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Insight into impact of geomagnetically induced currents on power systems: Overview, challenges and mitigation

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ABSTRACT

During Geomagnetic Disturbances (GMDs), the variation in the geomagnetic fields produce the electric field, which finally drives Geomagnetically Induced Currents (GICs) in electric power systems. In the last few decades, a range of detrimental effects of GICs has been observed. These effects include the heating and harmonic generation due to half-cycle saturation of transformers, vibrations in generators, unwanted tripping of protective devices, increased reactive power demand, and voltage sag. Also, the complete shutdown of a power system can be occurred due to the flowing of large magnitude GICs. In the future, substantial research will require to reduce the GIC impact on the operation of power systems. The main aim of this paper is to explore the expected challenges for power systems attributed to GICs. Towards this aim, the mechanism of GMDs and GIC is discussed first. Subsequently, the effect of GICs on various power system apparatus, namely, power transformers, generators, current transformers, relays, HVDC networks, and communication systems of utilities, are rigorously evaluated. Besides, this survey also comprises the discussion on the different mitigation techniques for reducing the GICs effect. Finally, the significant remarks are discussed for future research of the GICs effect on power systems.

1. Introduction

A considerable disturbance of Earth's magnetic fields, so-called GMDs, arises when the energy of solar wind is transmitted into the Earth's magnetosphere and ionosphere. During GMDs, the geoelectric field is induced, which causes the flow of GICs in power systems [1-3]. The GICs have a very low-frequency range of 0.0001 Hz to 0.1 Hz, and so it can be treated as a Quasi-Direct current [4]. In the power network, the GICs flow from the transmission lines to the ground through a neutral-ground connection of transformers [5-7]. This GIC adds to the ac exciting current of the transformers, subsequently causing the half-cycle saturation [8-10]. This nonlinear operation of transformers leads to an increase in reactive power demand, harmonic generation, and heating in the transformer [1, 2, 7-12]. All these effects are the source of other subsequent effects, including maloperation of protective relays, voltage fluctuations, and stability issues. In the worst case, the transformers damage and complete shutdown of the power grid can be possible. Also, the filter overloading and switching problems in HVDC systems occur [13, 14].

The first time in 1940, the malfunctioning of the power system apparatus was observed during an Easter storm in the USA and Canada [15]. Later in March 1989, the GMD with 500nT/min collapsed the Québec grid in 90 seconds [16]. During this event, seven static VAR compensators were tripped and so that the voltage was dropped to 0.2 pu. Additionally, due to loss of synchronism, Montréal's five lines were tripped, and the whole power network of Hydro-Québec turned into the blackout. Also, one transformer is completely damaged in the USA [17-21]. After this event, the research of GICs has been greatly increased amongst the utilities and researchers over the world. From the years 1989 to 1992, the cases of malfunctioning the power system apparatus due to 14 impacted GMD events are discussed in [20]. These cases involved shunt capacitance tripped by neutral unbalanced protection, 138 kV line tripped by overvoltage protection, capacitor neutral harmonic alarms, and the tripping of transformer protection in North America's power systems. Subsequently, in October 2003, around 50, 000 consumers of Malmo city of southern Sweden experienced the

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power blackout due to magnetic storms of Halloween [22, 23]. A significant number of studies of GICs effect on power systems all over the world are presented in the literature, including Ling'ao nuclear power plant of China [24], UK and French HV transmission systems [25], South Island power network of New Zealand [26, 27], Catalonian power transmission network of Spain [28], 132 kV transmission systems in Northern Queensland of Australia [29], 500 kV transmission system of S-E region [30] and Itumbiara-Sao transmission system [31] of Brazil, Lethabo power station of South African [32], Hokkaido power grid of Japan [33], and many other.

In the initial GIC research era, it was believed that the significant GICs effects would only occur in high-latitude regions such as Scandinavia and North America [1]. However, over time, it has been realized that the power grids of mid and low latitude regions, such as China, Japan, Brazil, and South Africa might also be affected by GICs [31]. These studies have also revealed that the larger transmission systems with higher voltage levels are more susceptible to the GIC effects [30, 31]. This is significant as mid and low latitude countries like China and India are planning to develop more EHV and UHV transmission systems [34]. Hence, extensive investigations are required to examine possible GIC effects on the power systems. In this paper, the induction process of GMDs and GICs is provided, which is followed by the discussion of the GICs effect on various power system apparatuses. Also, different types of GICs mitigation methods are extensively discussed. Finally, the remarks and recommendations are laid forward for future research and development activities associated with the impact of GICs on power systems.

2. Overview of GMDs and calculation of GICs

GMDs, also known as geomagnetic storms, and GICs turn out to be more recognized as a risk to the bulk power systems. The GMDs phenomenon and computation of GICs are discussed in the following subsections.

2.1. Physical aspects of GMDs

The considerable disturbances in the Earth's magnetic field were first noticed by Graham (1722) [35], and have been signified as a geomagnetic storm [36]. It is produced by the efficient energy exchange from the solar wind into the Earth's environment [36-38]. The geomagnetic storms originate due to the two kinds of manifestations driven by the solar wind: coronal mass ejections (CMEs) and corotating interaction regions (CIRs) [39, 40]. Due to high solar activities during solar maximum, the Sun releases numerous CMEs towards Earth per day, mainly associated with the most massive storms. The CMEs contain almost 1 to 10 billion tons of solar plasma material and interplanetary magnetic field (IMF) [41], and fly away from the Sun at very high speeds. The regions of enhanced density and a magnetic field called CIRs are produced due to the interaction of the high-speed solar wind streams (≥800 km/s) with the slow-speed streams (≈300 km/s) [39].

Dungey[42, 43] have explained the dynamics of geomagnetic storms in terms of the magnetic reconnections. The magnetic reconnection arises at the magnetosphere's dayside among the magnetic field of Earth and the southward oriented IMF. After the magnetic reconnection, when the magnetic field lines are moved in the magnetospheric backend, a neutral point is created. From this neutral point, the charged particles enter into the Earth's magnetosphere. The particles with high energy travel in the direction of Earth. However, they are diverted in spherical orbits around the Earth, establishing a ring current which produces a disturbance in Earth's magnetic field. The particles with low energy curl around the stretched field lines of Earth and resist the planetary atmosphere in the polar regions, producing greater auroras. The currents associated with auroras, also known as auroralelectrojets, can also cause a noteworthy disturbance in magnetic fields.

The CMEs and CIRs are associated with the solar cycle. The north and south poles of Sun completely interchange their places in about 11 years, called the solar cycle [44]. Solar maximum refers to the duration of the cycle when sunspots are most frequent, whereas the cycle period with lower sunspots is designated as a solar minimum. CMEs mainly cause intense storms during the solar maximum. In contrast, storms associated with CIRs are mostly weaker than those driven by the CMEs and commonly occur during solar minimum. The CIRs persist for a longer time and transfer their energy into the magnetosphere more efficiently.

Usually, the geomagnetic storms are characterized in the initial phase, main phase, and recovery phase [43, 45]. In the initial phase, the horizontal component of the geomagnetic field suddenly increases above the initial undisturbed level for a few hours. This initial phase is also known as a storm sudden commencement (SSC) phase. The main phase begins when the horizontal field component starts reducing from the initial phase level with a large magnitude. After attaining a minimum value at the end of the main phase, the horizontal field component recovers slowly towards the original unchanged value during the recovery phase. The CME driven storms have a smaller recovery phase about 1to 2 days. In contrast, the CIR driven storms have a longer one about many days.

The intensity of geomagnetic storms is commonly measured using Dst, Kp, K, Ap, and AE indices [46, 47]. In Table 1, the storms are classified based on Dst and Kp indices [35, 48-50]. The Dst index is calculated from the deviation in the horizontal magnetic field component per hour obtained from observatories. It specifies the magnitude of geomagnetic storms. It is measured using the unit of nano Tesla (nT). The K index provides the irregular deviation of horizontal field components every 3 hours at various observatories [51]. The Kp index is computed based on the K index's average from reference observatories [52]. The Kp index signifies planetary magnetic disturbance intensity as seen at sub-auroral latitudeson a 0-9 scale, with zero means no disturbance and 9 indicating an extreme geomagnetic storm. Also, the average number of various storms per cycle is provided in Table 1[49]. As can be seen, weak and moderate storms occur with an average of 65.28 % and 23.04 % of total storms. The events of strong, severe, and extreme storms occur in order of 7.68 %, 3.84 %, and 0.15 % of total storms. For the years 1957 to 1993, a total of 1085 geomagnetic storms were identified and analyzed based on the Dst index [35]. According to this study, the storms with weak and moderate intensity occurred in order of 44 % and 32 % of total storms. On the other hand, storms with strong, severe, and extreme intensity occurred 19 %, 4 %, and 1%, respectively. For solar cycle 23, 220 storms with Dst ≤ -50 are investigated and organized into four categories [53]. This study shows that moderate, strong, severe, and extreme storms occurred orderly 62.73 %, 30.45 %, 5%, and 1.8 % of total storms. Navia et al. have compiled top 50 storms for cycle 23 and cycle 24, and classified them based on the Kp index. According to this study, storms with the Kp index of 7, 8, and 9 were 30 %, 44 %, and 26 % of total identified events in cycle 23. Conversely, there was no storm with the Kp index of 9 in cycle 24. Moreover, storms with the Kp index of 5, 6, 7, and 8 occurred in order of 14 %, 56 %, 18 %, and 12 % of total storms in this cycle.

2.2. GICs in power systems

As discussed in the previous section, the numbers of space weather phenomena cause variations in Earth's magnetic field. The variations in the geomagnetic field produce the geoelectric field at the surface of Earth and human-made structures such as long transmission lines, as seen in Fig. 1 (a). This geoelectric field drives the GICs in long high voltage transmission lines, severely affecting the power systems equipment [54]. For modeling the GICs in power systems, two opinions exist in the literature [7]. These are based on considering voltage sources either in the ground connection points or in transmission lines. As discussed in [55], both approaches are the same in a uniform electric field. Nevertheless, in the case of a realistic electric field mainly produced by electrojet, the electric field is represented by a voltage source in transmission lines as presented by Fig. 1(b). Further, the considered voltage

Table 1
Classification of Geomagnetic storms and their effects on power systems.

Types of Geomagnetic storms	Dst (nT)	Duration (hour)	Kp values (every 3 hours)	Number of events/cycle	Number of storm days/cycle	Possible effect on power systems
Weak	−50 < Dst ≤ -30	1	5	1700	900	Minor fluctuations in the power grid
Moderate	−100 < Dst ≤ -50	2	6	600	360	Possibilities of voltage alarm in power systems of high latitude regions, and damages of transformers
Strong	−200 < Dst ≤-100	3	7	200	130	The need for voltage correction action and false alarm of operation of protective devices
Severe	−350 < Dst ≤ -200	>3	8	100	60	Possibilities of voltage control issues and malfunctioning of some protective devices
Extreme	Dst ≤ −350	<3	9	4	4	Issues of extensive voltage control and protection systems operation, transformer damages and complete blackout of some power grid

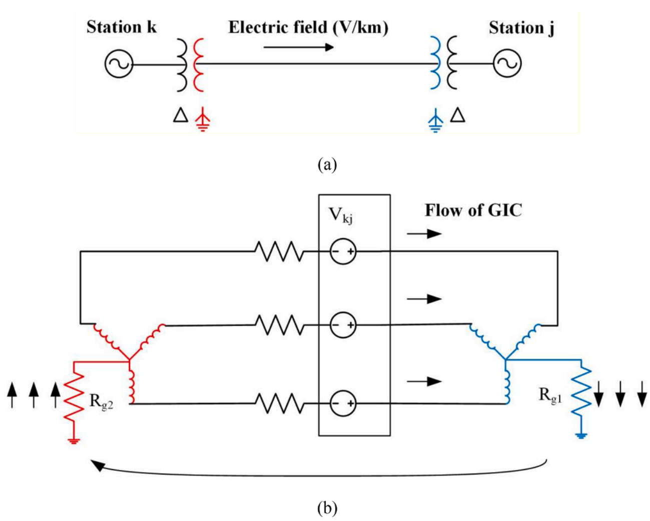


Fig. 1. GICs flow in transmission line and through transformers neutral-ground connection (a) Single line diagram of sample system with electric filed (E) (b) Three-phase model with induced voltage in transmission lines.

source in transmission lines is generally modeled as a DC source because of slow variation in geomagnetic fields.

The geoelectric field (E) is composed of the vector potential (A) with time derivation and gradient of scalar potential (Φ) [1, 7], which is shown by the following equation.

$$E = -\frac{\partial A}{\partial t} - \nabla\phi \tag{1}$$

In the above equation, the vector potential is formed due to variation in the magnetic field, whereas scalar potential is due to the charge distribution. Fig. 1 (a) shows the single line diagram of two substations, *j* and *k*. The induced geoelectric field is represented by a voltage source in the transmission lines between substation j and k, which can be seen in Fig. 1(b). The voltage source is calculated by integrating the electric field along with the length of the transmission line. It is expressed as follows.

$$V_{kj} = \int_k^j \overline{E}\cdot\overline{dl} \tag{2}$$

whereV_{kj} represents the voltage source between substations *k* and *j*, $\overline{E}$represents the electric field, and $\overline{dl}$represents the incremental length of the line. By assuming a uniform geoelectric field for the transmission line's geographical region, the line end-points' coordinates are essential. Thus, Eq. (2) can be rewritten as follows.

$$V_{kj} = L_N E_x + L_E E_y \tag{3}$$

whereL_N and L_E are the northward and eastward distance in km, respectively, whereas E_x and E_y are in order of northward and eastward electric fields (V/km). Further, for the transmission line between k^{th} and j^{th} substations, the Earth is considered ellipsoid with a smaller radius near to pole than near the equator [56]. The northward distance is given by,

$$L_N = \left(111.133 - 0.56\cos\left(2\theta_{kj}\right)\right)\cdot\Delta lat_{kj} \tag{4}$$

where$\theta_{kj} = \frac{lat(k)+lat(j)}{2}$

Δlat_{kj}represents the latitude difference between k^{th} and j^{th} substations.

Similarly, the eastward distance is given by,

$$L_E = \left(111.5065 - 0.1872\cos\left(2\theta_{kj}\right)\right)\cdot\cos\theta\cdot\Delta lon_{kj} \tag{5}$$

Δlon_{kj} shows the longitude difference between k^{th} and j^{th} substations.

Based on the method suggested in [57], the flow of GICs through the *n* earthed substations can be calculated using the following equation.

$$I_n = (1 + YZ_n)^{-1} J_n \tag{6}$$

whereI_n is $n \times 1$ matrix of GICs flowing into Earth, and *1* is the $n \times n$ unit matrix. *Y* represents the $n \times n$ network admittance matrix and mainly depends on the resistance of the conductors. Z_n represents the $n \times n$ matrix containing earthing impedance. Based on the calculated voltage using Eq. (2), elements of the $n \times 1$ column matrix J_n can be stated as follows.

$$J_{n,j} = \sum_{k\neq j} \frac{V_{kj}}{R_{kj}} \tag{7}$$

whereR_{kj} is the resistance of transmission line between k^{th} and j^{th} substations. If the earthing impedance is zero, J_n is called perfect earthing currents.

From the above discussion, it is cleared that the calculation of GICs is divided into two phases [1]; the geophysical and engineering phases. The geophysical phase estimates the geoelectric field based on the knowledge of GMDs and the structure of ground conductivity. For accurate calculation of the geoelectric field, the geomagnetic induction process is presented using different earth conductivity models in [54, 58]. Based on the estimated geoelectric field and complete knowledge of power networks, the calculation of GICs is performed in the engineering phase. The comparative study of various approaches for GICs calculation is presented in [59].

3. GICs impact on equipment of power systems

Due to GICs, a range of effects has been observed in power system equipment. These problems are thoroughly discussed in the following subsections.

3.1. Impact on power transformers

As discussed in [11], Δ-connected winding in the transformer does not have the issue of GICs flow due to the absence of a neutral-ground point. On the other hand, Y-connected winding has a neutral-grounded point to discharge the unbalanced AC current. This neutral-ground connection in Y-connected winding provides a path for the flow of GICs through the transformers, as shown in Fig. 1(b). The flow of the GICs through the winding of transformers produces DC flux, which supplements the alternating flux produced by the AC current, causing the saturation of the transformer core during the one-half cycle. This nonlinear operation of the transformer leads to harmonics production, transformer heating, increase of reactive power consumption and voltage fluctuations [27, 60-62].

Furthermore, different types of transformers are not equally prone to GICs consequences, but they depend on their design [9, 20, 63]. The risk of damaging the leads and windings is higher in the 1-Φ shell and core configured transformers. In the case of the 3–Φ power transformers, the core type with five limbs and shell-type with seven limbs are less affected to winding damage. The heating of structural elements in the saturated core's vicinity may be possible in these configured transformers. However, it does not seriously affect the functional capability of transformers [20]. Since the 3-Φ core type with three limbs designed transformers offer high magnetic reactance to the GIC flow, it is less vulnerable to the GIC effects [20, 61]. The various effects of GICs on transformers are extensively discussed as follows.

3.1.1. Half-cycle core-saturation of transformers

The flow of GICs through Y-connected transformers can bias the excitation characteristics of the transformer [9]. It can be noted that the low level of GIC, which is about 10′s ampere can drive the transformer into half-cycle saturation because the transformer is generally designed to operate near the saturation region for the usual operation of AC flux. The flux excitation characteristics of the transformer with and without GICs are presented in Fig. 2 (a) and (b), respectively.

It is observed from Fig. 2(a) that under normal conditions, transformer works in the linear region of excitation characteristics, and even a large power transformer draws low exciting currents, which are about 1% of rated full-load current. Usually, transformers operate in a flux range quite close to the saturation or knee region on the characteristic.

On the other hand, as shown in Fig. 2 (b), the excitation current can be increased around 10 to 15% of full-load current during the positive half cycle due to the presence of GICs and so transformer experiences the half-cycle saturation. Because of the deficit of the least reluctance path provided by the steel-core, the flux is pushed out from the saturated core, causing leakage flux so-called stray flux at the surrounding of the core, as shown in Fig. 3. This stray flux exerts influence on the walls of the tank, core clamps, and flux shields. Overall, the transformer's half-cycle saturation is a direct or indirect root cause of all other adverse effects on the power system apparatus.

3.1.2. Increase of reactive power demand

The high excitation currents cause core saturation, which increases the reactive power consumption by the transformer [64, 65]. The 1-Φ transformer uses a comparatively higher reactive power than 3- Φ transformer [66, 67]. Though, shell type absorbs the higher reactive power than five limbs core type transformer because the shell-type design is more affected to half-cycle saturation [9, 65]. In the event of GIC occurrence, electric power systems experience a significant reactive power demand. If available resources such as Static Var Compensators (SVCs) and Shunt Capacitor (SC) bank, do not provide this additional reactive power demand, the reduction in system voltage will go below the secure limit and may result in the blackout of power systems [61].

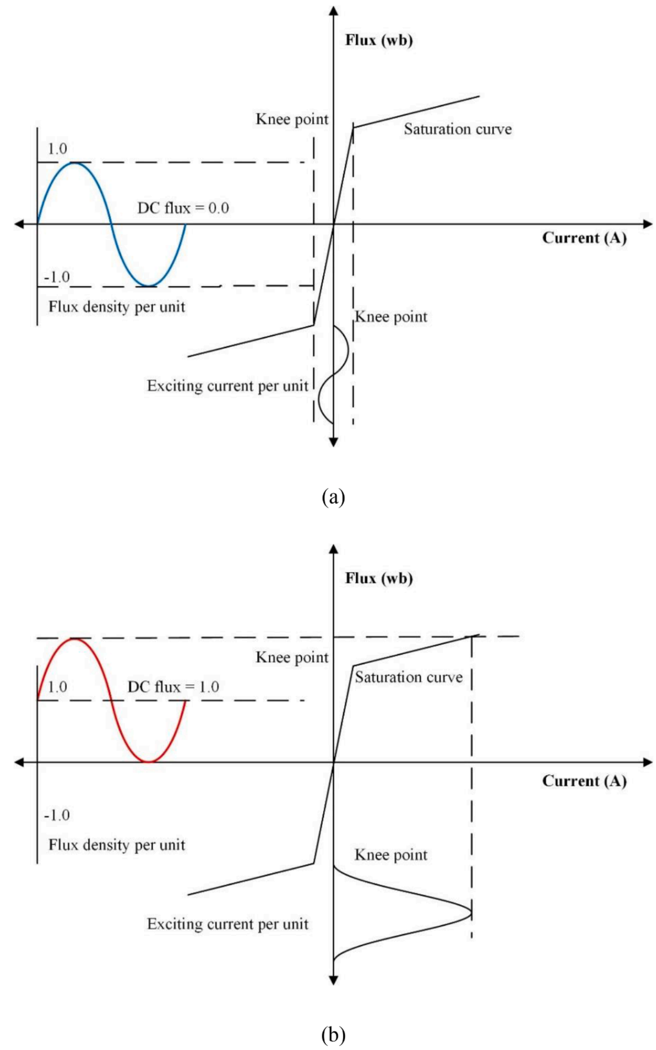


Fig. 2. Flux vs. excitation current characteristic of transformer for (a) absence of GICs (b) presence of GICs.

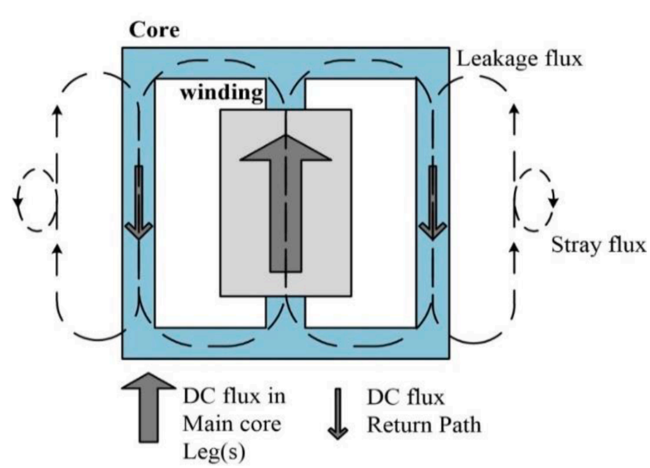


Fig. 3. The return path of DC flux in 1-Φ core or shell type transformer.

3.1.3. Harmonic generation

During half-cycle saturation, transformers draw the large magnetizing current containing both odd and even harmonics [68]. Typically, the magnetizing current holds only odd harmonics in unbalanced situations, and the power system's apparatus can easily handle them [69]. In contrast, even harmonics are not normally observed. Also, the magnitude of the harmonics will increase with increasing the GICs [61]. Moreover, the harmonics in excitation current can generate various unwanted issues such as overloading of SC bank, unwanted tripping of protective relays, extensive losses, heating and vibration of rotating machines, etc. [20, 70, 71].

3.1.4. losses, heating and vibration

The excitation current with significant magnitude and its interrelated harmonics produce higher magnitude stray flux, which contains rich-harmonics [60]. As a result, eddy current and resistive losses have been increasing in the winding and other transformers' structures, which increase the overall losses and temperature [64, 72]. During the core saturation, the main flux leaves the desired path and spread over the tie-plates, yoke-clamps, tank, and winding due to the fringing effect [73, 74]. This effect also accelerates the temperature and losses and thus aging the insulation in the transformer [75]. Besides, the higher noise level of core and vibration of the tank are supplementary consequences, which can be the root cause of loosening of the terminal leads as well as damage to other tank fixtures [60, 72].

3.2. Impact on the generator

It is evident from Fig. 1 (a) and (b) that the GICs do not flow in the generator, because of Δ-y connected step-up transformer located near to it. Although, the generator is still prone to the increment of reactive power demand and the harmonic generation caused by the half-cycle core saturation phenomenon [71, 76]. The supplemental reactive power demand is fulfilled by a generator that increases the field current and so increases the thermal stress. If the limit of reactive power feeding capability is reached, the generator will not be capable of regulating the system voltage and preventing the system collapse.

Additionally, as discussed in [77, 78], the tripler harmonics do not enter the generator circuit as the delta winding traps them. Nevertheless, the second and eighth harmonics establish the negative sequence current, and likewise' fourth and tenth harmonics establish the positive sequence current. The negative sequence currents overheat the rotor's end-rings, whereas the positive sequence currents cause the rotor vibration. Both of these effects increase with increasing the GICs in the transformer [9].

3.3. Impact on Current Transformers (CTs)

Saturation of CTs can arise due to GICs, like dc offset current during a fault [79, 80]. However, the magnitude of GICs is much less than the dc offset current. Also, the core of CT is designed in such a way that it can sustain the large fault current without undergoing saturation [9]. Therefore, the GICs impact is less on CT performance. Nevertheless, in the condition when both fault and GICs occur at the same time, and the dc offset of fault current and GICs are additive, then CTs experience quick saturation. Nonetheless, the same as power transformers, CTs also generate harmonics in output because of their half-cycle core saturation [79].

3.4. Impact on the operation of protective relays

The problems in the operation of protection systems due to the GICs are discussed in [12, 20]. These problems include the failure of neutral overcurrent relays, neutral overvoltage relays, neutral unbalanced protection, phase overcurrent relays, Buchholz relays, and differential relays. Due to the nuisance tripping of these relays, various power system elements such as capacitor banks, transmission lines, SVCs, transformers have been disconnected from service.

Modern numerical relays are replacing the conventional electromechanical relays. However, these digital relays calculate the RMS value based on the measured peak value of quantity. Due to half-cycle saturation, the harmonics contents increase, and that trips the numerical relays for lower current instead of desired current settings [9, 20, 78, 81]. Although this problem can be avoided by increasing the settings, it reduces the security of protection systems [78]. Furthermore, the Shunt Capacitors (SCs) are generally grounded and provided the neutral overcurrent protections. However, the SCs offer low impedance to the harmonics and cause a false tripping of neutral overcurrent relays and so undesirable disconnection of SCs [78]. The chances of nuisance tripping can be reduced by using the filters, but not completely eradicated.

Furthermore, differential protection is unit protection and have to respond only against the internal fault. It is commonly used to protect generators, power transformers, buses, ac motors, etc. As shown in Fig. 4, the inequality between entering current i_1 and leaving current i_2 indicates an internal fault, and the difference between these currents (i_1-i_2) circulates through the differential relay. If this difference in currents is higher than the value of the setting, the relay trips instantaneously. During a heavy external fault, the ratio error is possible to occur on either side of CTs. This ratio error then creates a difference between the current of the secondary of CTs and thus false tripping of the relay. The restraining and operating coils based percentage-biased differential protection has been invented [79, 80]. However, there is still a nuisance tripping of differential relays during the magnetizing current, which flows during the switching of transformers. The magnetizing current has high components of even and odd harmonics, and these components are negligible in case of fault current. Based on this concept, the biased differential protection is further modified using the harmonic-restrained coil, as shown in Fig. 4[82, 83]. This modification increases the protection capability to restraint the tripping during the magnetizing current and allows the tripping during an internal fault condition. During the half-cycle saturation, the exciting current will contain the even and odd harmonics. At the condition when both GIC and fault phenomenon coincides, the differential relay restraint the tripping [79, 80], and reduce the sensitivity and security of the protection system.

3.5. Impact on the operation of HVDC networks

Mohan et al. [14] have presented a detailed study of GICs impact on HVDC systems. According to this study, GICs in converter transformers cause the supplemental harmonics generation and ac voltage distortion, which produce the error in the firing angle of converters. Also, the presence of GICs under the light load condition can cause the parallel resonance at the fourth and sixth harmonics, which ultimately overloads the filters [14]. However, this problem does not exist in the case of a full-load condition [14]. Though, the audible switching noise level increases at the converter terminals due to the presence of the harmonics currents in the AC side.

3.6. Impact on communication systems of power utilities

In addition to the effect on power transmissions, solar phenomena can interface with electric utilities' communication systems. The utilities employ various types of communications systems, including wire-based systems (power line carriers and metallic cables), radio-based systems (lower, medium, high, very high, and ultra-high-frequency radio signals, microwave networks, and satellite systems) and fiber optics system [84]. Some of these communication systems can be affected by various solar phenomena, such as solar radiation and solar wind [9, 78, 84]. The solar radiations cause the ionization of the ionospheric layers of the Earth's atmosphere. It is known as an ionospheric effect. This effect results in attenuation of the field intensity of high-frequency radio signals (3-30 MHz) and absorption of low and medium frequency radio signals (less than 3MHz). However, very-high and (30-300 MHz) and ultra-high (300 MHz-3GHz) are not severely impacted, but phase and amplitude scintillations can be enhanced.

On the other hand, solar wind causes perturbations to the Earth's

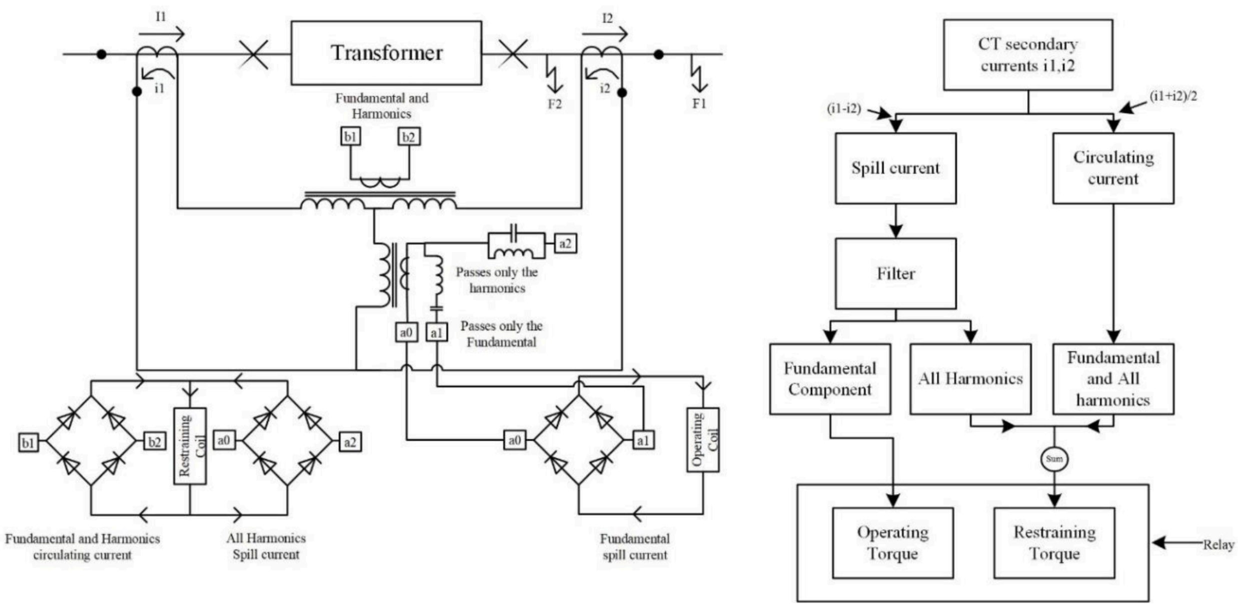


Fig. 4. Harmonic restrained bias differential protection.

magnetic field, known as a magnetospheric effect. This effect results in disturbance to cable communications. Furthermore, carriers utilized along with power lines are affected by harmonics, which are generated by half-cycle saturation of transformers during GICs. Moreover, these harmonics can also cause secondary interference in adjacent wire-based communication. The list effect of solar phenomena has been realized on fiber optics. The only recognized interfacing effect is the potential disruption of metallic conductors utilized to power fiber optic repeaters on long-distance circuits.

4. Devices used for mitigation of GIC

Based on some previous events, it has been realized that the risk of power system due to GICs may be higher than that assumed by the utilities. Therefore, additional devices become essential to install at the neutral of Y-connected transformers to reduce or block the GICs in power systems, as shown in Fig. 5. In the literature, GIC mitigation devices are categorized into two groups, namely, passive and active approaches.

4.1. Passive devices

Table 2 shows the passive devices used in the transformer neutral to mitigate the effect of GIC [9, 20, 78, 85-87]. All passive devices are used

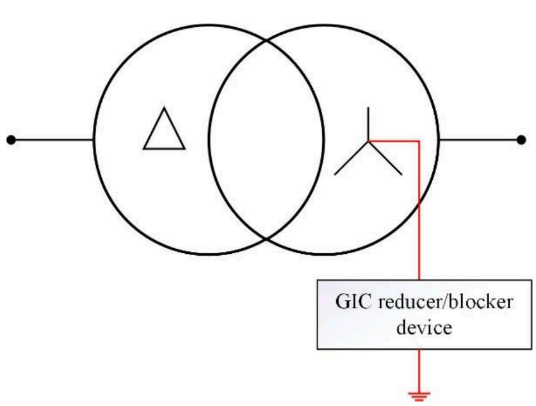
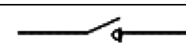
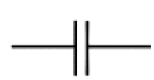
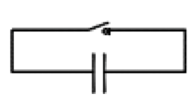


Fig. 5. Illustrative diagram of GIC blocking or reducing device at the neutral point of the transformer.

Table 2.
Passive devices used at neutral of transformers for GIC mitigation.

Sr. no	Device	Description
1		**Disconnecting switch:** It is a simple way to block the GICs by disconnecting the neutral from the ground. Disconnecting the neutral can cause voltage transient, the problem in ground fault detection, and insulation issues.
2		**Inductor:** Normally, an inductor is used to limit the ground fault current levels. However, GIC has a lower frequency, and so inductor cannot prove its effectiveness for reducing the GICs.
3		**Resistor:** Resistor at neutrals does not entirely block GIC but reduces it. Also, it can form the sensitivity issues in protective devices.
4		**Capacitor:** Capacitor connection at neutral completely block the GIC. The adoption of this method can origin the Ferro-resonance problem.
5		**Capacitor with bypass switch:** The capacitor is switched at neutral only during the GIC event, thus limiting the possibility of Ferro-resonance at the time of switching.

to block the GICs except resistive method. The capacitor-based approach is more effective than the other mentioned approaches. It is because the capacitor offers a low impedance path to power frequency current and a high impedance to DC quasi GICs. However, the capacitor’s use only for GIC blocking does not justify its cost [9, 20, 86]. Moreover, the capacitor in neutral can produce transient overvoltage in case of nearby ground faults. This overvoltage cause overcharging and damage to the capacitor [88]. Another suggested solution is to use the series capacitor in the phase conductors of the transmission line [89, 90]. This method enhances the power transfer capability of transmission lines and blocks the flow of GICs in transmission lines. However, this method causes the flow of larger GICs in an adjacent line where the series capacitor is not installed [85, 91].

4.2. Active devices

Active devices encompass the semiconductor-based control circuit for reducing the GICs [78, 85]. In this approach, Semiconductor GIC Reducer (SGICR) can quickly open and close the ground connection whenever the GIC is sensed. The Insulated Gate Bipolar Transistor (IGBT) or Gate Turn Off Thyristor (GTO) has been used to connect and disconnect the neutral connection at a frequency of 1 kHz for chopping of dc voltage [85]. These switching actions diminish the average GICs but do not eliminate them. The demerits of completely isolating the neutral experienced in passive devices have been resolved using the active devices. Thus, the complications in sensing the ground fault and voltage transient are overcome.

The example of the SGICR circuit with complete protection is illustrated in Fig. 6[85]. As shown in Fig. 6, the SGICR is connected in parallel with the Surge Arrestor (SA), resistor, and circuit breaker (CB2) as a regular bypass path. The Earthing Switch (ES) is also used to protect SGICR by providing a momentary bypass path. The CB1 is further connected in series with SGICR for providing the supplementary protection. It is noted that the SGICR device operates automatically whenever the GIC detector measures the GIC magnitude above the threshold value. However, it has been taken out from mitigation mode by the manual operation. If GIC is not detected or below the preset value, the CB1 is kept open, and CB2 is close. In the case of ground fault sensed through CT-2, switching actions are stopped by opening the SGICR through the CB1. Whenever SGICR is kept open in a ground fault condition, the ground connection is provided through the resistor R. Another active device-based approach is proposed in [92], in which IGBT based controlled ground resistor is placed in the neutral with adjustable duty cycles. In this approach, the zero-sequence current is also suppressed by a ground-controlled resistor. In other words, three situations, i.e., the GIC events, ground fault occurrence, and ground fault during the GIC event, are considered in this technique.

Similarly, the Fuzzy logic controlled variable resistor approach has been presented for suppressing the GIC in [93]. Bolduc et al. [94] have developed the Neutral Current Blocking Device (NCBD) technique in which the capacitor and electronics components (bridge rectifier, thyristor, and Zener diode) were integrated. In this method, the NCBD switching operation was performed several times in a short duration whenever the GIC had been observed.

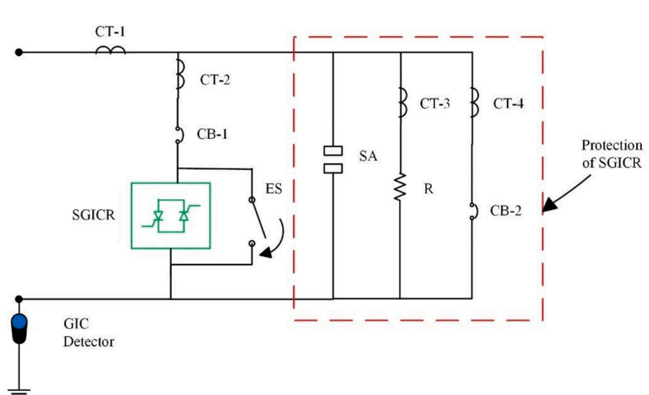


Fig. 6. Circuit diagram of SGICR for mitigation of GIC.

5. Discussion and future planning

In this section, the outcomes of the review and remarks on future planning of power systems have been provided.

5.1. Discussion

Table 3 presents a brief discussion on the outcomes of the review, including the impact of GICs on power system equipment and GIC mitigation techniques.

5.2. Future planning

It is evident from the literature that GIC become a global problem, and its consideration is strongly needed in the planning and operation of the power grids. Based on modern power systems and conducted review, some recommendations and suggestions for future planning are provided as follows.

Large-scale power grid: In the early stages, the GICs effects were considered only in high latitude areas due to extreme solar storms. Over time, it has been realized that the considering GICs in mid and low latitude areas is also essential due to the increase in numbers of transmission lines and upgrading of voltage level to EHV and UHV. It is also worthy to note that the fast-growing and large populated countries like India and China in the mid-low latitude region are developing large-scale grids for satisfying the increasing power demand. These power grids comprise the EHV and UHV transmission network and smart grid with advanced communication infrastructures. The transmission line design for these higher voltage levels results in lower resistances and, in consequence, larger GIC values. Also, the fault and interruption due to natural disasters like GICs can result in blackout and economic losses. These are the evidence that suggests considering the GICs impact while planning the large-scale grid.

Large microgrid: Nowadays, the interest in increasing the size of a microgrid is amplified for reducing the transmission and distribution losses, enhancing the power reliability, and encouraging the use of renewable energy resources. It can also be noted that the microgrid is not confined to the distribution network but also reaches HV and EHV networks [95]. However, there is no publication which studies the impact of GICs on microgrids connected to HV and EHV systems, and therefore the impact of GICs on microgrid is a topic that needs to be explored.

Smart Grid communication: The Smart Grid is the new generation of the electrical grid having real-time monitoring and smart controlling, self-healing, high reliability, and security of energy using digital communication systems. Because of its great merits and advancements in policies, pilot projects for the deployment of Smart Grid have been started worldwide. However, intelligible and secured communication infrastructure is one of the key attributes needed for the successful development of smart gird [96-98]. These communication systems include Cellular and Mobile Networks, Microwaves, Power line communications (PLCs), Wireless local area networks (WLANs), fiberoptic, etc. [97]. However, the impact of solar phenomena on communication infrastructures can be needed to investigate the smooth and efficient deployment of the Smart Grid.

Transformer design: The GICs mainly flow through the transformer windings and affect the thermal and magnetic capabilities of transformers. IEEE working group on GICs recommends considering the IEEE Std.C57.91 and IEEE Std.C57.163 during the designing of large transformers [64].

Investigation of the performance of distance protection: The high voltage transmission lines are generally protected by distance protection. Therefore, the effect of both GIC and its mitigation devices on distance protection's performance can be required to investigate. In [99], the effect of GICs blocking devices on the performance of distance relays have been examined. The capacitor-based Neutral blocking devices with

Table 3
Outcomes of the review.

Review of particular	Sub-particular	Outcomes
GIC impact on power system apparatus	Power transformer	• The neutral-ground connection in Y-connected winding offers a path for the flow of GICs through the transformers. •These GICs produce DC flux, which eventually adds in the AC flux, which causes the half-cycle saturation of the core. • The excitation current drawn by the transformer is about 1% of full load current, while it can be increased around 10 to15 % in the presence of GICs. This high excitation current leads to core saturation and increase reactive power absorption. This additional and unpredictable reactive power demand can collapse the system voltage and, in the worst case, shut down the power grid. • This large magnetizing current contains both even and odd harmonics, which cause several issues in transformers itself as well as in a generator, compensating devices, protective relays, etc. • Due to the core saturation, the stray flux exerts on the different parts of transformers such as the wall of the tank, core clamps, shields, etc., which increase the losses and thus the heating in transformers. • It is also observed that the effects of GICs depend on the design of transformers. For example, 1-Φ transformers are more susceptible to GIC than 3-Φ transformers, 3- Φ core type with three limb transformers more impermeable than other forms.
	Generator	• The generator has to supply supplemental reactive power demand caused by half-cycle saturation, which increases the field current and thus increases the thermal stress. • Furthermore, the negative sequence components produced by the second and eighth harmonics cause the overheating in end-rings. In contrast, positive sequence components produced by fourth and tenthharmonics cause the vibration in the rotor.
	Current Transformers	• The CTs can be saturated due to GICs like DC offset during a fault. However, the core of CT is designed in such a way that it can sustain heavy fault current without falling into the saturation region. Hence, GIC has less effect on the performance of CTs.However, when GIC and fault simultaneous occur, the core of CT can be saturated rapidly. • Like power transformers, CT also undergoes half-cycle saturation and generates harmonics, which ultimately produces the erroneous input for relays.
	Protective relays	• GICs can cause the undesirable operations of protective relays, such as neutral overcurrent relays, neutral overvoltage relays, neutral unbalanced protections, phase overcurrent protection, gas-operated relays, and differential protection. • There is also evidence that the maloperation of relays turns into a blackout of power systems.
	HVDC networks	• Due to GIC in converter transformers, the harmonic generations and voltage distortion has arisen, which changes the firing angle of converters. • Also, the audible switching noises level increases at the converter terminals due to harmonics' presence on the AC side. • In light load conditions, fourth and sixth harmonics produce the parallel resonance condition and cause the overloading of filters.
	Communication systems of power utilities	• The solar radiations and solar winds cause ionospheric and magnetospheric effects. These effects are the source of several issues in the communication systems of power utilities. • The ionospheric effect causes absorption and loss of high-frequency radio signals. On the other hand, the magnetospheric effect causes disturbances in cable communications. • The interference and distortion in carriers utilized along with power lines can result from harmonics generated during the half-cycle saturation of the transformer.
Mitigation methods	Passive devices	• The devices such as disconnecting switch, inductor, resistor, capacitor, and capacitor with bypass switch are utilized to block the GICs in neutral of transformers. Amongst these, capacitor-based mitigation techniques are widely suggested by researchers in the literature, as the capacitor offers a low impedance path to power frequency current and high impedance to low frequency GICs. • However, the utilization of the capacitor solely for blocking the GICs does not justify the cost. Also, overcharging and transient are additional issues. • For increasing power transfer capability and blocking the GICs, the utilization of the series capacitor in transmission lines is also presented as a cost-effective solution. Nevertheless, it causes the larger GICs to flow in a nearby line where the series capacitor is not installed.
	Active devices	• In this method, semiconductor devices and their control circuit are used to reduce the GICs. In this method, the neutral-ground connection is very rapidly open and close in a short time whenever the GIC is observed. This quick switching action reduces GICs but cannot block it entirely. • The mitigation techniques based

(continued on next page)

Table 3 (*continued*)

Review of particular	Sub-particular	Outcomes
		on this approach are capable of resolving issues associated with the passive approach, but they involve the complicated and expensive circuit. • Several research papers have been presented about these ideas, but the power utilities are not seriously considering them.

three different values are considered for testing the functionality of mho type distance relays. This study can be extended by considering the impact of different mitigation devices on different types of distance relays.

*Measurement and monitoring of GICs:*The monitoring of GIC in the power network is an urgent need so that its effect can be reduced before intensifying to a particular threatening stage. For effective measurement and monitoring of the GICs, the Electric Power System Research Institute (EPRI) has developed the SUNBURST network [78]. Furthermore, the magnetometers can also be used to record the change of the magnetic field of the Earth's surface [100]. GICs can be measured by the magnitude of DC current flowing through the ground-neutral connection of transformers. The Hall-effect transducer can measure both AC and DC current effectively [64]. The digital instrument transformers with Intelligent Electronic Devices (IEDs) make the relays, and digital fault recorders enable to measure this Quasi DC current. When the transformer undergoes half-cycle saturation, harmonics are generated, which results in increases in the reactive power consumption and heating in the different parts of the transformer. These changes can also be used to monitor the GICs indirectly. Recently, Wang et al. [101] have proposed a time-frequency analysis with a convolutional neural network approach for GIC detection. Further studies with the detection method can also be performed for various models of transformer saturation.

Mitigation techniques: Passive methods can block the GIC, but it moves elsewhere in the power systems. So, these methods do not give a complete solution for the mitigation of GICs. Also, passive devices-based techniques hold some challenges in the case of the ground fault condition. These challenges can be resolved using active methods, but it is quite expensive and complicated. When shield wire is connected to tower and substation ground, it provides an additional path that increases the GIC in transmission lines and transformers [102]. Therefore, the presence of the shield wire poses a new challenge in developing GIC mitigation devices. Overall, the development of an economical, robust, and effective mitigation method for GICs is still an active area of research.

6. Conclusion

The geoelectric field produced during the GMDs leads to the flow of GICs in the power systems. The GICs with significant magnitude can affect the operation of various components of power systems. In this paper, the induction process of GICs from GMDs is elaborated. After that, the effects of GIC on various power system apparatus are reviewed in detail. Also, the different mitigation methods are discussed with their competence. The outcomes of the review and future planning of power systems considering GICs are also discussed in the final stage of the paper.

The GICs generally result in positive half-cycle saturation of transformers. This nonlinear state of transformers is the root cause of various consequences, which includes heating and vibration in the transformer; generation of harmonics that create problem in the operation of protection devices, HVDC networks, generators, and communication systems; increase in reactive power consumption that leads to voltage fluctuation and stability issue. In extreme conditions, all these issues can result in a complete shutdown of the grid in the worst case. Several studies in the literature have suggested employing passive and active approaches to limit the flow of GICs. However, both approaches have their limitations, and therefore some effective mitigation method still needs to be developed. All over the world, the growth of EHV and UHV power grid, large microgrid, and Smart Grid technology are considerably increased. Therefore, there is a profound need to investigate the GICs impact on these modern power systems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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