considered as described below.

## 6. GIC CONFRONTATION METHOD

Fig. 10(a) shows a series of events which finally lead to blackout. Ever-increasing technology advancement and electrical power system connection cause its more affectability and increases the necessary actions against the GMD. The methods decreasing the impact of this phenomenon on transformers are explained.

### 6.1. Preserving Power Network

As shown in Fig. 10a, a series of small events occurs which leads to a GMD and/or blackout. Thus, any action that is able to cut this series will be useful. Clearly, it is impossible to prevent the sun activities and its reactions. Therefore, following induced DC voltage in transformer winding closed-loop, earth and transmission lines, the necessary reduction action can be applied [55]. By preventing transformer against the GIC, the power network will be stable. Hence, the transformer must be non-affect by the GIC and/or network

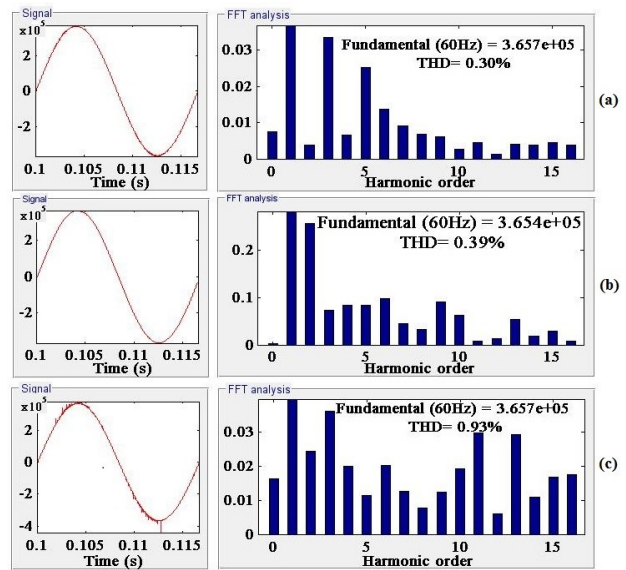


Fig. 9. Transformer voltage. (a). no GIC, (b). with GIC, and (c) with GIC - protection method by capacitance blocker.

operates separate from transformers. Therefore, the strategies using this method (Fig. 10b) can be classified in 4 categories.

Following detecting the GIC, the transformer neutral protection is activated to prevent the core saturation. If the network is as such that the blocker of neutral wire was not efficient, other methods can be used to prevent the transformer saturation. If transformer is saturated and the previous method does not help, typical protective equipment and relays with correct regulations for such phenomenon is employed to prevent the network collapse. If protective system is not capable and the method is non-efficient, by exiting on-load transformers and/or a higher probability damage over a short time, the power network can be kept active. The last method is also appropriate for protecting the transformer itself from more damages and whole destruction. This is used as final method and the last procedure.

## 6.2. Reduction Methods

### 6.2.1 DC blocker strategy

The most important and applied device that acts as DC blocker is a series capacitor. However, capacitors are costly components that in principle have other goals such as compensation of the demanded reactive power in power networks. Since the GMD occurs in a geographical region, fixing series capacitor for any transmission line is impossible economically [56]. Therefore, DC blocker in neutral can be a solution [57]. The GIC is injected through the earthed neutral to the transformers winding. So, if a device blocks the flow of DC current to the neutral, the GIC and its impacts do not appear. Under normal conditions, only unbalanced current passes the neutral point and its voltage level is very low. Generally, transformers are earthed with low impedance. Earthing has several advantages in the economical design of power systems and has a basic role in its protection.

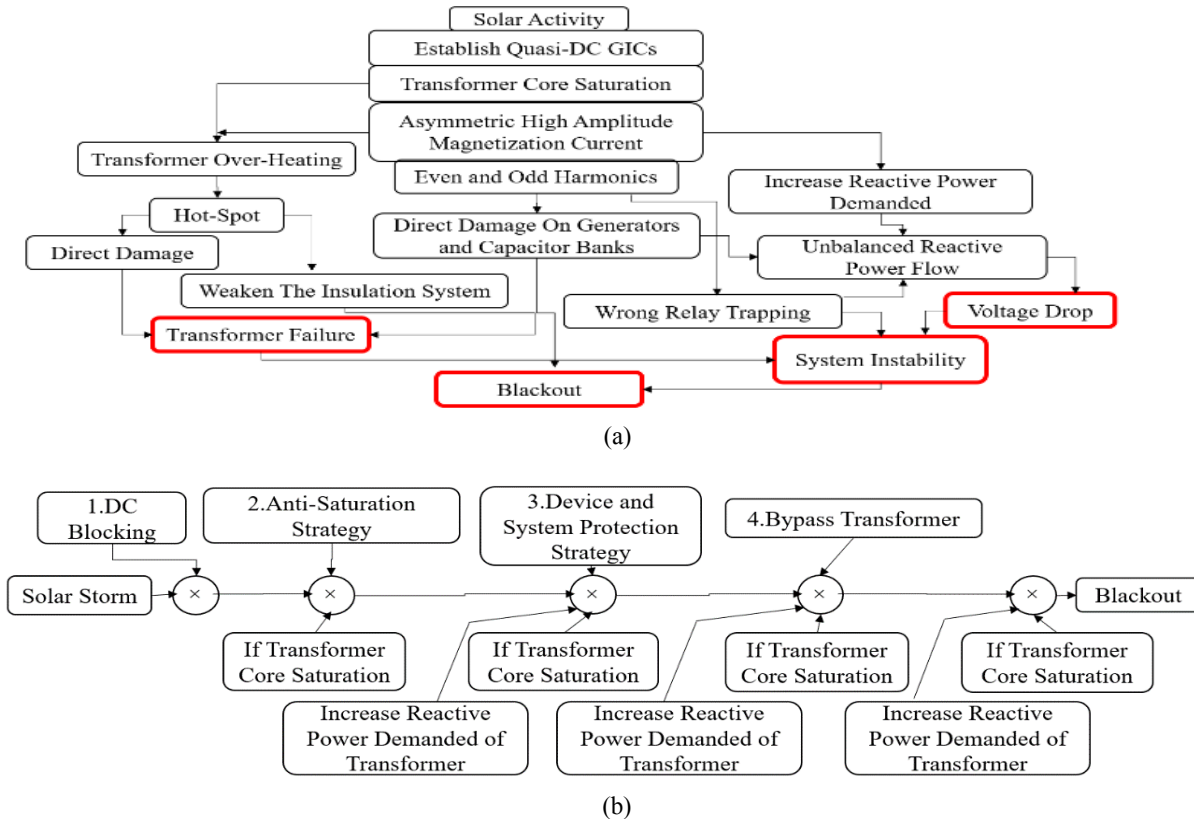


Fig. 10. (a)Destruction trend and GIC affectability on transformer, (b) Strategies of preventing power network

Although a neutral blocker device can be useful for the protection of system and transformers against the GIC, it must not disturb the main operation of the earthed neutral and it generates some problems for safety of the transformer under different power network disturbances. An earth connection must tolerate around 200 A AC current due to unbalanced load currents over a long time and suffers SC current up to 10 kA. Another problem is the basic insulation level (BIL) of the neutral point [58]. There is a challenge in the DC blocker devices that it must not cause extra voltage in the neutral point [58]. The main base of this device is the use of a capacitor for blocking DC current by a resistance for DC current reduction [60]. Fig. 11 shows overall structure of this device. Generally, these devices consist of the parallel branches and a control system used for position change between them. One of the branches is related to the DC blocker which is chosen if the GIC is detected. The branch can be a resistance and/or capacitance. There is other branch for normal operation of the system which chooses a path with the lowest impedance. Other branches have been fixed for protection of the device from over-voltage due to over-load in the neutral connections. For example, suppose there are an earth SC fault and the GIC simultaneously. The device is capable to detect both. For correct and optimal control and

reduction of earth effect in system, other operating cases must be taken into account to achieve efficient device.

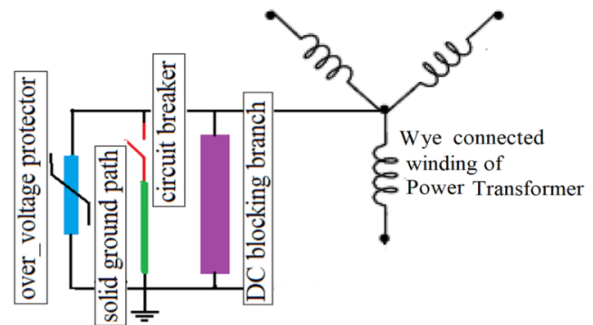


Fig. 11. Overall structure of a DC blocker.

Considering the power transmission system structure damageability of the system differs for different GICs, Closer inspection of the system indicates that the best path for the GIC is a star-connected transformer the earthed neutral wire. Taking this into account, one of the methods for system protection against the GIC is changing the neutral wire material. There are 6 combinations for neutral wire as described below:

1. **Cut-off Switch:** It is one of the most rudimentary methods. Disconnecting the neutral wire causes some problems including non-predictability of the transient voltage and difficulty of detecting earth fault, insulation problems and reliability reductions (for single-phase to earth fault).
2. **Inductance:** Normally, inductance in the neutral is used for the reduction of the fault current level.
3. **Resistance:** Resistance cannot fully eliminate the GIC, although it reduces the protection sensitivity and dimensions of the equipment [61, 62].
4. **Capacitance:** Capacitance can also remove the GIC, but it may generate Ferro-resonance, particularly in large systems [63].
5. **Capacitor and Switch:** This method minimizes possible Ferro-resonance [63].
6. **Using Semi-Conductor Switching Device (SGICR):** Assume that there is GIC in the system and it has been detected by a detector. The switches must be on and off by the frequency of 1 kHz. By this, the mean DC current is decreased, but does not fully removed. Rating of SGICR is small due to carrying only a part of the unbalanced currents. SGICR does not totally eliminate GIC, therefore, on the contrary to the switch disconnection method, the prediction of transient voltage and fault diagnosis by this method are not problems anymore. The GTO and/or IGBT is used as the switches. The ideal is that the GIC effects is controlled using the injected flux variations over half-cycle of the transformer saturation. In total, for n connections of neutral wire to earth, n-1 switching system is enough for the reduction of the GIC. The main idea of the SGICR is that it

connects to the earth for AC voltage and disconnects for DC voltage. Here, there are two operating cycle and switching frequency for quality control of the contact. The reduction level of the GIC is determined by the introduced plan with duty cycle. Larger duty cycle can decrease the GIC more. In fact, operating cycle determines the time over every cycle in which neutral insulated from the earth. The important factor in SGICR operation is the switching frequency. Switch selection conditions are as follows:

- Switching frequency must be quick enough, so it is close to zero in every repetitive open and close.
- High frequency leads to more expensive equipment.
- Operating cycle and frequency must be chosen properly.
- The human audio frequency is in the range of 20 Hz - 20 kHz and this must be taken into account for transmission line near residential area [63].

The above-mentioned cases are related to the neutral wire. To pass this high current from the protective

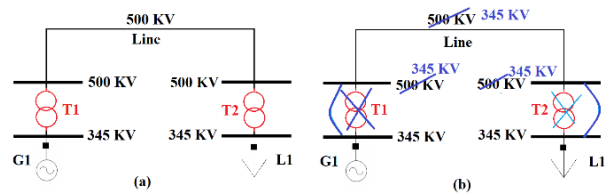


Fig. 12. (a) Bypass circuit of transformer in normal operation of system and (b) bypass circuit of transformer in presence of GIC [12].

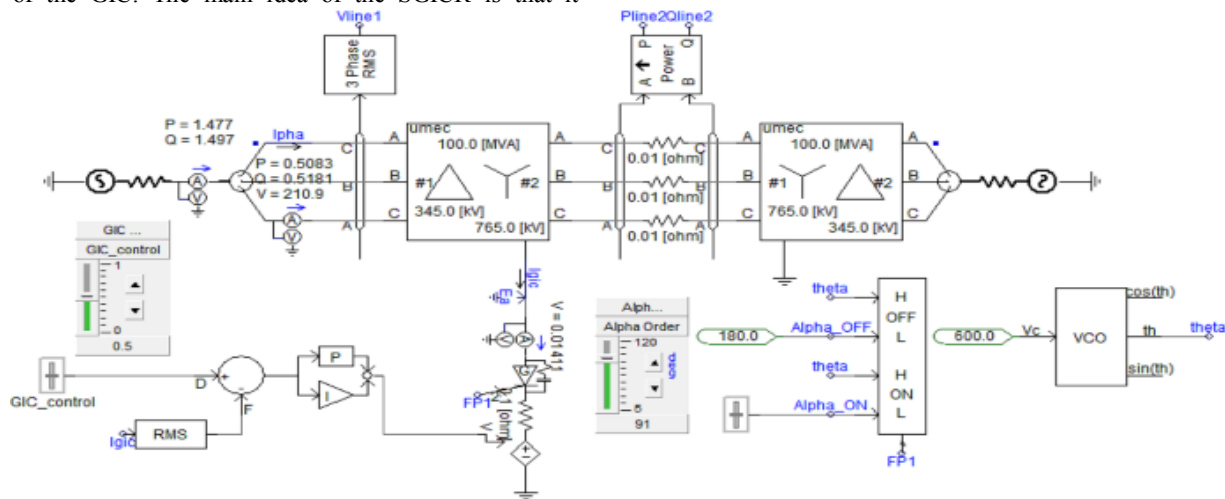


Fig. 13. Schematic of simulated circuit with SGICR protection.

component needs a separate protection, and use of spark arrester in the neural part is one of the methods. All FACT protections tools can be used to protect neural protective component. In the following part power system simulation by capacitance protection blocker is carried (Fig. 4b).

According to Fig. 8c and Fig. 9c, the system has been improved very well and voltage and current decreased. Considering the fundamental component of the excitation

current, there is 60% reduction in the fundamental and 3rd harmonics as shown in Fig.8c. The main disadvantage of this method is Ferro-resonance phenomenon. Harmonic reduction with the presence of capacitance protection is clearly seen. Fig. 5c shows clearly the improvement of the hysteresis loop. The system magnetization characteristic is well improved after protection. The reduction of minor loops and the increase in system symmetry in the protection case indicates the efficiency of the protection method by the capacitance blocker.

### 6.2.2 Anti-Saturation strategy

There are three methods to prevent the core saturation. The first strategy is the use of three-phase three-limb unit. Considering the high reluctance path for zero sequence flux, even large GICs cannot easily saturate the transformers [50]. The second procedure is the use of  $\Delta$ -connected windings. This connection can delay the core saturation for a few minutes. The third method is the compensation of MMF due to GIC. This can be done by inserting an additional winding in each phase and injecting an appropriate DC current. In fact, this method artificially act similar with  $\Delta$  -connected windings to prevent the core saturation [34, 64].

### 6.2.3 Strategy of protection component of devices and systems

If the GIC occurs and transformer saturates, it is still possible to take some actions to reduce the undesirable impacts of saturation. Study of GIC impacts on power networks shows that if the GIC imposes a saturation on transformer, it results in a magnetization current that is not that much sensitive to the core dimensions, and current and voltage level. To achieve an appropriate and efficient algorithm, a precise investigation of this phenomenon is required to prevent the network collapse.

### 6.2.4 Restoring

Following the GMD occurrence, the electrical energy consumers can still use the energy for a while by bypassing the faulty transformers using short circuit. This could be suggested as the last method for returning the power to the network over the shortest possible time. To bypass the operating voltage of the transformer will be the voltage of the LV side.

Fig. 12 shows how this method works [12]. Generally, this method is a short time solution, because the losses are high and transmission lines is not design to carry this current. This method as the last solution is used to rescue the transformer.

## 7. RESULT AND DISCUSSION

In this part, samples of the protections are applied and compared. The proposed network consists of a simple line containing two transformers with active saturation characteristic (Fig.13). Table 2 summarizes the parameters of the simulated transformer. Fig. 14 and Fig. 15 show the distortion of the current waveform in the presence of the GIC. The system perceives variations in the presence of the GIC from waveform harmonic and the demanded reactive power. Significant increase of the demanded reactive power has been shown in Fig. 14. other destructive effects of GIC on transformers as such system perceives variation in the presence of the GIC from that 1.48 MVAR rises up to 244 MVAR (Fig. 15a and 15b).

It is noted that the transformer capacity is 100 MVA which is higher than the rated capacity of the proposed transformer. Also other parts of the transformer can be seriously damage. The line current in Fig. 14a and b shows that the harmonic rises up to 200% and the current

reaches 570 A. Rising THD up to 17 % is clearly visible in Fig. 14 b. The GIC generates the harmonic by DC shift in the transformer saturation characteristic which saturates the transformer core. Furthermore, the protection methods through the neutrals are investigated.

There are protective methods in neutral wire where the existing methods are a combination of these methods. Using resistance, inductance and capacitance are older methods. Among these methods, the inductance cannot be very useful due to its no coordination with very low frequency of the GIC. There are two other methods. First is the permanent bypass of the proposed equipment such as resistance or capacitance and the second is the use of power electronics devices. Inserting a resistor increases the resistance, which prevents the flowing the GIC current through transformer neutral and opening the switch by detecting the GIC. Apparently, this is the best method for the system protection against destructive effects of the GIC; however, in real cases, disconnecting the switch results in unpredictable voltage transients, difficulty in detecting faults and insulation stresses.

Capacitance also reduces the GIC current, but may generate Ferro-resonance in the system. The bypass capacitance has no Ferro-resonance problem and can decrease the GIC. Using power electronics switches are almost taken from bypass capacitances. Figs.14-16 show GIC has no much change in the presence of inductance due to low frequency of the GIC. Inductance cannot return the phase current and its harmonic amplitude to the normal case. Inserting resistance in the neutral wire causes 70 times reduction of the phase current and closer to the operating normal current. However, its major problem is increasing THD up to 33% (and 16% compared to presence of the GIC) and serious distortion of the waveform.

Presence of capacitance in the transformer neutral can return the system to its normal operating condition. However, this causes Ferro-resonance. Presence of switch for bypass capacitance is very appropriate and effective and also prevents the Ferro-resonance. Therefore, the GTO power electronics switches have been used for protection. The harmonics level in the presence and absence of bypass are given below. Impact of the presence of the switch with 1 kHz frequency can be seen more in the content of the odd harmonics.

Comparison of Fig. 14a and Fig.14g indicates that the content of the fundamental current seriously decreases for GTO protection method. Fig. 14 g shows the reduction of the odd harmonics content of phase current by GTO protection. On and off of pulse frequency of GTO is 1 kHz.

The snubber circuit consists of 5 k $\Omega$  resistance and 1 nF capacitance. Fig. 16f shows oscillations in the range of minimum current is the disadvantage of capacitor with bypass protection method. Uniform and shedding performance in power electronics switch is its advantages compared with only capacitance and bypass capacitance which makes it more applicable. According to Figs.17, when power electronics switch is used for the system protection, reactive power reduces dramatically and the

inductance which has no frequency conformity with low frequency the GIC, is not useful. When an inductance is used for system neutral protection, the active power system also is not useful. In Fig. 17 a THD level of phase current, for the case in which resistance is used for neutral wire protection, is larger compared with the case with no protection in the system. Therefore, inductance has no much efficiency in the reduction of the THD and reduction of the THD for protective systems with capacitance and bypass capacitance is optimal and appropriate.

In normal operating condition, the power system current and voltage signals only have odd order harmonics. Even order harmonics appears in a signal when the positive and negative half cycles of the signals do not have a similar shape. Fig.20d shows the THD of the current with even harmonics. It is apparent that in the methods which are not efficient, the value of even harmonics is more than others.

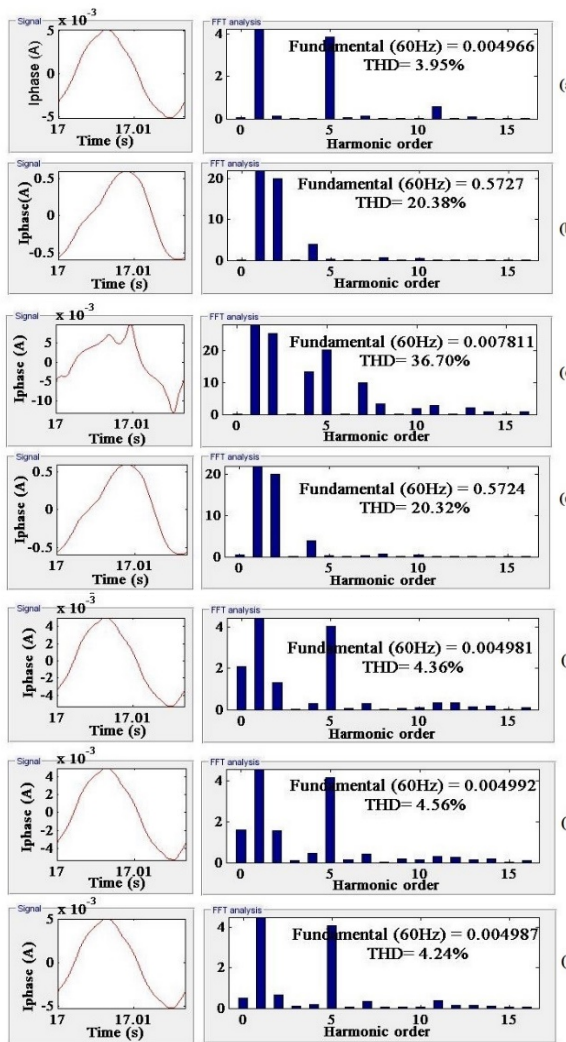


Fig. 14. (Left) Phase current and (right) THD of phase current a) .normal operation of system (no GIC), (b). with GIC, (c). with GIC and resistance protective, (d) with GIC and inductance protective, (e). with GIC and capacitance

protective, (f) with GIC and bypass capacitance protective and (g). with GIC and GTO protective in transformer neutral.

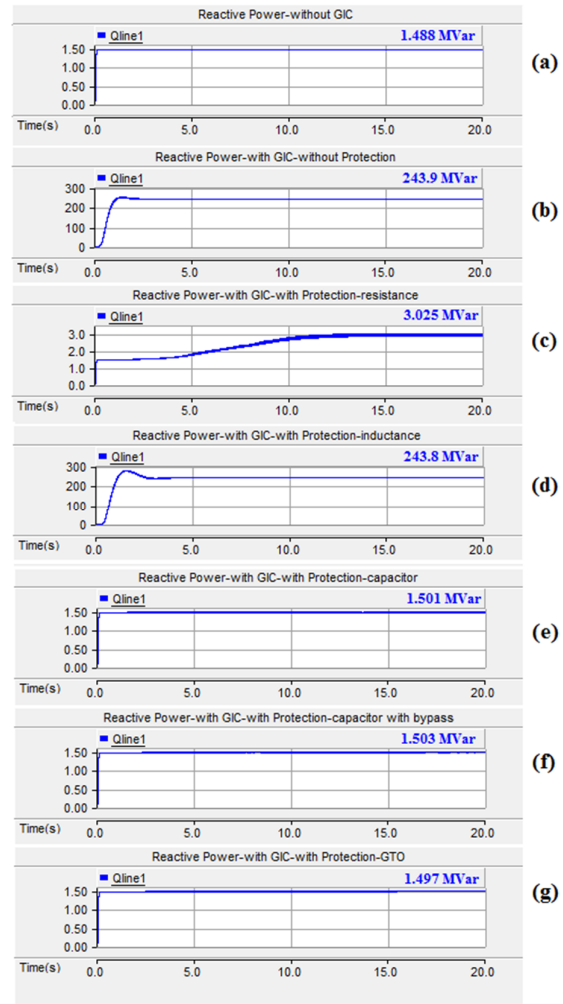


Fig. 15. Reactive powers for different cases.

TABLE 2 Parameters of simulated three-phase transformer in PSCAD.

Symbol	Quantity	Value
$P_{nom}$	Transformer rating power (MVA)	100
$V_1$	RMS primary voltage (kV)	765
$V_2$	RMS secondary voltage (kV-)	345
$F_{nom}$	Base operation frequency (Hz)	60
-	Leakage reactance (pu)	0.010
-	No load losses (pu)	0.015
-	Copper losses (pu)	0.020

Resistance protection in the neutral wire has the highest value of even order harmonics the THD among 5 investigated methods and in the methods in which capacitor is used as the protection method, this value is the minimum and the system operates near its normal operating condition [64–66]. Table 3 summarizes the merits and drawbacks of the 5 protection methods.

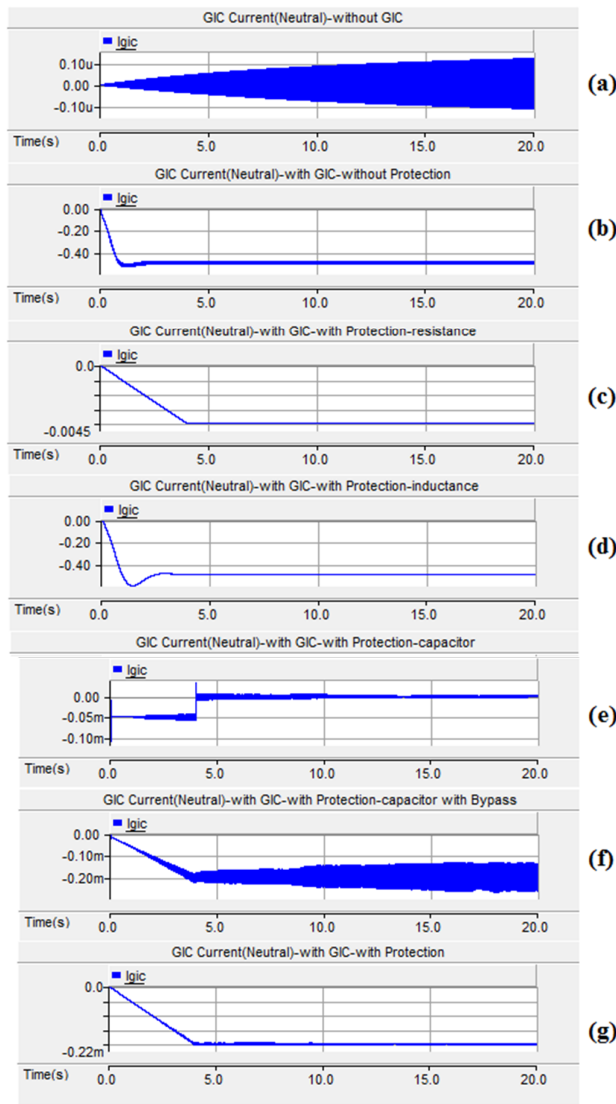


Fig. 16. Transformer neutral current. (Continue Fig.18)

### 8. CONCLUSION

GIC is a phenomenon that can disrupt power supply. Transformers are one of the important equipment of power grid and its protection is essential. Due to the effects of GIC on the power transformers, many protection methods have been proposed for this purpose. Some of these methods were analyzed and the protection through neutral wire was described above. The full disconnection of neutral wire must not be the base of the protection due to many problems. Using inductance is not efficient and inserting the resistance in the transformer neutral distort the current following the neutral wire. In addition, it is not much efficient compared with other methods. Using a capacitance distorts the voltage and may generate Ferro-resonance in large systems. Since the simulated system is too simple, it is not easy to see this clearly. Using bypass capacitance and employing power electronic switches have high reliability from efficiency point of view. Using protection systems are other ways which must be considered. These include spark arrester and FACTS tools.

Increasing the sensitivity of the neutral wire leads to faster changes in the power system when a problem is occurred in the neutral wire and it can be a problem. So, system operation in normal case and in the presence of the GIC must be realized and all these involve a comprehensive control system.

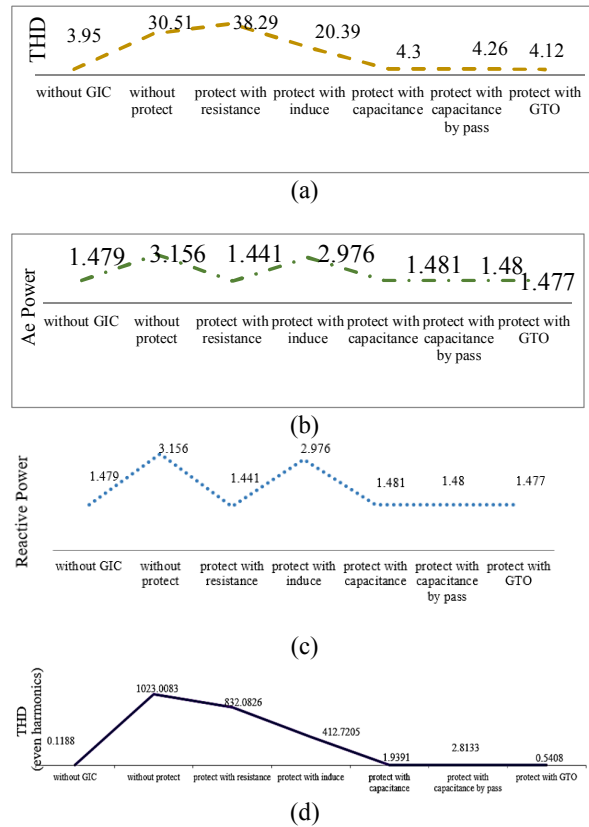


Fig. 17. (a)THD, (b) Active power, (c) Reactive Power, (d)THD with even harmonics for 5 protective methods and previous case and after non- protective GIC.

TABLE 3 Merits and drawbacks of 5 protection methods

state	Merits(M) and Drawbacks(D)	
protect with resistance	M	Decreasing the demanded reactive power Reducing the value of the first harmonic
	D	Increasing THD, specifically even order harmonics (worst in the all methods)
protect with induce	D	Incapability in reducing demanded reactive power
		Increasing the system's loss
		Incapability if reducing THD and even order harmonics (50%)
protect with capacitance	M	Increasing the main harmonic
		Decreasing the demanded reactive power
		Reducing the value of the first harmonic
		Reducing THD to the system's normal operating conditions
	D	Reducing the even order harmonics to the system's operating condition Reducing the system's loss May generate Ferro-resonance

protect with capacitance by pass	M	Reducing demanded reactive power
		Reducing the value of the first harmonic
		Reducing THD to the system's normal operating conditions
		Reducing the even order harmonics to the system's operating condition
		Reducing the system's loss
	No Ferro-resonance	
D	Noise creation in the transformer's neutral	
	Protection devices are required	
	Control devices are required to distinguish emergent and normal conditions	
protect with GTO	M	Reducing demanded reactive power to the normal operating condition
		Reducing the value of the first harmonic
		Reducing THD to the system's normal operating conditions
	D	Reducing the even order harmonics to the <u>system's operating condition</u>
		Protection and control devices are required

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