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The Impact of Geomagnetically Induced Current on Single-Phase Saturable Transformer

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Abstract: Changing of magnetic fields can cause electrical currents, known as geomagnetic ally induced currents that caused by solar storm. This current can affect power system especially power transformer as it can generate quasi direct current through the neutral of the transformer. Previous studies have shown that the risk is not just limited to high and mid-latitude locations, but extends to power grids at lower geographic latitude as well. This paper presents the simulation of GICs using a single-phase saturable transformer under steady state and operation with GIC in MATLAB SIMULINK. The simulation results illustrate that when transformers are under influence of GIC, magnitude off lux and magnetizing current are increase with in time and distort the core of hysteresis curve. It indicates that GICs generated by solar storms can saturate the transformer, cause other effects such as transformer heating and creating large amount of harmonics. The findings have proven that GIC is a threat to the power transformer and can damage power system network.

Keywords: Geomagnetically Induced Current, Transformer, Magnetic Field

I. INTRODUCTION

Geomagnetic disturbance (GMDs) is a sequential variation in the magnetic field of the earth caused by solar activity such as earth-directed coronal mass ejections (CMEs) or solar coronal holes. Geomagnetic induced currents (GICs) are the earthly effects due to GMD, which are low frequency but high impact events [1]. GMDs are naturally occurring phenomena in the earth's magnetic field that begins with activity from the sun. High activity from the sun can generate powerful solar flares with intense bursts of radiation and disrupt GPS and communication signals when reaching the earth.

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However, the biggest threat is coronal mass ejections (CME) because it is a hug eruption that sends. Bursts of solar Pl as main to space. At infinite amount of speed, CME that hits thee art could spark geomagnetic storms and wipe out power grids, thus and leave earth in the dark.

While the storms create beautiful aurora, they can disturb navigation systems such as satellite communication system and generate harmful geomagnetic induced currents (GICs). Additionally, it has been revealed that GMD can produce high levels of geomagnetic field and high electric fields can therefore be created that could threaten the stability of power grids at any latitude [2].

The magnitude of GIC is governed by the magnitude and orientation of the geomagnetic disturbance, which depends on the location of earth and mostly occurred in the northern and southern part of the earth. Besides, proximity to a large body of Water Ocean can make the magnitude of GIC to be higher than the resistance of the soil. The most important factors that determine the magnitude of the GIC are the height and direction of the transmission line. The longer the transmission line and direction whether it is north south or east-west, the higher will be the induced voltage. Thus, the magnitude of GIC can increase when the voltage ratings is at 500kV.

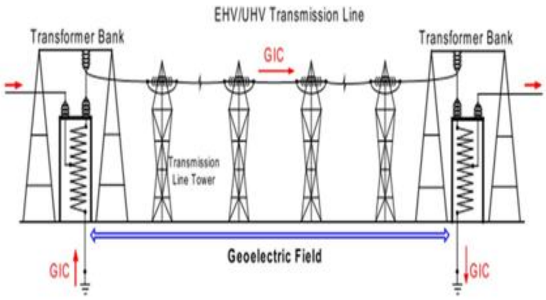


Fig. 1 GIC flow in a power system network [3]

The main threat that a geomagnetic storm poses to the power grid are the circulating low frequency currents known as GIC, which are generated as a result of a GMD. Figure 1 shows the flow of GIC in a power system network and the current enters the transformer through the grounded neutral. The magnetic field links the transmission lines with the transformer and the ground, hence GIC flows through when there is a magnetic field in the system.

II. GIC PHENOMENON

Previous studies have discussed the significant of GIC impact to the transformer, which in many cases were experienced by the countries with high latitude compared to mid and low latitude.

The most powerful power grid failure was Hydro-Quebec, which had collapsed in 13th March 1989 that leads to blackout. Table 1 indicates the historical account of significant space weather activities during the existence of GIC.

Table. 1 Historical account of significant space weather activities Events Year Effects on the power grid

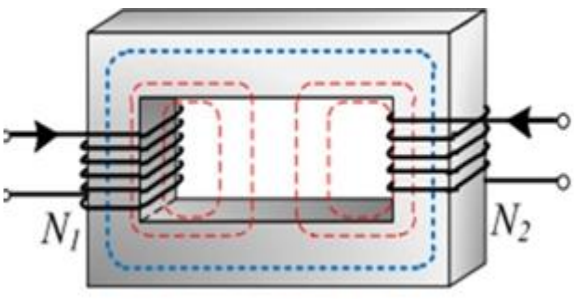
Events	Year	Effects on the power grid
The Carrington Event [4]–[6]	1859	• Largest recorded geomagnetic disturbance • Telegraph operations in North America has been disrupted
The Solar Storm[7], [8]	1921	• Blown out fuses and injured electrical apparatus • Telegraph communication was disrupted in cities • Some cable and telegraph lines did not work
The Quebec Blackout [9]–[11]	1989	• The transformers were driven into the saturation region • Caused the blackout of 745 kV transmission system • Massive reactive power shortage • Blackout ultimately left 6 million of customers without power for 9 hours
The Halloween Solar Storm[12], [13]	2003	• Leaving about 50,000 customers in the dark for 1hour • High value of transformer GIC neutral current of 330 A was observed during this event leading to its failure

There have been several studies on GICs reported at relatively high latitude countries such as Canada and Finland and mid-latitude countries such as the UK and Russia. In addition, studies also done at low geographic and geomagnetic latitudes which is at South Africa and Brazil [14]. Therefore, for the countries that are considering the GIC activity to be relatively 'safe', power transformer has a tendency be exposed to failure due to space weather events. Other research work also identified that *dB/dt > 30 nT/min* magnetic field threshold would affect the power system and power transformer.

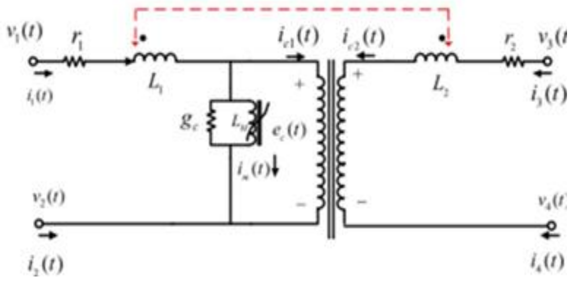
Only a few amperes of dc current are sufficient to drive the core of a large single-phase transformer into the saturation region. From the previous research work, transformer with star or wyes connections linked by long transmission lines [15] are susceptible to GIC problem due to the induced currents flowing through the transmission lines and grounded neutrals [16].

III. MODEL OF SATURABLE TRANSFORMERS

Figure 2 shows a core of a single-phase two wind in transformer with a magnetic circuit. The transformer consists of two windings and a metallic core on which the windings are wound [17].



(a)



(b)

Fig. 2 Single-phase transformer model: (a) two-winding transformer, (b) equivalent circuit [18]

The winding coils acts as an inductor and when an alternating current is allowed to flow through any of the windings, there will be an alternating flux produced surrounding the winding. The magnitude of this flux is proportional to the magnitude of the current flowing through the winding. The existence of GIC is related to the Faraday's Law of induction where the induced electric field on the surface can be calculated from the rate of change of the magnetic field as presented in equation(1).

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad (1)$$

Since the entry point of GICs is through the grounded neutrals of the transformer, they are the most affected equipment during a geomagnetic disturbance. During the disturbance, transformers are driven to saturation region of their operating curve; which are described as half cycle saturation. Half cycle saturation causes ever another problem like increase in reactive power consumption in the windings which is a power loss, heating up of windings due to leakage of magnetic flux and high harmonic content in phase currents.

Transformer design is a major consideration as it can influence the transformer effect. To evaluate the impact of GIC on a single–phase saturable transformer due to core saturation, an appropriate model of transformer is required.

IV. NUMERICAL SIMULATIONS AND RESULTS

A simple power system network is modelled to simulate GIC phenomenon in order to study the impact of GIC on a single-phase saturable transformer as shown in Figure 4. A single-phase core design transformer is much more responsive to GICs influence than most standard three phase designs. The transformer model is specified and scaled to simulate the effects of GIC to actual transformers. The focus in this simulation is to simulate the behavior of hysteresis curve, flux and magnetizing current in the transformer winding caused by GIC. Hence, a single-phase, two winding with a system voltage of 500/230kV is modelled to determine the transformer behavioral on with saturation modelling. The input of the transformer is connected to a pi model transmission line and the output is connected to a load resistor. A resistive load of 50 ohm was considered as the rated load [16]. Figure 3 shows the simulation circuit of a single-phase transformer using MATLAB SIMULINK.

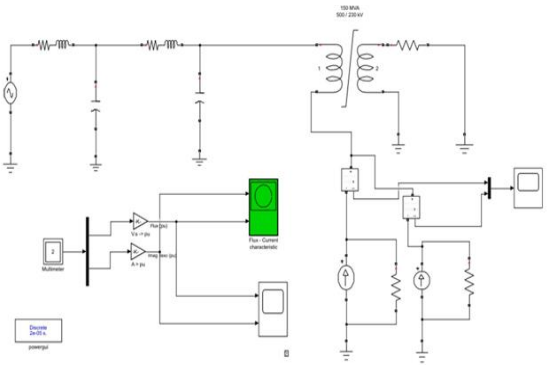


Fig. 3 Simulation circuit for single-phase saturable transformer

The transformer's characteristic flux-current saturation is modeled with the hysteresis. The function of a multimeter and a scope block are used to monitor and measure waveforms of flux and magnetization current. To monitor the transformer operating point moving on the flux-current characteristic, a X-Y graph block is used. GIC in that simulation circuit is introduced as a slow varying two AC current source in the grounded neutral of the primary winding [19]. The parameters of transformers and transmission lines are listed on Table 2 and Table 3.

Table. 2 Transformer Parameters

Power Ratings (MVA)	150
Voltage (kV)	500/230
Inductance (p.u)	0.08
Resistance (p.u)	0.002

Table. 3 Transmission lines parameters

Power Voltage (kV)	500
Length (km)	300
Resistance per phase (Ohms/km)	0.059
Inductance per phase (mH/km)	1.67

This section discusses the results of two different operating conditions, steady state condition and operation condition with GIC. During steady state condition, the power transformer is operating at an alternating current (AC) with a frequency 60Hz. When the system is operating with GIC, the injection current was varied at three different magnitudes, 0 A, 100 A and 200 A. The behaviour of the single-phase transformer is represented by the B-H wave form; hysteresis curve, magnetizing current and flux are shown respectively.

A. Hysteresis Curve

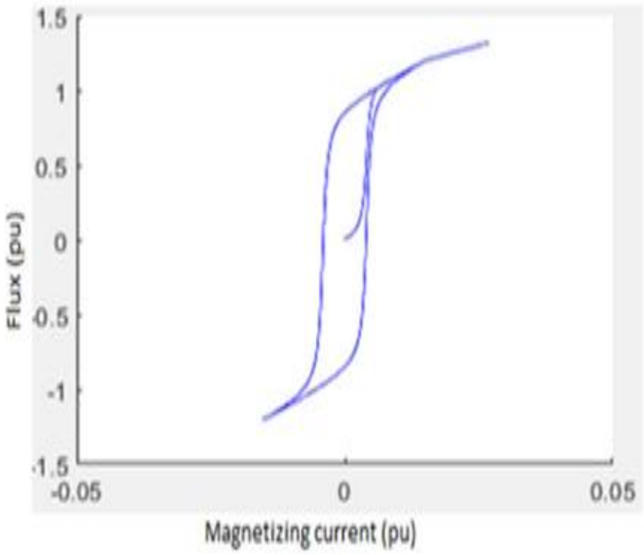


Fig. 4 Hysteresis curve with no injection of GIC

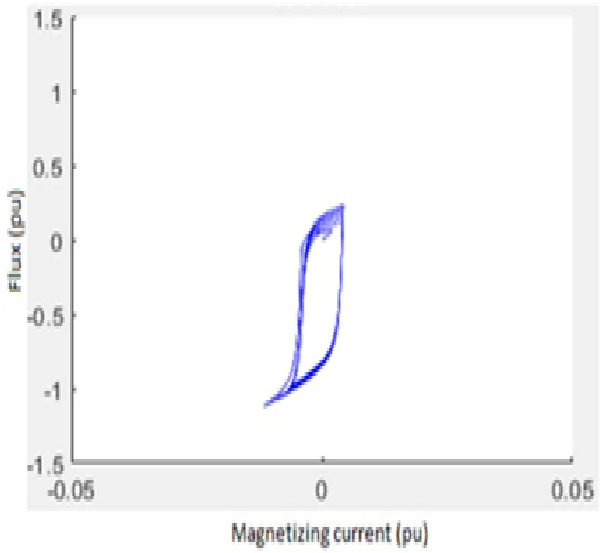


Fig. 5 Hysteresis curve with 100 a injection of GIC

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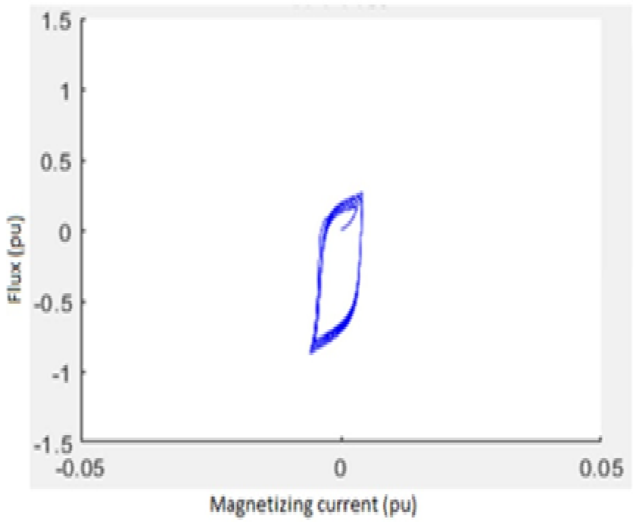

Fig. 6 Hysteresis curve with 200 a injection of GIC

Hysteresis curve with injection of 0A, 100A and 200A GIC are shown in Figure 4, 5and 6. In the simulation, the flux-current characteristics are plotted using an XY signal scope after converting both the quantities into per unit system. The flux-current characteristic of transformer core materials is non-linear and the graph is distorted when injection of GIC is increase. At steady-state operation, the transformers are designed to operate in the linear region where the magnetization current has a linear relationship with the flux that produced in the windings. However, at the saturation condition, the excessive flux causes the core to operate beyond its saturation limits. Because of that, this excessive flux pull seven more exciting current in to the core, thus affecting its linearity and resulting in increasing core losses and harmonics incurrent.

As GIC enters the windings of the transformer through the grounded neutral, the AC currents cause additional flux due to the high number of windings. This excessive flux biases the operating point of the flux-current characteristics into the saturation region from the line ar region. As a consequence, the core is not only excited by the sinusoidal magnetizing current but also by the ACGIC current. Thus, in one cycle, the afflux and dcbi as are in the same direction causing an excursion in the flux-current operating point.

B. Flux and magnetization current waveform

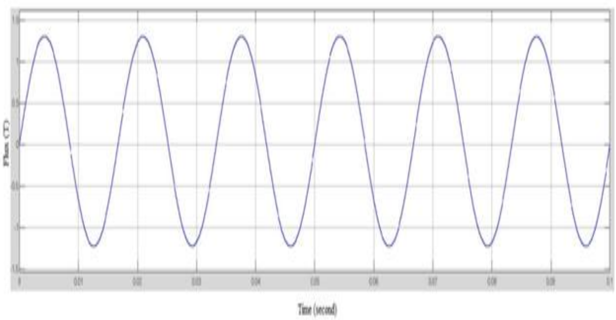

Fig. 7 Flux waveform with no injection of GIC

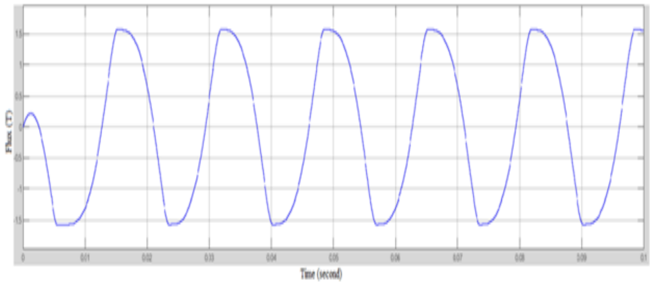

Fig. 8 Flux waveform with 100 a injection of GIC

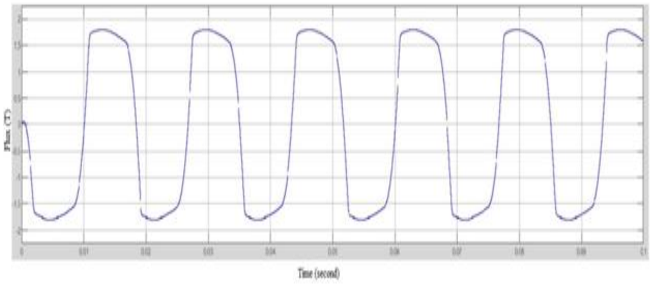

Fig. 9 Flux waveform with 200 a injection of GIC

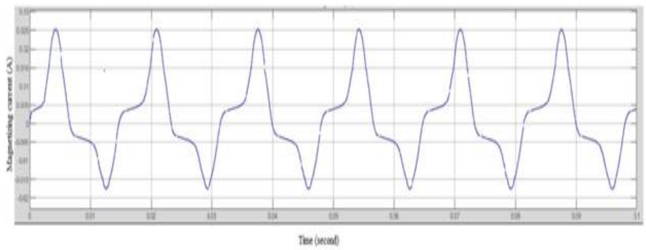

Fig. 10 Magnetizing current with no injection of GIC

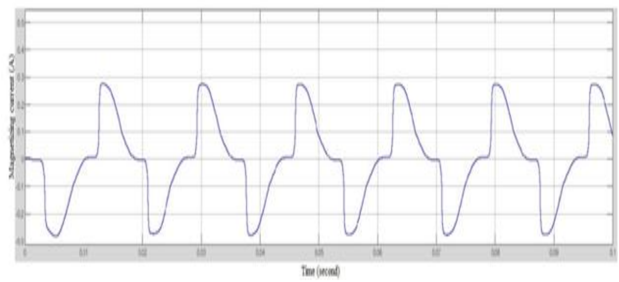

Fig. 11 Magnetizing current with 100 a injection of GIC

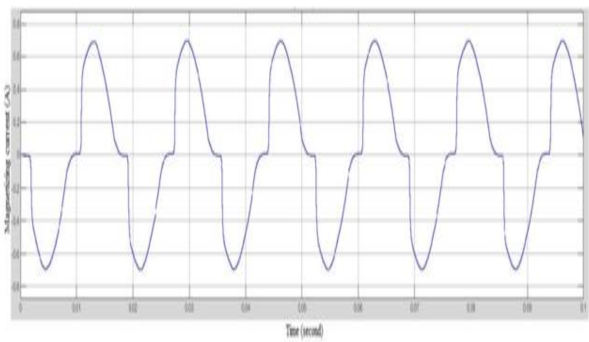

Fig. 12 Magnetizing current with 200 a injection of GIC

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The waveforms of the flux and magnetizing current are shown in Figure 7 until 12. The magnitude of the flux is1.3T when the transformer is operating under steady-state conditions and the wave form is pure sinusoidal. But, when injected with 200 A of GIC, the magnitude becomes 1.8 T. The effect of GIC also can be observe from magnetizing current which is in steady-state the magnitude is 0.025A, butitbecomes0.7Aafter in ejected with 200A of GIC. It shows that magnitude of flux and magnetizing current increase when GIC flows through the transformer and the waveforms become distorted due to transformer core saturation.

The continuous operation of the transformer in the saturation region causes the core to saturate with flux. After a few cycles of operation, magnetic reluctance increases due to core saturation and the excess induced flux. This is because of DC bias tends to stray out of the core and penetrates into other internal components of the transformer tank as indicated by magnetic simulations. As a result, this will lead to several other issues such as increased reactive power consumption and absorption, current harmonic generation and transformer heating.

V. CONCLUSIONS

This paper studies the issue of geomagnetic phenomenon as a potential disturbance to a power transformer, using the results obtained from simulation of GICs to a single-phase transformer being modeled in MATLABSIMULINK. The performance of a single-phase transformer under steady state condition and with operation of GIC has been analysed based on hysteresis curve, magnetizing current and flux. Simulation results discuss that when transformer under steady state conditions, magnitude of flux and magnetizing current are increase within time and distort the core of hysteresis curve. Simulation results have indicated that GICs generated by GMD can saturate a single-phase power transformer and can cause another effects such as transformer heating and creating large amount of harmonics. As GIC is induced in a transformer, it will generate half cycle saturation that can cause the transformer fails to operate. It has been proven that GIC are a credible threat to power system network and technological system need to be investigated intensively and should be extended to a wider region.

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