Power Grid Stability Protection against GIC Using a Capacitive Grounding Circuit

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***Abstract*-- This paper investigates a method to minimize the flow of geo-magnetically induced currents (GIC) through power transformers. The solution examined was an AC grounding path provided by a capacitor between the earth ground and the neutral point of a power transformer only when GIC was detected. The effectiveness and problems of this approach were investigated through simulation of a 765 kV transmission system in an electromagnetic transient (EMT) simulation program.**

***Index Terms*—transformer protection, GIC, harmonics, grounding circuit, capacitor, MOV, power grid, operational stability, SolidGround™**

I. Introduction

FLOW of geo-magnetically induced currents (GIC) through power transformers can cause operational instability issues and equipment damage in power systems during geomagnetic storms. One example of power disruption due to GIC is the collapse of Hydro Quebec power system in 1989. During this event, grid instability problems resulted from loss of several Static VAR Compensators (SVC) in the Quebec system. In addition reports of damage to transformers have been made from inside and outside the Hydro Quebec system during and after the event [1].

During a geomagnetic storm, a portion of earth could experience a time varying magnetic field, inducing an electric field up to 6 V/km or more on the earth surface [2, 3]. This resulting earth surface potential (ESP) acts as a voltage source applied between neutrals of the Y-connected transformer windings that may be located at opposite ends of a long transmission line. The resulting flow of current between the neutral currents is called GIC and has a very low frequency content (in the range 0 to 0.2 Hz), thus appearing as a quasi-DC in comparison to the power frequency. Values of GIC in excess of 80 to 100 amperes per phase have been measured in some three phase power systems [2,3]. When this current enters a transformer, it may shift the operating point of the magnetic characteristics to one side, if the zero sequence reluctance of the transformer is low. This may ultimately cause the transformer to enter the saturation region in a half cycle. The resulting large asymmetrical exciting current increases the reactive power consumption and creates additional hot spot heating [2-6]. In addition these asymmetrical exciting currents can affect other equipment such as static VAR compensators and capacitor banks, which are susceptible to tripping due to increased harmonic levels during geomagnetic disturbances [2, 3]. The loss of these reactive supplies, coupled with the increased transformer losses will challenge the security and reliability of the power system.

Capacitors on series compensated transmission lines can effectively block the flow of GIC, but installation of series capacitors just for the purpose of blocking GIC is not considered economical. Most literature on protection of transformers during GIC [5 -10] proposes use of a neutral impedance, generally a capacitor, to block or limit the quasi-DC current. Although the use of a ground capacitor limits the flow of DC current through the transformer, the high voltage buildup across the capacitor during high ground faults and possible ferro-resonance conditions have become problematic. In order to overcome these issues, applicability of different control mechanisms has been investigated and reported in the literature [5 -10]. These methods include the use of sophisticated control circuits which includes air gaps, power electronic control devices, etc. The implementation of these methods in actual systems has become challenging due to high installation cost and reliability issues.

This research investigates the development of an economical control mechanism for transformer ground protection against GIC. A novel feature of the proposed approach is the use of a capacitor in the grounding circuit only when GIC is present. Under normal conditions grounding is provided through a switch assembly. However, when a GIC event is detected, a capacitor is energized to block the GIC and provide an AC ground path by opening a bypass switch assembly. The level of voltage harmonics and the DC component in the neutral current are used to detect the flow of GIC. The voltage that could build-up across the capacitor during ground faults and potential ferro-resonance conditions are overcome by using a surge arrester (Metal Oxide Varistor, MOV) connected in parallel with the capacitor. Since the occurrence of the faults during GIC is rare, a replaceable surge arrester (MOV) that provides a permanent short circuit at high currents is proposed. The use of a DC disconnect switch, a high speed grounding switch, and the use of a sacrificial surge arrester (MOV) are some of the other novel features in the proposed approach. The proposed design is based on commercially available equipment that can be preassembled at a factory, and is a practical and cost effective solution.

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II. Proposed Protection DESIGN

The method proposed for transformer GIC protection [11] is shown in Fig.1. The switch assembly S is closed during normal operation providing an effective neutral to ground connection. The switch assembly is opened when a flow of GIC is detected. The presence of GIC is detected by monitoring both the quasi- DC component in the ground current and the harmonic level (THD) in the transformer voltages or currents. The current shunt resistor R_{sh} is used to monitor the ground current that could include a quasi - DC component. This shunt resistor can be a substantial piece of brass with several redundant electrical connections to provide a highly reliable grounding component. Alternatively, a Hall Effect current sensor could be used in the neutral connection in place of the shunt resistor for sensing the presences of a GIC event.

The opening of the switch assembly allows the capacitor to provide an AC neutral ground path and at the same time blocks the quasi DC GIC current. The DC disconnect switch used in the switch assembly S is designed to break DC and quasi DC currents. The voltage ratings of the commercially available DC disconnect switches [12] are lower than the neutral voltages expected during ground faults as will be shown later in this paper. Thus the switch assembly S is comprised of a DC disconnect switch connected in series with an AC grounding switch. When a flow of GIC is detected, the switch control logic will ensure that the switch assembly opening is started before the neutral voltage exceeds the DC disconnect switch voltage rating. The AC grounding switch, which is opened nearly simultaneously, provides sufficient insulation against the neutral voltages experienced during ground faults. Once both switches in the assembly are opened the DC disconnect switch is reclosed but the grounding switch remains open until a system operator declares the GIC event to be over.

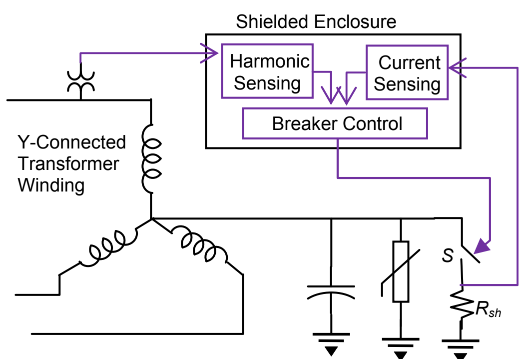

Fig. 1. Proposed protection design

In the rare case of a simultaneous GIC and a ground fault, a parallel connected surge arrester (MOV) protects the capacitor from an overvoltage event. In such a situation, the surge arrester (MOV) is allowed to enter its "pressure relief mode" as a sacrificial element. The surge arrester is designed to handle the initial fault current until the bypass switch assembly is automatically reclosed. This automatic switch reclosing is accomplished using a signal from a current transformer (CT), not shown in the figure, to reclose the switch assembly S. The switch assembly S will remain closed via the use of a lock-out relay, not shown in Fig 1, to provide a normal grounding path until the surge arrester is replaced. It should be noted that surge arresters provide a short circuit state after entering the "pressure relief mode" hence both the arrester and the switch assembly will conduct the ground fault current should this rare event occur.

III. Simulation Based Investigation

In order to investigate the applicability of the proposed protection concept, a simulation based investigation was carried out using a test transmission system simulated in PSCAD/EMTDC®.

A. Test System Model

The structure of the test system used for the simulation study is shown in Fig. 2. The three sources shown in Fig. 2 are system equivalents. They were simulated using the three-phase source model in PSCAD/EMTDC® master library. The source model used can accommodate different positive and zero sequence impedances. The initial values of the source voltages and phase angles were adjusted to maintain the required power flow. Transmission lines were modeled using frequency dependent models that accurately simulate the high frequency behavior and coupling effects. A ground resistance of 100 Ω/m [13] was considered in modeling the transmission lines. The transformers were modeled using the detailed transformer model available in PSCAD/EMTDC® master library. This model is capable of simulating AC saturation according to the characteristics specified by the user of the model. The model can be used to simulate phenomena such as half cycle saturation of the core. Although this transformer model in the PSCAD/EMTDC® master library does not model the hysteresis in the magnetic core, it is considered accurate enough to demonstrate the proposed protection concept. The parameters of the test system are given in the Appendix.

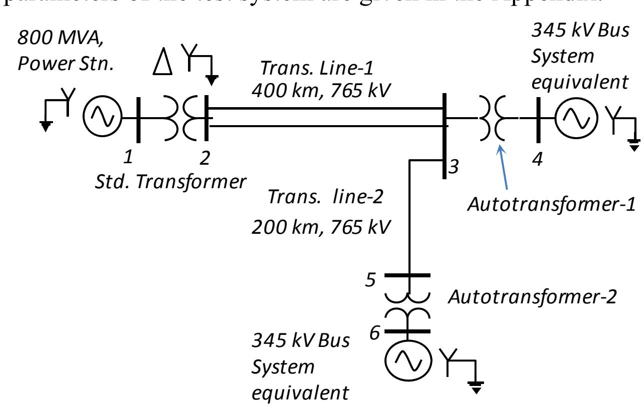

Fig. 2 Test system

Faults were simulated using the fault model available in PSCAD/EMTDC®. This model can be used to simulate different types of faults (phase to ground, phase to-phase, three-phase) with different fault impedances. The timing of the faults can be set by the user.

B. Modeling of GIC

Although injecting a quasi-DC current to the transformer neutrals using a controlled current source allows studying the effect of GIC on transformers, this approach is not suitable to study protection against GIC. When breaking an existing current path in the circuit, a current source would attempt to force its current through an alternative path, for example through an open switch modeled as a very large impedance, creating spurious voltages.

The cause for flow of GIC is the earth surface potential, and, therefore, it is more appropriate to directly model the earth surface potential as voltages acting across the transformer neutral points. In order to facilitate this representation, a local ground bus was introduced at each of the substations and the earth surface potential differences were modeled as slowly varying voltages injected between the true circuit ground and the local substation grounds. The relative magnitudes of the injected voltages (using controlled voltage sources) at the local grounds were adjusted considering distance between the substations. All voltage measurements were made with reference to the local grounds.

C. Modeling of Protection Design

GIC protection was provided to all three transformers. A neutral grounding capacitance of 2,650 μF (equivalent to 1 Ω impedance for a 60 Hz frequency) was used at all three transformers. A breaker model in the PSCAD/EMTDC® was used to simulate switch assembly S (DC disconnect in series with a grounding switch). The grounding switch (So. States model HRU 27kV, 150 kV BIL) was modeled as a switch that can only open when no current is flowing. This can be achieved by setting the "open possible at any current" option in PSCAD/EMTDC® breaker model to "No" and setting the current chopping limit to zero. The DC disconnect switch was simulated by allowing the breaker to open at any current with a current chopping limit above the switch rated current. The DC disconnect switch (ABB model E3H/E MS EMAX 1250 Amp, 1kV continuous rating, 12kV rating for one second) considered in the study has a capability of breaking 35,000 Amps at a maximum voltage of 1,000 V. The same trip signal was applied to both breakers in the model. The surge arrester (MOV) model available in PSCAD/EMTDC® master library was used for simulating a 5 kV MOV, with the nonlinear characteristics given in the Appendix.

The protection and control logic, which includes voltage harmonic sensor, current sensor, and breaker control circuit was implemented using the models available in the PSCAD/EMTDC® [14] control systems library. Fig. 3 shows the block diagram representation of the main functions of the proposed protection scheme. The input voltage is a signal from a CVT which samples the phase voltage characteristics. The current signal input is a sample of the transformer neutral current. The Fast Fourier Transform (FFT) component in PSCAD/EMTDC® was used to estimate harmonics in the protection signals.

The FFT component was used to extract the higher order harmonics to determine the THD. The DC magnitude of the ground current can be obtained by low pass filtering the measured ground current or by further processing the FFT signal. The THD and the DC current component were compared against the threshold levels to determine the presence of any GIC events in the system. In order to avoid tripping during other events such as temporary faults, inrush current, etc., a trip signal is not issued unless high level of THD or neutral DC current persists over a preset time delay.

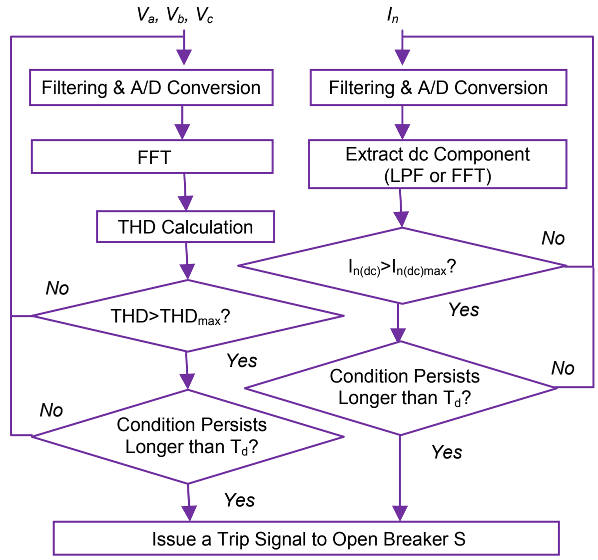

Fig. 3. Implementation of protection design

D. Determination of Threshold Settings

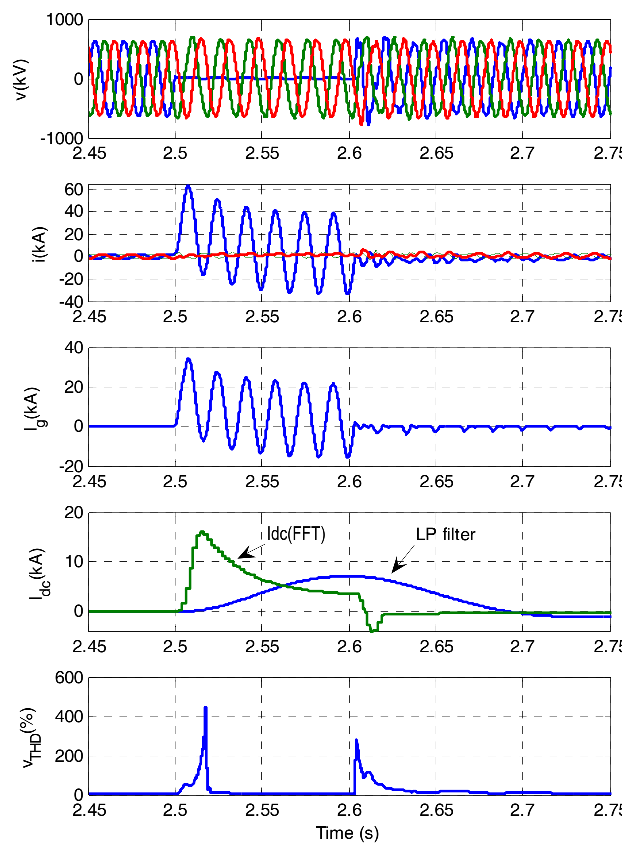

Fig.4. Variation of transformer voltage (V), winding current (i), ground current (Ig,) quasi - DC component of ground current (Idc) and THD voltage (VTHD)

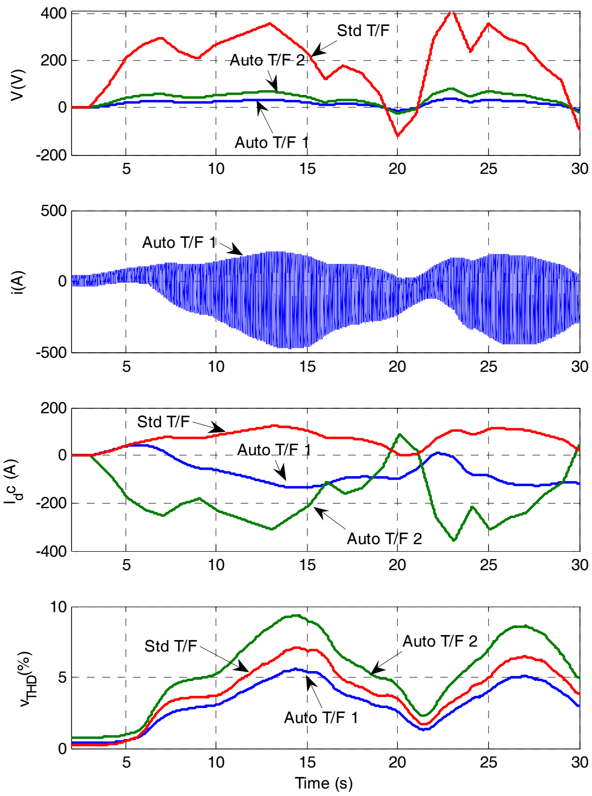

Fig.5. Variation of (a) voltages injected at all three substations, (b) ground current at t/f T_1 (c) DC component of all three ground currents (d) THD of all three transformers during a GIC

In order to determine the proper settings for the proposed protection design, variation of the ground current was investigated under different fault scenarios (ABC-G, A-G, A-B, AB-G, etc.) and GIC events. An example simulation of phase A to ground fault on bus-3 are shown is shown in Fig. 4. It was assumed that the transformer neutral is solidly ground at the time of the fault. In Fig. 4, variations of the ground current, DC component of ground current and the voltage THD observed at auto transformer T1 during a temporary phase-A to ground fault (cleared after 0.1 s) are shown. For this fault, a ground current of over 20kA was observed.

As it can be seen from Fig. 4, high levels of harmonics are observed at the fault inception and clearing points, but the magnitude of THD quickly decays. The slow variation of the quasi - DC component in the ground current is due to the time constant of the low pass filter used to extract the DC component. The DC component could alternatively be extracted through the FFT process, if a faster response is desired. The DC component calculated using FFT is also shown in Fig. 4. In order to avoid the operation of the proposed protection device due to the short term DC current and harmonics observed during temporary faults, a time delay T_d (around a half second) can be introduced. This will also prevent the operation (undesired tripping) of the protection device due to transformer inrush currents observed during transformer exercitation.

A GIC event was simulated and the behavior of the auto-transformer during disturbance was investigated. Fig. 5 shows the variations of the injected earth surface potentials, the neutral current of transformer T_1, the DC components of all three ground currents and voltage THD of all three transformers during a GIC. Although the DC current observed during the GIC events are not as high as the DC currents during faults, due to its continuing nature (slow variation) it can result in transformer saturation. This will ultimately result in large reactive power consumption in the transformer. The variations of the three phases of the autotransformer T_1 winding current and voltage during the GIC are shown in Fig. 6.

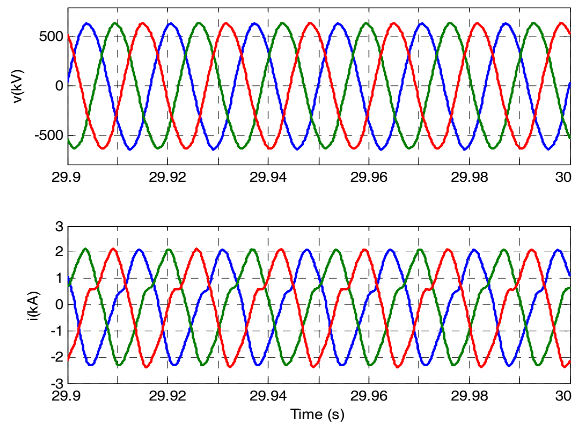

Fig.6. Variation of transformer voltage and winding current during GIC

In order to ensure proper protection against GIC events the threshold levels of the DC currents (and harmonics) need to be made significantly small compared with the DC currents (and harmonics) observed during the faults. The following settings were used for harmonic detection and DC magnitude detection.

Harmonic detection: $THD_V > 1.5\%$, $T_d = 0.5$ s (THD threshold should be adjusted according to the background voltage harmonic level.

DC current detection: $I_{n(dc)} > 20$ A, $T_d = 0.5$ s

E. Operation during GIC

In this simulation, the collective operation of the proposed GIC protection at different transformers was studied. The GIC protection was allowed to operate automatically, that is whenever the respective thresholds of DC component in the ground current or the transformer voltage THD are exceeded. It was observed that GIC protection at Auto-transformer 1 was automatically initiated first, immediately followed by the GIC protection at the standard transformer. As expected, the GIC protection in Autotransformer 2 did not operate due to the lack of ground current after the capacitors were inserted to the grounding paths of the other two transformers.

Fig. 7 shows the variation of neutral ground DC current, THD and operation of the protection device at auto-transformer 1 during the GIC event. The switch assembly was operated due to high DC component in the ground current (> 20 A). However, due to time delay, the estimated DC current at the time of DC disconnect switch opening was about 45 Amps. The voltage across the DC switch is well below its maximum operating voltage (1,000 Volts) at 45 Amps. The variation of ground current and ground voltage and transformer winding voltage and winding current are shown in Fig. 8 and 9 respectively. As it can be seen in Figs. 7, 8, and 9, the opening of the switch assembly effectively reduced the DC current during the GIC, and thereby prevented transformer saturation.

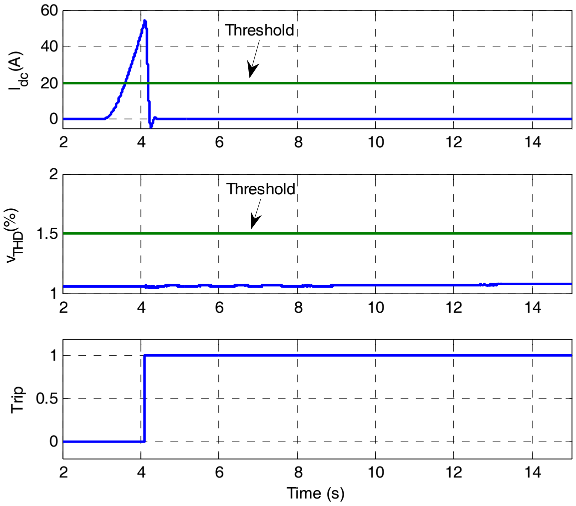

Fig.7. a DC current observed through the sensor, b THD observed in transformer voltage and c binary GIC event signal

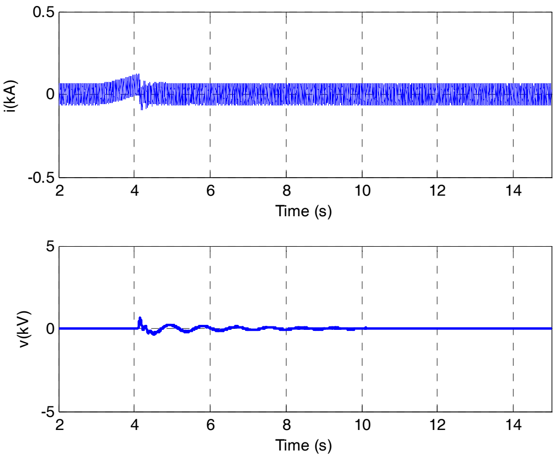

Fig.8. Variations of the transformer T1 neutral current and the neutral voltage

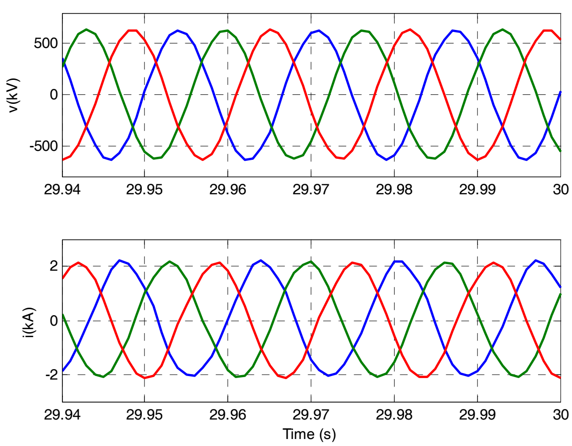

Fig.9. Variation of three phase transformer winding voltage and winding current during GIC with ground protection

F. High Neutral Voltage and Ferro-resonance

The occurrence of a ground fault while the GIC protection is active may result in high neutral voltages and ferro-resonance conditions. A simulation based study was carried out to investigate evidence of such phenomena. Results of this study showed the presence of high neutral voltages and ferro-resonance. Although a larger capacitance could be used to reduce the neutral voltages, the presence of ferro-resonance conditions cannot be totally eliminated as it is dependent on factors such as system parameters and location of the fault. The use of very high capacitances for this application is not practical due to cost. Simulations were carried out to investigate the effectiveness of the surge arrester (MOV) connected in parallel with the capacitor to limit the high neutral voltage and the ferro-resonance conditions during ground faults when the capacitor bypass switch assembly S is open. The results are presented below.

G. Results with Surge Arrester (MOV)

Fig. 10 shows the variations of neutral voltage on the auto-transformer-2 during a phase A to ground fault simulated with and without the surge arrester (MOV). As it can be seen from Fig.10 the use of a surge arrester (MOV) eliminates the excessive voltages observed during ground faults. The rating of the MOV used in this simulation was 5 kV.

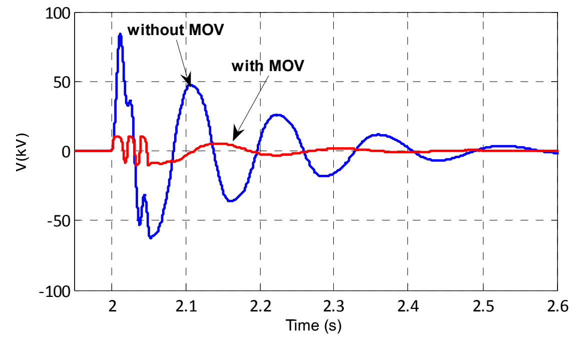

Fig.10. Variation of neutral voltage with and without MOV

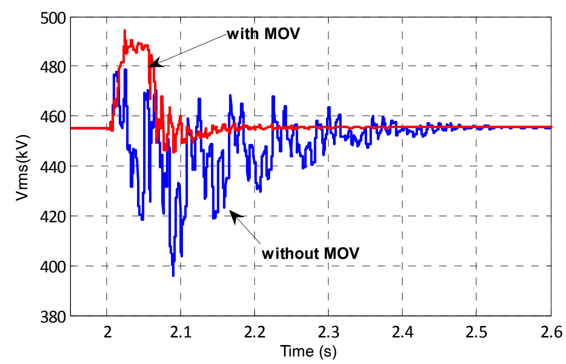

Fig.11. Variation of phase-C RMS voltage on bus-5 during the fault with and without MOV

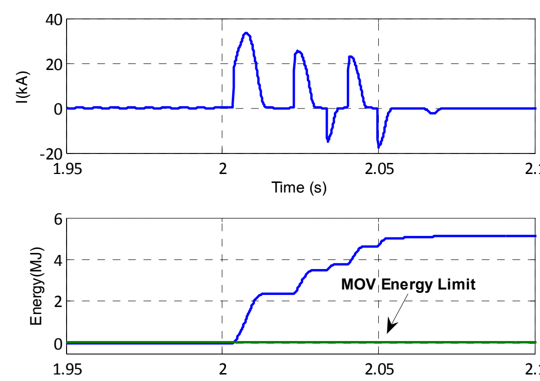

Fig.12. Variation of current through the MOV and its energy dissipation

The variation of phase C rms voltage on bus-5 during this fault, with and without a surge arrester (MOV), is shown in Fig. 11. The high oscillations in a healthy phase rms voltage indicate the existence of ferro-resonance conditions. As it can be seen from Fig. 11, the operation of the surge arrester (MOV) limits the over voltages and dampens the oscillations in the voltage during the fault. The variations of the current through the surge arrester (MOV) and energy dissipated in it during the fault are shown in Fig. 12.

H. Surge Arrester (MOV) Selection

The use of surge arresters (MOVs) to protect capacitors is quite common. Series compensated transmission systems are one common example. In these systems, sophisticated equipment such as high rated surge arresters (MOVs) and air-gaps are used. The use of similar arrangement for ground capacitor protection is not appropriate due to high installation and maintenance cost. An inexpensive surge arrester [15] is considered adequate for the proposed GIC protection design. The energy dissipated in the MOV during the ground fault, shown in Fig. 12, rises well above the MOV energy rating of the class of MOVs considered, before the capacitor bypass breaker S can be closed. Thus the MOV will enter into its' pressure relief mode. This sacrifice of the MOV is intentional, since the occurrence of a ground fault during GIC is a rare event, replacement of the MOV is considered more economical than providing protection to the MOV. According to the manufacturer, these MOV devices "fail" into a permanent short circuit, which has sufficient capacity to carry the expected level of ground currents. However, should a rare simultaneous GIC and ground fault condition occur the surge arrester will need to be replaced.

IV. CONCLUSIONS

A practical capacitive transformer neutral grounding design is proposed to block the flow of GIC. The novel feature of the proposed method is the use of a capacitor in the grounding circuit after a bypass switch opens when a GIC event is detected. By this means the user will be able to operate the system most (99.8%) of the time with a normally grounded connection without the use of a capacitor or resistor blocking device. Additionally, the design uses a sacrificial surge arrester (MOV) to prevent over-voltages and ferro-resonance in the rare event of a ground fault when the GIC protection is active. It was shown that GIC conditions can be successfully recognized by monitoring the transformer voltage harmonic level and the neutral current DC component. Studies carried out using a transmission system simulated in an electromagnetic transient (EMT) type simulation program proved the validity of the proposed design.

V. APPENDIX

TABLE-I- LINE PARAMETERS

Line	Type	Length	+/Zero Seq. Impedances (Ω)
Bus 2-3	Double circuit	400 km	4.97+j135.44/115.35+435.14j
Bus 3-5	Single circuit	200 km	2.48 +j67.72/57.68+217.57j

TABLE-II- TRANSFORMER PARAMETERS

Transformer Type	Capacity	Leakage reactance	No load losses	Cop. losses at rated I
Auto-transformer-1	900 MVA 765 kV/345kV	0.01 pu	0.015 pu	0.02 pu
Auto-transformer-2	300 MVA 765 kV/22kV	0.01 pu	0.015 pu	0.02 pu
Std. transformer	1000 MVA DY-22kV/65kV	0.01 pu	0.015pu	0.02 pu

TABLE-III- SURGE ARRESTER (MOV) CHARACTERISTICS

Current (kA)	Voltage (kV)	Current (kA)	Voltage (kV)
0.0001	5.0	0.6	9.265
0.02	5.5	0.8	9.405
0.1	7.0	1.0	9.5
0.25	8.695	2.0	15.0
0.4	9.075	100.0	16.0

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