

Mitigation of Geomagnetically Induced Currents by Neutral Switching

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Abstract—This paper presents a novel mitigation technique to reduce the effects of geomagnetically induced currents (GICs) on high-voltage power systems. The method consists of connecting switching devices at the neutral grounding connection point of transformer banks. Only one transformer bank needs to be grounded through a switch to reduce GIC in a two-terminal system. For multiterminal systems, $n - 1$ switches are necessary and the operation is independent from each other. The switching frequency and the duty cycle are selected from a tradeoff between the effectiveness of the method and the detection of fault currents. Transient simulations on a two-bus 230/500 kV system show that the proposed switching at the neutral successfully mitigates the GIC. This proposed technique opens the door to a new family of GIC mitigation methods.

Index Terms—Geomagnetic disturbance (GMD), geomagnetically induced current (GIC), geomagnetism, half-cycle saturation.

I. INTRODUCTION

GEOMAGNETICALLY induced current (GIC) is the product of variations in the Earth's normally static magnetic field. These variations are caused by explosive solar events, such as flares and coronal mass ejections (CMEs), that hurl vast amounts of magnetized plasma into space [1]. Low-frequency currents caused by this solar activity flow in the Earth and on long man-made conduction paths, transmission lines as discussed here, that act as “antennae.” GIC are quasi-dc currents that can disrupt the normal operation of the power system and can, in some cases, damage equipment [2].

As illustrated in Fig. 1, the geoelectric field causes a dc shift in the transformer flux. Flux exceeds the knee point of transformer cores which operate beyond the linear portion of the B-H curve at each half-cycle. This causes current to rise continuously in each cycle as long as the dc is present until the system can no longer handle the high magnitude unbalanced half-cycle saturation. The saturation level depends on the amount of GIC and B-H characteristics, such as operating point, air-core inductance, and transformer design type.

Single-phase transformers are vulnerable to half-cycle saturation the most because the dc flux has the lowest reluctance path

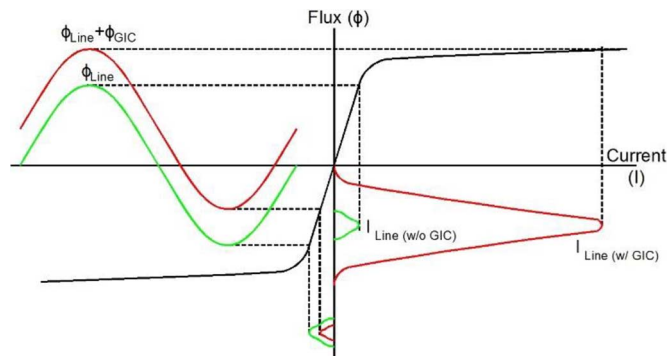


Fig. 1. Half-cycle saturation due to dc voltage caused by GMD.

through the core compared to other types of transformer designs [2]. Thus, semi-saturation can occur for relatively low levels of GIC. In addition, the largest GIC flow in an HV network normally takes place at voltage levels above 230 kV. Transmission circuits below 230 kV generally have much higher dc resistance per-unit length, and their contribution can be ignored in most cases [3]. Also, transmission lines for voltage levels higher than 230 kV tend to be relatively longer. Magnetic variation due to solar activity induces a geoelectric field which produces voltage between 1.2 and 6 V/km [4]. Moreover, for 500 kV lines up to 200–300 mi as studied here, there is almost a linear relationship between the length and the induced dc current [5]. Based on this information, the system studied here assumes the worst case scenario to show the effectiveness of the method.

As observed in past GMD events, the half-cycle saturation of these high-voltage transformers may give rise to harmonics, heating, and an increased need for reactive power compensation [3], [6]. The most severe recorded GMD event, the Carrington event, occurred in 1859. During the storm, auroras (northern lights) were observed on the sky. Fortunately, there was no power grid at the time. Today's power systems are becoming increasingly more vulnerable to GMD. Space storms of the magnitude of the Carrington event would cause a long-term catastrophic power grid collapse with major social economic disruptions if it were to happen today [7], [8]. The most notable GMD events that had a substantial effect on power systems were the 1989 geomagnetic storm [9] and the Halloween storm of 2003 [10]. These past events showed that GMD does pose a serious risk on power systems. Therefore, regulatory agencies have put forth operating procedures to mitigate GIC as guidelines for utilities [3]. At the same time, the power industry has started to produce solutions to mitigate GIC. A study of the available GIC mitigation devices is given in [11]. Since the GMD of March 13, 1989, there has been a greater interest

Manuscript received September 09, 2014; revised December 03, 2014; accepted April 10, 2015. Date of publication May 21, 2015; date of current version July 21, 2015. Paper no. TPWRD-01058-2014.

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Digital Object Identifier 10.1109/TPWRD.2015.2434411

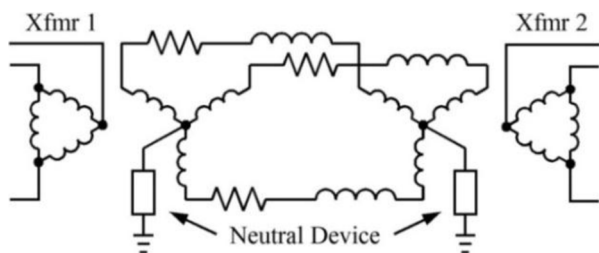


Fig. 2. Power system used to compute and mitigate GIC.

TABLE I
DEVICES THAT CAN BE USED AT THE TRANSFORMER NEUTRAL FOR THE
MITIGATION OF GIC

1.		Disconnect at Neutral
2.		Inductor at Neutral
3.		Resistor at Neutral
4.		Capacitor at Neutral
5.		Capacitor with by-pass at Neutral

in academic research as well. Many papers are published in this regard covering the following topics: existing technologies and power systems studies on transformers and utility transmission systems [12]–[21], adverse effects of GIC, such as harmonics [22]; reactive power demand [23]; transformer hotspot [24]; models of GMD, transformers and monitoring systems [25]–[29]; as well as proposed mitigation and blocking devices [30]–[33].

Some of the devices that can be used as neutral devices for the mitigation of GIC are shown in Fig. 2 and listed in Table I.

A brief description of the techniques listed in Table I follows:

- 1) *Disconnect at neutral*: The most obvious way to block the GIC is to disconnect the neutral from the ground where the GIC enters. But opening the neutral causes unpredictable voltage transients, hinders the ground fault detection, and may result in safety and insulation problems especially under single-phase-to-ground faults.
- 2) *Inductor at the neutral*: Inductors are generally used in the neutral to reduce the ground fault current levels. Since the GIC frequency is very low, such an inductor has very little effect on reducing the GIC.
- 3) *Resistor at the neutral*: Resistor in neutral does not eliminate the GIC although it can substantially reduce it at the cost of loss in protection sensitivity and size of the equipment [32], [33].
- 4) *Solidly connected capacitor at the neutral*: Capacitors in neutral totally eliminate the GIC but may cause ferroresonance especially if installed system wide [32], [33].
- 5) *Capacitor at neutral with bypass*: This method allows switching the capacitor to neutral only during the GIC

event; therefore, it limits the possibility of ferroresonance to the duration it is switched in [32], [33].

In addition to the neutral blocking devices mentioned before, the series capacitor in each phase of the transmission line blocks the GIC for that line. Therefore, in places where series capacitors are being used for reactance compensation, there is no need for further GIC mitigation devices. However, using series capacitors for the sole purpose of blocking GIC is not justified because of the high cost. It is important to note that the capacitor completely blocks the GIC which, in turn, can cause even larger GIC flow in other lines [40].

This paper proposes a novel mitigation technique consisting of installing semiconductor switching devices between the transformer neutral and ground. When GIC is detected, the semiconductor gic reducer (SGICR) opens and closes the connection to ground at 1 kHz. The switching action reduces the average dc current but does not completely block it. Thus, the disadvantages of completely disconnecting the neutral (unpredictable voltage transients and difficulties detecting faults) are eliminated.

The effectiveness of this method is demonstrated with time-domain simulations on a realistic system where the parameters were taken from [6], but the system was simplified for the demonstration of the SGICR. This is a first study intended to gauge the technical feasibility of the proposed method. Note that the rating of the SGICR is relatively low because in steady state, it carries only the sum of the unbalanced load currents. Although each case would require a careful study, 10% of the line rating is a good start in determining the SGICR's ratings. SA's protective level can be set lower than that of the SGICR withstand rating. However, SA's rating should be chosen such that the existing transformer neutral is also protected. Also, during normal operation (no GIC in the system), the SGICR can be easily bypassed. One of the strengths of this method over capacitor-type GIC blocking is that SGICR only reduces the GIC and does not block it as the capacitor does. Depending on the duty cycle, GIC passes through the transmission line, but not long enough to saturate the core.

II. TECHNICAL BACKGROUND

A. Semiconductor GIC Reducer (SGICR) Operation Principle

The proposed method suggests using a semiconductor switch at the neutral of the transformer as shown in Fig. 3. The SGICR switches on and off at low to midfrequency, chopping off the dc voltage caused by GMD. Gate turnoff thyristors (GTOs) or insulated-gate bipolar transistors (IGBTs) can be used for this application. These switches are well established in HVDC for medium power applications [35]. The mitigation of GIC occurs due to the reduction of the half-cycle flux injected into the transformer.

Fig. 4 compares GMD voltages injected into the transformer with and without the SGICR. Note that the flux injected into the transformer is, in fact, the area under the voltage given by Faraday's law

$$V = \frac{d\Phi}{dt} \Rightarrow \Phi \int V dt \quad (1)$$

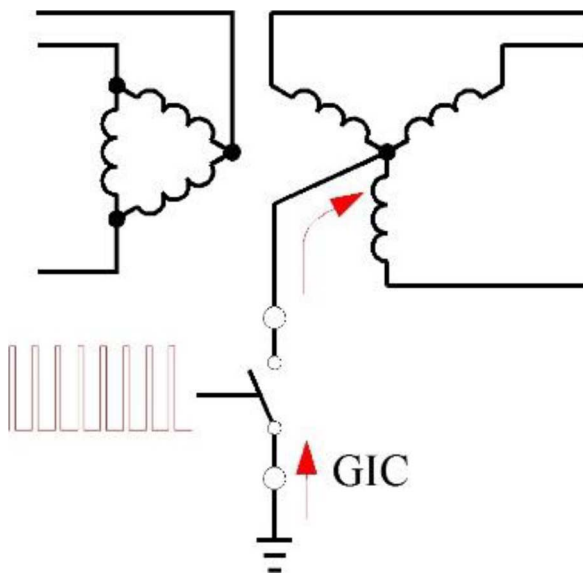


Fig. 3. SGICR at the secondary neutral.

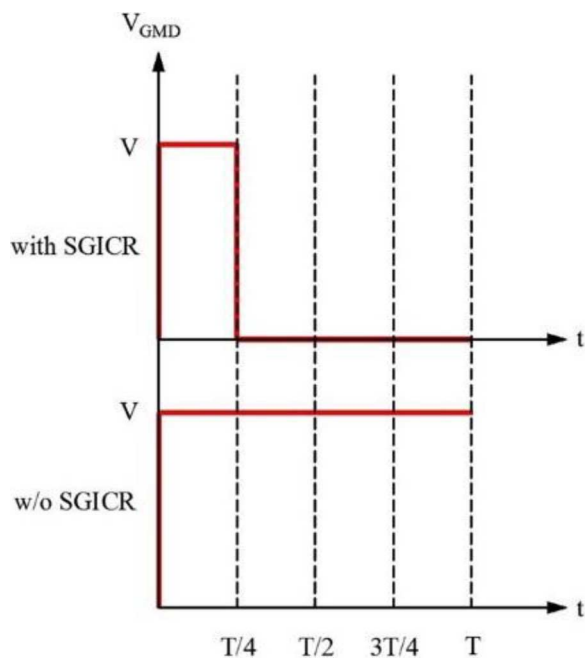


Fig. 4. Voltage caused by GIC with and without SGICR.

where V is the voltage and Φ is the flux. Therefore, when a duty cycle of 0.25 is used, dc flux injected by GMD is reduced to 1/4th. Since the dc flux caused by GMD is reduced, half-cycle saturation is also mitigated. This reduction would change depending on the time constant and whether there is a tertiary winding.

The switching frequency needs to be chosen according to the following criteria:

- 1) Ungrounded neutral may hinder the protection system to detect ground faults and may allow the neutral voltage to reach values that cause insulation hazards and safety risks. Therefore, the switching should be sufficiently fast such that the neutral instantaneous voltage is kept close to zero by closing it to ground frequently.

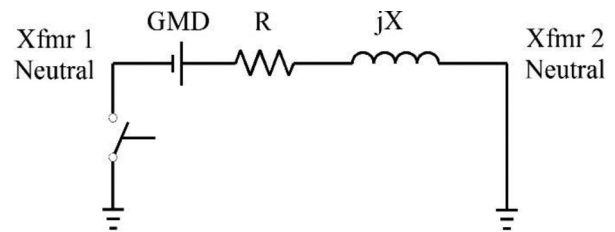


Fig. 5. Simplified circuit.

- 2) The switching frequency should allow a cost-efficient device. Typically, the higher the frequency, the more expensive the switching device and associated components are.
- 3) The device needs to turn on and off fast enough to meet the required duty cycle (D) and the frequency (f). For example, when $D = 0.25$ and $f = 1.2$ kHz, the device has to be able to switch on and off with 20–30 μs rise/fall time within 208 μs (on time = $DT = 208 \mu\text{s}$).
- 4) Finally, human hearing spans ranges from 20 Hz to 20 kHz. Depending whether the station is in a residential area or not, the appropriate frequency needs to be chosen or sound attenuation needs to be established because the SGICR itself would be a source of noise when in operation.

Without loss of generality, let us assume that there is no return path for GIC other than the neutrals of the transformers as shown in Fig. 2. Then, there is no need for switching at both transformers. Switching at only one transformer would be sufficient to break the return path of the GIC and establish mitigation both at the local end and at the remote end.

Fig. 5 shows a very simplified version of Figs. 2 and 3 where all resistances and reactances are lumped together with the return path through neutrals at each side. As shown, there is no return path for the GIC when the switch is opened. For n neutral-to-ground connections in the system, $n - 1$ switching devices are sufficient to mitigate the GIC based on the same logic. However, if only one SGICR is used at one side, periodic testing with a supervisory alarm would be needed to decrease chances of failure. If the cost is justified, SGICR at both sides would ensure GIC mitigation in case one fails.

B. SGICR Protection

The SGICR needs to be protected against fault currents since the available fault current at the transmission level is very high and would damage the SGICR. This protection can be similar to protection of other GIC blocking devices, such as the neutral capacitor blocking device in [32] or devices mentioned in [11]. Similar protection schemes are also used for flexible ac transmission system (FACTS) devices that typically consist of spark-gap/surge arrester for over voltages and a fast operating bypass switch. Such a protection scheme for FACTS is discussed in [36].

A similar protection scheme is shown in Fig. 6 for the protection of the SGICR where a resistor (R), surge arrester (SA), and a circuit breaker ($CB2$) are connected in parallel with SGICR as a permanent bypass route. This protection scheme is dashed together in Fig. 6. In addition, SGICR is further protected by an earthing switch (ES) as a temporary bypass and by a circuit breaker ($CB1$) in series. The surge arrester limits the voltage to

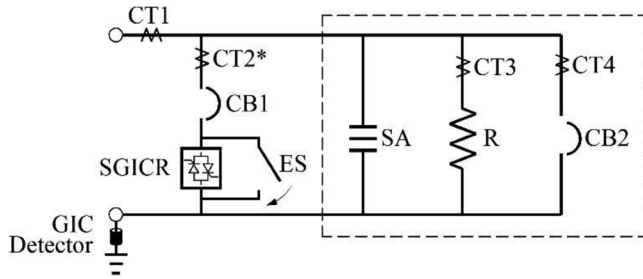


Fig. 6. Complete circuit for the proposed GIC mitigation method.

be below its protective level. A spark gap can also be used in parallel to provide protection while diverting the current through CB2. This allows all the other shunt equipment to be sized below the protective level, which saves space and cost. The resistor in parallel is large in value (50–100 Ohm) and provides a solid neutral to ground connection. CB1 and CB2 are coordinated to bypass the SGICR in the event of ground faults such that the fault current is always diverted through CB2. ES is designed to close very fast. Such ES are already commercially available under the name Ultra-Fast Earthing Switch (UFES) which closes in less than 1.5 ms [34]. This switch is used to provide temporary bypass while the circuit breakers would take 1–2 cycles to establish permanent bypass to ground. At the same time, line breakers are also sent a trip signal to clear the fault. During the transition, any transient voltage is drained through the SA and there is always a ground through R. There are a few variations possible with this arrangement. CB1 is redundant to line circuit breakers. Hence, it can be replaced with a fuse for cost/space savings. Also, CB2 will never be used to interrupt current but to provide a solid connection to ground. Therefore, it can be replaced with a circuit switcher or special equipment can be built for this application designed only for fast closing. Finally, thyristor valves can be utilized as an alternative to mechanical switches as fast bypass devices (in place of ES) as it is used in the case of series capacitor protection in [36].

CT1 in Fig. 6 is for line protection relays. CT2 is for SGICR which needs to be capable of measuring dc as well as ac; therefore, it is shown with an asterisk to distinguish it from other ac CTs. A Hall-Effect transformer is suitable for this application. The GIC detector can still be used for redundancy. In either case, the input from the CT2 and GIC detector needs to be entered into the logic of SGICR so that the proper actions can be taken as outlined in Fig. 7. CT3 and CT4 are not mandatory but can be used to check the status of CB2 (on/off) and as a redundant input to relays and SGICR in case other CTs fail.

C. Mitigation Mode and Fault Clearing Process

The proposed SGICR device is only operational when GIC is detected. It goes into mitigation mode automatically once the GIC level measured through the detector is above the threshold in magnitude and duration. It goes out of the mitigation mode only by an operator. This semiautomatic approach is intended to prevent multiple ON/OFF switchovers.

In the GIC mitigation mode, SGICR is on with CB1 closed and CB2 and ES open. However, if GIC is not detected or it is below the preset threshold, the SGICR is off with CB1 open

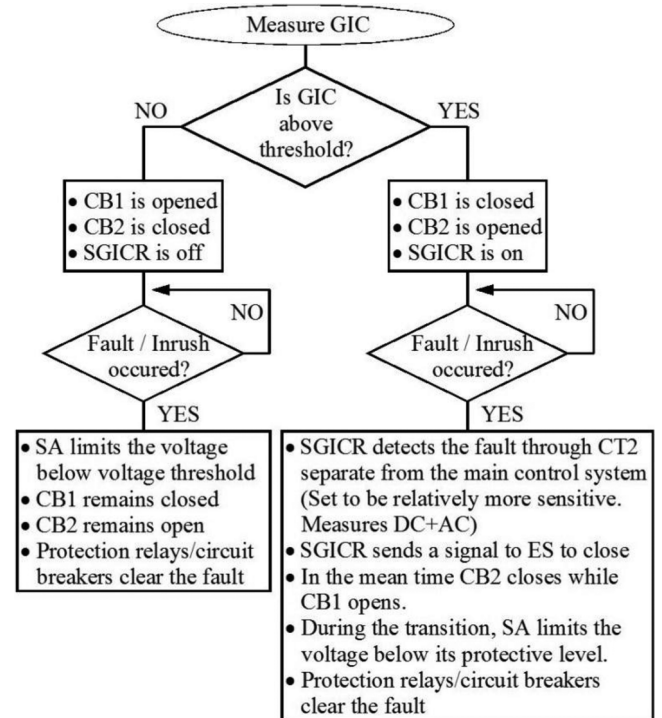


Fig. 7. Fault interruption process.

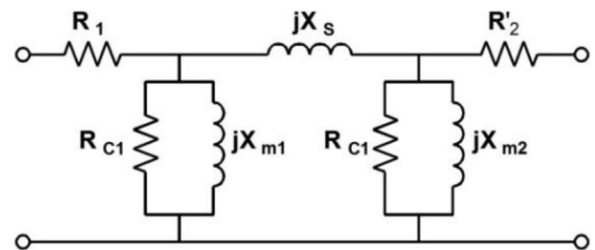


Fig. 8. PI transformer model.

and CB2 closed. Depending on whether the system is in GIC mitigation mode or not, the system will handle the fault currents differently. This is explained in the flowchart of Fig. 7.

If the system is in GIC mitigation mode, SGICR detects the fault through CT2, stops switching, and the control signal keeps the SGICR open. This trigger can be a preset instantaneous current value. The preset value is such that the SGICR can still be open. When the SGICR is open, the only ground connection is through “R” while CB1 is opening and CB2 is closing. Since the ES is faster than CB2, SGICR will be temporarily bypassed while the transition of current from CB1 to CB2 is taking place for permanent bypass. The voltage that builds across the resistor and SGICR is limited through the surge arrester during the transition.

In order to safely divert the current away from SGICR, the ES needs to close very fast before current levels through the SGICR reach above its threshold. The SA protective level is set below the withstand voltage of the SGICR.

If the system is not in the GIC mitigation mode, CB2 remains closed, CB1 remains open until the fault is cleared, and GIC is detected.

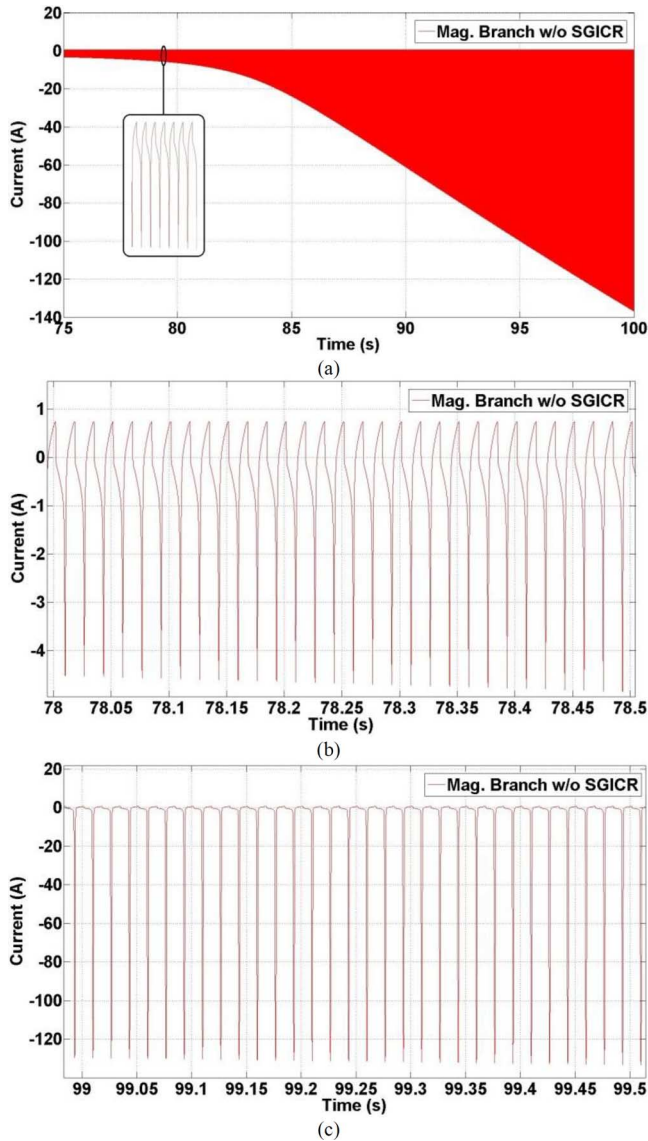


Fig. 9. (a) Magnetizing branch current without SGICR (solidly grounded)—half-cycle saturation observed. (b) Zoomed-in graph of Fig. 9(a) during initial saturation. (c) Zoomed-in graph of Fig. 9(a) during heavy saturation.

D. Duty Cycle and Frequency Parameters for SGICR

The underlying idea of the SGICR is that the ground should be connected from the viewpoint of the ac voltage (normal operation), but it should be disconnected from the viewpoint of the dc voltage (GIC). Two parameters control the quality of the connection: switching frequency and duty cycle.

The switching frequency should be selected so that the reference to ground is not lost. To keep the neutral voltage within acceptable values, it is necessary to ground the neutral at a high frequency. The upper limit of the frequency is determined by the semiconductor switching capabilities. If the switching frequency is too low, the neutral voltage can reach high values that would cause insulation/safety issues. In addition, lower frequency operation may hinder the detection of ground faults. The addition of SGICR would require minimal to no modification on the existing protection relays. This is because SGICR enables

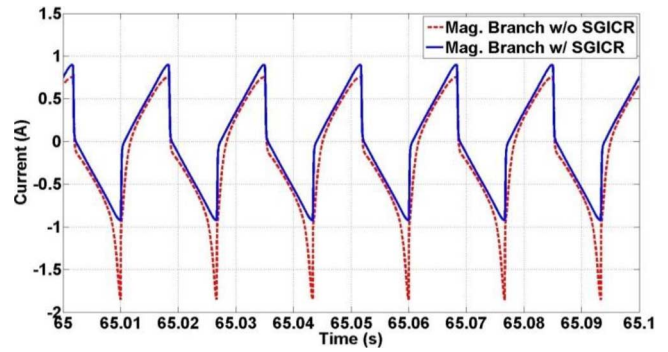


Fig. 10. Magnetizing branch currents with and without SGICR—comparison as the half-cycle saturation starts to occur.

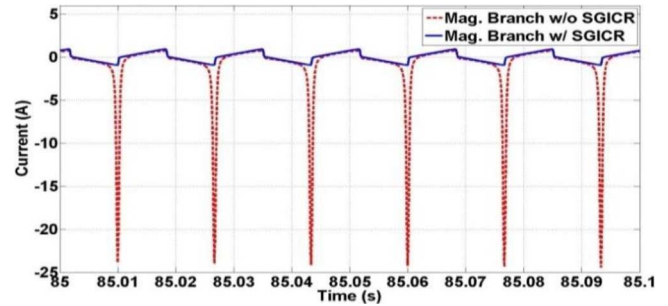


Fig. 11. Magnetizing branch currents with and without SGICR—comparison as deep half-cycle saturation is established.

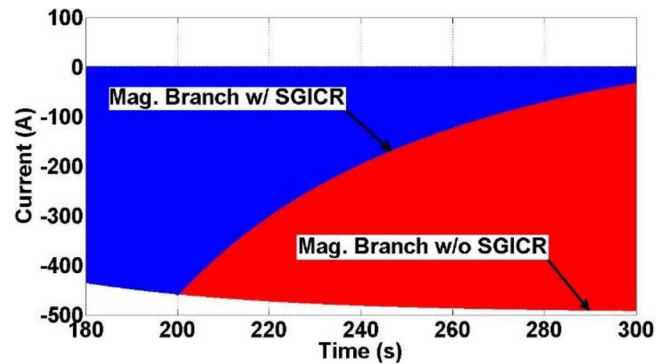


Fig. 12. Magnetizing branch current comparison with and without SGICR.

ground fault detection by frequently closing neutral to ground. Once the fault is detected, the SGICR is bypassed within 1.5 ms using the device described in [34]. At the same time, the permanent bypass is triggered as previously described above in Section C, restoring the neutral to a solidly grounded system. However, ON/OFF status from the SGICR and its switching frequency would need to be entered into the neutral/ground elements of relays so that the frequency of the SGICR can be filtered out. In addition, further study for the ground element would be required to make sure the fault pick-up time is within the requirements. Since SGICR is not the switching line current, no additional harmonics due to SGICR are expected or observed in the simulations. On the contrary, SGICR reduces half-cycle saturation and, hence, the harmonics associated with it.

The duty cycle determines how long the neutral is disconnected from the ground within each cycle of the SGICR

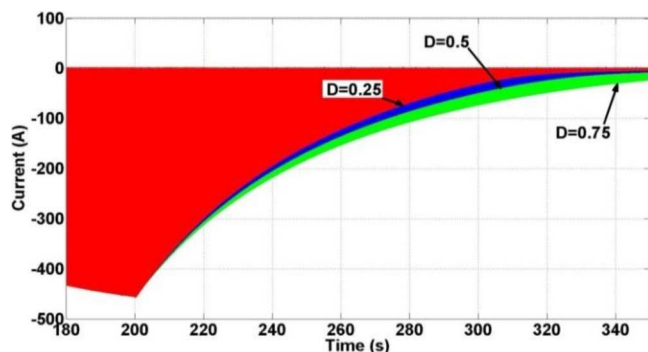


Fig. 13. SGICR duty cycle comparison.

switching operation, which dictates how much of the GIC is cut off. The more severe the GIC is, the smaller the duty cycle should be. Also, in the beginning of SGICR operation, the duty cycle can be kept smaller for quicker reduction. However, the smallest value for the duty cycle is determined by semiconductor switching capability, such as rise time, fall time, heating, and proper control system.

III. SIMULATION MODEL

The transformers were modeled based on the pi model as shown in Fig. 8, which produces more accurate results for transient saturation than the traditional T model [37]. Also, the hysteresis model is used instead of a saturation model for simulation of the core as suggested in [38], which explains the importance of the magnetic status of the core when simulating GIC effects.

SGICR is modeled as a controlled switch and a signal generator. Simulations are conducted on a simple two-bus 230/500 kV system where the values were taken from [5] and then simplified to a two-bus system. As discussed in the Introduction, single-phase transformers are most vulnerable to GIC. Therefore, 240-MVA single-phase transformers arranged in delta-wye banks are simulated where the primary resistance is 0.015Ω and secondary resistance is 0.219Ω . They are connected through a 500-km transmission line as shown in Fig. 9 where the total decline resistance is 20Ω . DC voltage across the line is 6 V/km. The operating source was assumed to be exactly 1 p.u. All simulations were conducted in the EMTP-RV using composite network modeling to enable future simulations of larger systems.

IV. RESULTS

The results shown in Fig. 9 are obtained from the case where the neutral is solidly grounded to show the validity of the model. As seen, the half-cycle saturation increases while the GMD voltage is present at the neutral. These results are in line with the results of [39].

Figs. 11 and 12 show the magnetizing branch currents of two systems with and without SGICR. In Figs. 10 and 12, the red solid plot shows the system without SGICR while blue dashed line shows the system that utilizes SGICR. While the GIC starts to cause half-cycle saturation in the system without SGICR, the other system maintains normal operation. Also, Fig. 12 shows the effectiveness of this method where the system is allowed to

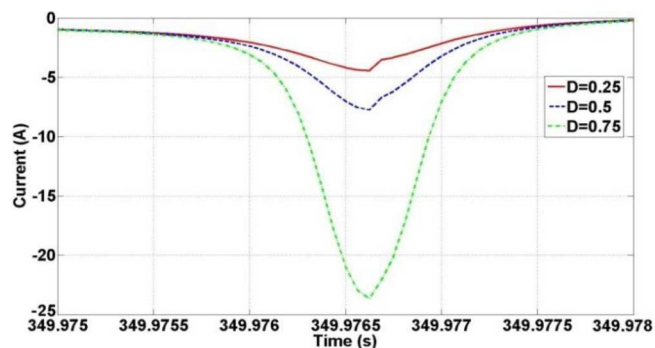


Fig. 14. SGICR duty cycle comparison—zoomed in.

get half-cycle saturated. Once deep half-cycle saturation is established, the SGICR is turned on. As seen in Fig. 12, mitigation starts as soon as SGICR is turned on while the system without SGICR is still in saturation.

The effect of duty cycle is shown in Figs. 13 and 14 where the SGICR is turned on after half-cycle saturation with different duty cycles. As seen, all three duty cycles successfully reduce the saturation but a smaller duty cycle has a greater reduction effect. This is more apparent in Fig. 14, which is a zoomed-in version of Fig. 13.

V. CONCLUSIONS

A novel method to mitigate GIC has been introduced in this paper. The method relies on the switching capability of HV power electronics that support the duty cycle and switching frequency demand of the SGICR. A switching frequency of 1.2 kHz (which gives 10 operations every half cycle at 60 Hz) and a 0.25 for duty cycle were selected. These are the two major factors of the GIC mitigation method proposed in this paper.

Unlike existing capacitor GIC mitigation techniques, neutral switching reduces dc current instead of blocking it completely. Therefore, half-cycle mitigation is accomplished while allowing GIC to flow. SGICR enables the detection of fault currents by closing the neutral to ground often while reducing GIC with the same operation. Therefore, the SGICR does not affect the overall system operations, such as fault detection, insulation coordination, and safety. All of these issues are resolved by frequently grounding the neutral connection of each transformer bank while providing an innovative and effective alternative to traditional GIC reduction techniques.

ACKNOWLEDGMENT

The authors would like to thank Prof. An T. Le from the University of South Florida for his input in reviewing existing GIC reducers and their protection schemes.

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