Power Grid Protection against Geomagnetic Disturbances (GMD)

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***Abstract*-- This paper describes the design, construction and testing of a protective electrical system which is an effective and reliable solution for blocking the DC current in the neutral of grounded "Y" configured power transformers. The blocking design uses sensors and electronic controls to automatically remove a metallic grounding path, leaving a capacitive blocking device in the transformer neutral connection. The sensing electronics detects the quasi-DC current in the transformer neutral or the total harmonic distortion (THD) on the grid, resulting from a geomagnetic disturbance (GMD); thus activating the protective mode of operation. In practice it is anticipated that this protective system will operate in the capacitively grounded mode of operation less than 0.1% of the time which limits the probability of experiencing a ground fault while in the capacitive blocking mode.**

***Index Terms*— geomagnetically induced currents (GIC), geomagnetic disturbance (GMD), power grid operational stability, power grid protection, power grid voltage collapse, solar storms, solid ground, transformer grounding circuit, transformer neutral blocking, and transformer protection.**

I. Introduction

GEOMAGNETIC disturbances (GMD) have been shown over many decades to cause serious issues for electrical power systems including the potential for voltage collapse in power grid transmission systems. Geomagnetically induced currents (GIC) in high voltage power transformers can cause serious power grid instability issues and, in some cases, power system equipment damage during geomagnetic storms [1-6].

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In addition to wide area power system voltage collapse, several publications have also shown that GIC currents in transformers can produce large harmonic currents which have the potential to damage or reduce the life of power components [7-11]. A paper by Delaiba A. C., et.al. shows that harmonics can significantly reduce the life expectancy of power transformers [10]. The March 1989 solar storm not only resulted in the Quebec power system collapse but also destroyed a large power transformer at the Salem NJ generation plant [12]. A. Rezaei-Zare and L. Marti have stated that their "… simulation results reveal that the generator capability limit can be exceeded at moderate GIC levels, e.g. 50A/phase, and the rotor damage is likely during a severe GMD event." [11]. It has also been established that large harmonics can damage customer equipment as well [13].

Recently, Pulkkinen et.al. published geo-electric field projections that quantified the expected magnitude of a 100 year solar storm [14]. These statistical projections based on geomagnetic data collected over 14 years show that mean values for the 100 year peak geo-electric magnitudes are in the range of 0.5 to 20 V/km depending on latitude and specific soil conductivity. The 20 V/km was for soil conductivity like that of the Quebec area. The geo-electric fields published earlier by Kappenman et.al. [15] when scaled up by a factor of two to be consistent with a 100 year storm, from a geomagnetic field change of 2,400 nT/min to 4,800 nT/min, gives very similar projections for the same regions i.e. the same soil conductivities. For example the scaled up Kappenman et.al. projections a range from 4.8 V/km for the southern states (AL, GA, NC, SC, and TN) to 15.2 V/km for Quebec and Ontario and other northern US states (WI, MI, VT and NH) which is quite comparable to the recent 20 V/km projection by Pulkinen et.al. It should also be noted that the scaled up Kappenman et.al. projections for lower New York, east Pennsylvania and New Jersey is 31 V/km because of the soil and water boundary conditions in that area. Therefore, recent peak GMD geo-electric field magnitudes based on geomagnetic measurements [14] are consistent with earlier calculated projections [15] when adjusted for an equivalent 4,800 nT/min geomagnetic field rate of change.

The use of a 100 year storm criteria for infrequent events that carry high consequences is quickly becoming adopted by many industries. As an example, the Hurricane Sandy which impacted the east coast in October 2012, represents a 100 or more year storm of high impact and consequences for which power outage losses were many billions of dollars [16]. In addition to solar storms, similar large quasi-DC currents in power lines can also be induced by the third component (E3) of an electro-magnetic pulse (EMP E3) [17]. Accordingly a mitigation solution for geomagnetic disturbances also provides mitigation against EMP E3 threats.

Mitigation solutions to deal with the GMD issue have been previously proposed which include both operational procedures as well as permanently installed equipment to block the flow of quasi-DC GIC in the system [16-23]. It has been concluded by several authors that a neutral DC current blocking capacitor represents the “best” approach for mitigating GIC in a transformer [22-23].

The benefits of a neutral blocking solution are the following:

- Significantly reduces the potential of system voltage collapse and grid instability
- Protects older, more vulnerable transformers from GIC half cycle saturation, heating and increased dissolved gas buildup [15]
- Investment payback for a single unit is estimated to be within one to two years of installation in cases where it eliminates the need for uneconomic dispatch. For example in 1992 G. A. Gucchi stated that “If we responded every K alert of level 5 or greater, PJM would have spent over $100M in excess incremental costs”. [24]
- Automatic and instantaneous response to GIC and harmonics, obviating the need for human decision making and intervention, with attendant potential for error
- Effective for a wide range of GMD geo-electric field magnitudes

This paper also describes an automatic fail-safe and cost effective transformer neutral blocking system. It was designed, extensively simulated using PSCAD/EMTDC, constructed and tested. The system consists of a bank of HV capacitors, a HV power resistor, a neutral connection switch assembly, a metal oxide varistor (MOV), two current transformers (CTs), maintenance switches, sensing and control electronics, and a seismic rated structure to reliably secure the electrical components.

The neutral blocking system was successfully ground fault tested at the KEMA laboratory in August 2012 and power grid tested at the Idaho National Laboratories in September of 2012. Based on these tests, along with PowerWorld GIC grid modeling results, a production system will soon be installed in the American Transmission Corp. (ATC) high voltage power transmission grid in northern Wisconsin.

Several potential installation and operational issues related to automated GIC blocking systems have been raised by various power industry representatives. The primary issues have been concerned with the reliability of the system, the potential to damage nearby power equipment, loss of an effective ground and resonant interactions with the power transmission system. These issues are addressed in this paper and the results show the risk of these issues negatively affecting a power grid operation are shown to be manageable.

It is concluded that an automatic GIC neutral blocking device connected to HV and EHV transformers in a power grid provides a compatible, reliable and cost effective GMD mitigation solution.

II. Summary of the Threat

FLOW of geomagnetically induced currents (GIC) through power transformers can cause operational grid instability issues and equipment damage in power systems during geomagnetic storms. One historical example of power disruption due to GIC is the collapse of the Hydro Quebec power system in March 1989 [1]. During this event, grid instability problems resulted in the harmonic filter banks tripping off and the loss of several Static VAR compensators (SVCs).This GMD event was responsible for collapsing the Hydro Québec power grid in less than ninety two seconds. It took Hydro Québec nine hours to restore the grid to the 83% power level. In addition, reports of damage to transformers both within and outside the Hydro Québec system during and after the event have been published [25-28]. The most notable damage was the total loss of a large 1,200 MVA step-up transformer in Salem, NJ which resulted in the shutdown of a nuclear generator plant [12].

Numerous additional power grid stability and equipment damage issues have been reported and several authors have attributed these issues to GMD events. A few include

- Power failure at British Columbia Hydro and Power Authority, February 9-10, 1958 [6]
- Transformer failure St. James Bay, eight days after the Great Red Aurora, Dec 19, 1980 [25-26]
- South African Grid Instabilities, March & Oct 2001 [27]
- Power grid outages and loss of transformers in South Africa and Sweden, October 30, 2003 [28]

In addition to the above events, numerous geomagnetic disturbances and large auroras have been recorded in scientific journals, newspapers, and magazines over many centuries.

III. Automatic Fail-safe Protection System

An automatic fail-safe neutral blocking system for protection against GIC has been tested and demonstrated in the western United States grid during a grid experiment at the Idaho National Labs. A schematic of this approach is shown in Figure 1. A feature of the design is the use of a capacitor in the grounding circuit only when GIC is present [29]. Under normal conditions grounding is provided through a switch assembly. However, when a GIC event is detected, the DC currents are blocked by opening the switch assembly and transformer neutral AC grounding is through the capacitor bank. The DC current in the neutral or the voltage harmonics on the phase lines are used to detect the presence of GIC currents. The harmonic signals are captured with a transducer with good frequency response such as a Current Transducer (CT). The harmonic trigger levels will in many cases need to be set at or above the IEEE 519 recommended harmonic limits. The voltage that could build-up across the capacitor bank during ground faults and potential ferro-resonance overvoltage conditions are overcome by using a Metal Oxide Varistor (MOV) connected in parallel with the capacitor. Since the occurrence of a simultaneous fault while the system is in the GIC protective mode is rare it is anticipated that the MOV would only need to be replaced under a rare circumstance. The need for replacement is provided by a signal from a CT transducer placed in series with the MOV. The use of a DC disconnect switch, a high speed AC switch, and the use of an MOV are some of the other novel features in the design. This system described in this paper is comprised of commercially available equipment that is factory assembled and tested. The system is a very practical, reliable and cost effective means for providing neutral blocking on transformers in high voltage transmission systems and in Static VAR Compensators (SVCs).

The operation of this neutral grounding system can be described using Figure 1. The switch assembly “S” is closed during normal operation providing a metallic transformer 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 (either THD or specific harmonics) in the transformer voltages or currents. A one milli-ohm shunt resistor is used to monitor the ground current. This shunt resistor is a substantial piece of maganin™ metal alloy 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 presence of a GIC event.

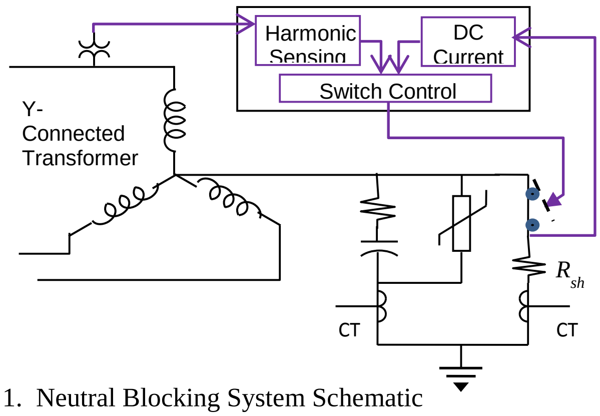

Figure 1. Neutral Blocking System Schematic

The opening of the switch assembly allows the capacitor bank to provide an effective 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 rating of the DC disconnect switch is lower than the neutral voltages expected during ground faults. So to protect this DC switch, an AC switch with a high standoff voltage capability is placed in series with the DC switch. Therefore the switch assembly S is comprised of a DC disconnect switch connected in series with an AC switch. When a high GIC flow is detected, the switch control logic ensures that the switch assembly opening is initiated before the neutral voltage exceeds the DC disconnect switch voltage rating. The AC 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 AC switch remains open for a preset time duration controlled by a SCADA system or a system operator. If the GIC event is still present the system automatically returns to the GIC blocking/protection mode.

In the rare case of a simultaneous GIC and a ground fault, a parallel connected MOV protects the capacitor from an overvoltage condition. In such a situation, the MOV is allowed to enter its “pressure relief mode” as a sacrificial element. The MOV is designed to carry the fault current until the switch assembly is automatically reclosed. The MOV device remains intact during and after a pressure relief event. It thereby provides a continuous low impedance current path to ground.

A Jacob’s ladder is mounted on the MOV, see figure 2, and electrically connected in parallel to the MOV to direct any remaining arc currents up and away from the MOV after the pressure relief mode is experienced. The MOV is mounted horizontally to enhance the movement of the arc away from the MOV. The Jacob’s ladder horns were a bronze alloy which was 5/8 inch thick and 2 inches wide. The top of the horns were 16 inches above the top of the MOV. The narrowest distance between the horns was 2 inches at height of 3.5 inches above the top of the MOV. The upper tips of the horns had a separation distance of 12 inches.

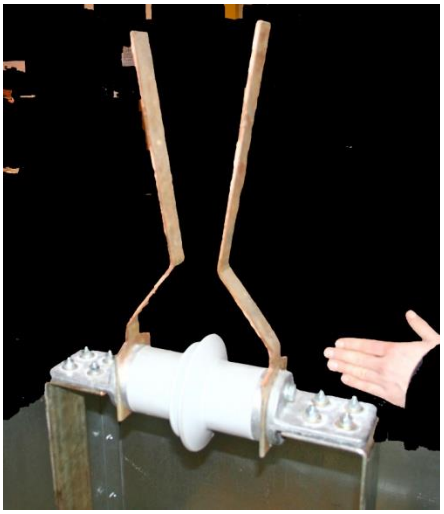

Figure 2. Jacob's Ladder and MOV

The MOV and Jacob's ladder are mounted in a metal enclosure which has four sides and a bottom but with an open top. This enclosure was designed to prevent any damage to nearby components in the event the MOV pressure relief mode should be encountered. The automatic switch reclosing is accomplished using a neutral instantaneous over current relay connected to the secondary output of a current transformer (CT), located below the capacitor as shown in Figure 1. The switch assembly will remain closed via the use of a lock-out relay, not shown in Figure 1, to provide a normal grounding path until the MOV is replaced. It should be noted that MOVs provide a low resistive (typically 1 – 5 ohms) state after entering the "pressure relief mode" hence the switch assembly will conduct most of the ground fault current that the system experiences if the ground fault occurs while in the GIC blocking mode. It should be noted that such ground faults will be cleared by breakers in the network by the normal processes with existing relay settings in place by the utility.

In some cases a utility may desire additional ground fault protection. In such cases a suitable spark gap could be provided in parallel with the MOV to provide an additional conduction path to ground.

At this point GIC may still be flowing, but the blocking device is now permanently bypassed. This unlikely case which results from a ground fault during a GIC event is no worse than the present case with no blocking. Those transformers for which the sacrificial MOV has entered the pressure relief mode due to a fault will tend to be in the geographic vicinity of the fault rather than over a wide area.

A second CT shown in Figure 1 monitors the neutral AC current while the system is in the normal mode of operation (i.e. switch assembly in the closed position). This monitoring is required so that if there is a significant imbalance (i.e. 150 amps rms) the SCADA system will disable the neutral blocking system from switching into its protective mode and notify the system operator of this imbalance current issue. This action is required to prevent a large imbalanced AC current from damaging the power resistor.

The electronics which control the neutral blocking system have adjustable settings for both the quasi-DC current and harmonic trigger levels. The DC current trigger can be adjusted from 6 to 500 amperes with an adjustable time delay of 0 to 10 seconds. The harmonic trigger levels available are 1.5, 3, 5, and 10% total harmonic distortion (THD). By reprogramming the electronics other trigger levels can be selected. The detection bandwidth for the harmonic sensing was adjustable between 300, 600 and 1,200 Hz. For the results reported here the bandwidth was set at 1,200 Hz.

The normal mode of operation of the neutral blocking system is with the switch assembly in its closed position. When either a quasi-DC or harmonic level is sensed which is above the trigger levels, the electronics provides an adjustable delay before the DC switch is commanded to open. For the tests reported in this paper the delay was set at 0.8 seconds. The AC switch is then opened from a signal derived from an auxiliary contact on the DC switch. After the electronics senses that the AC switch is opened it sends a signal commanding the DC switch to close. The AC switch will then remain open until a SCADA controlling system instructs the AC switch to reclose.

A system operator can select from several different strategies for placing the neutral blocking system back into its normal mode of operation. For example a significant GMD event impinging the earth may last from 12 to 24 hours. So the controlling SCADA system could be programmed to place the system back into its normal mode after 24 hours.

A second strategy might be to program the SCADA to return the system to normal operation after a shorter period which is consistent with the duration of the larger spiking GIC currents which is typically less than 30 minutes. In this scenario the system would not be put back into the normal operation mode (i.e. the AC breaker reclosed) if the DC voltage on the capacitor bank was above a preset value. This capacitor voltage is monitored with a voltage probe. If the large spiking GIC currents return after the system has been returned to its normal operation mode (i.e. breakers reclosed), the system will once again detect their presence and return the system to the protective mode for another 30 minutes. This later strategy then reduces the amount of time the system is in the protective mode and therefore reduces the probability for experiencing a ground fault while in the protective mode. In turn, the probability that the MOV will enter its pressure relief mode (i.e. it is sacrificed and requires replacement) is greatly reduced.

If the MOV should happen to enter its pressure relief mode and need replacement, the system will detect the presence of the ground fault current through the MOV and command the switch assembly to reclose. This action is controlled by a lock-out relay such that the switch assembly will remain closed until the MOV is replaced. This action then protects the transformer and the capacitor bank from any further ground faults. It should be noted that a newer version of this system will offer a permanent Thyristor bank instead of an MOV to eliminate the need for replacing components in the system.

The system was simulated using PSCAD EMTDC [30] for a simplified bus model [31]. The results showed effective sensing of the presence of GIC was provided by either the measurement of the quasi-DC neutral current or the harmonics on one of the phases. Additionally, the study showed that the power resistor and the MOV provided damping of unwanted resonances.

It is intended that the neutral blocking system be actively available to provide GIC neutral current blocking at all times with only a few exceptions. It is anticipated that an operator will likely program a controlling SCADA system to perform a self-test of various functions in the neutral blocking system on a periodic bases (i.e. for example once a month). It is recommended that a routine inspection of the system be performed once per year or every 3,000 switching operations. However, during these maintenance periods the transformer will still be operational and active since a maintenance switch is provided with the SolidGround™ system.

A production qualified system was designed, tested and demonstrated. A photo of this production SolidGround™ transformer neutral blocking system is shown in Figure 3. This production unit is assembled in the factory. Its physical dimensions are about 7’ 11” by 7’ 11” by 12’ 3” tall. The weight of the complete unit is approximately 6,000 pounds.

Figure 3. Emprimus Neutral Blocking System

The useful life of the neutral blocking system is estimated at 30 years. It is recommended that the AC and DC switches be serviced every 15,000 operations. A Solid Ground product brochure [32] and additional details can be obtained from the High Voltage Products group at ABB.

The components and their ratings used in the neutral blocking system are the following:

DC Circuit Breaker: four pole, rated voltage 1,000 volts, rated continuous current 1,200 amps.

AC Circuit Breaker: Single Phase outdoor rated type FSK Vacuum Breaker, Rated voltage 25 kV, rated continuous current 1,250 amps, rated making current (close and latch) 63 k amps.

Capacitors: Fourteen (14) 400 kVAR (total bank 5,600 kVAR), 2.4 kV AC rated, externally fused, 2,650 μFarads capacitance (one ohm reactance at 60 Hz).

Capacitor Fuses: 5.5 kV, 63 amp current limiting type with blown fuse indication.

Power Resistor: One (1) ohm, 200 continuous amps, short circuit rating 30 k Amps for 0.2 seconds.

Shunt Resistor: one (1) milli-ohm resistance, rated at 1,000 amps continuous, capable of multiple 22,000 amp fault current events.

Metal Oxide Varistor (MOV): polymer MOV, clamps at 11,000 volts, mounted horizontally.

Jacob’s Ladder Attached to MOV: Constructed from 5/8 inch diameter bronze alloy, 16 inches tall with 2 inch gap at apex which was 3.5 inches from the bottom of the ears.

Current Transformers: Two 800:5 CTs

Over Current Relay: Electromechanical CO9, 20 milli-seconds to close trip contacts

Type 86 Lockout Relay: manual reset, indictor flag

Emprimus Control Electronics: Quasi-DC current sensing, Phase Harmonic sensing, trigger output signals to open and close the DC and AC breakers, with communications to station SCADA systems.

Maintenance Switch: 27 kV, rated at 1,200 amps continuous current for 3 seconds and 99,000 amps peak current, with Kirk Key interlock.

III. Ground Fault and Power Grid Testing

The neutral blocking system was ground fault tested at the KEMA-Powertest facility in Chalfont, PA in mid August 2012. Three simulated faults levels (5kA, 10kA, and 20kA all rms values) were applied to the system while the system was in the normal mode of operation (i.e. the switch assembly was in the closed position). The duty cycle for these currents was 8 ± 2 cycles. The system was tested at the 20kA level an additional five times to ensure that the system could withstand the rapid duty cycle caused by automatic reclosing. The test facility was not able to supply enough energy to perform this test quickly enough to fully simulate automatic reclosing, but it was fast enough to demonstrate that there were no overheating concerns in the design. During the above tests the following measurements were recorded:

- Neutral Current (Total, Symmetrical and Peak)
- Neutral Voltage
- Capacitor Bank Voltage
- Test Transformer Voltage
- Test AC Generator Current
- Temperature of the system shunt resistor

The detailed results of the above tests while in the normal mode of operation clearly showed all components (i.e. the switches and the shunt resistor) passed this phase of testing.

The second phase of the KEMA testing was to simulate ground faults when the system is in the GIC protection mode (i.e. the AC switch in the switch assembly is in the open position). The simulated line to ground faults applied were 20kA symmetrical with an asymmetric offset factor of > 2.6. The duty cycle for these currents was 8 ±2 cycles. Each of these tests causes the MOV to go into its pressure relief mode. These tests were repeated fourteen times. During these tests the above described parameters were again recorded.

The results of the testing while the system was in the GIC protective mode clearly showed that the system operated as designed. The system, under its various modes of operation, conducted fault currents, allowing them to be cleared by the normal processes while protecting the capacitor bank from damage. A set of typical voltage and current plots are shown in Figure 4. The MOV entered the pressure relief mode at a voltage of 11.5kV which occurred at about 3 milliseconds into the first cycle (i.e. a little over 1/6th of a cycle). The arc on the Jacob's ladder continued for five cycles after the MOV entered into high current conduction. The voltage rise on the capacitor bank at the time the MOV entered into high current conduction was 5.5kV or about one half of the voltage on the neutral connection. This voltage decayed as expected with a time constant of about 2.65 milliseconds, the time constant of the resistor capacitor combination. The second plot in Figure 4 shows evidence of a few hundred volts on the capacitor bank that lasts for about 5 cycles after the MOV has entered the pressure relief mode. This voltage is associated with the arc current on the Jacobs ladder which is mounted on the MOV

During this ground fault testing phase a total of fourteen (14) MOVs where scarified to ensure that the MOVs, Jacob's ladder and switch reclosing all performed as designed. In all cases the system and components performed as was expected. Subsequent resistance measurements of the spent MOVs showed resistance values in the range of 2 to 5 ohms with a mean value of 5 ohms. This indicates that the MOV horizontal mounting with a vertical Jacob's ladder does direct the current arc away from the MOV which prevents an open circuit or non-conducting spent MOV. The design is such that the MOV will fail as an open circuit only in extremely rare cases.

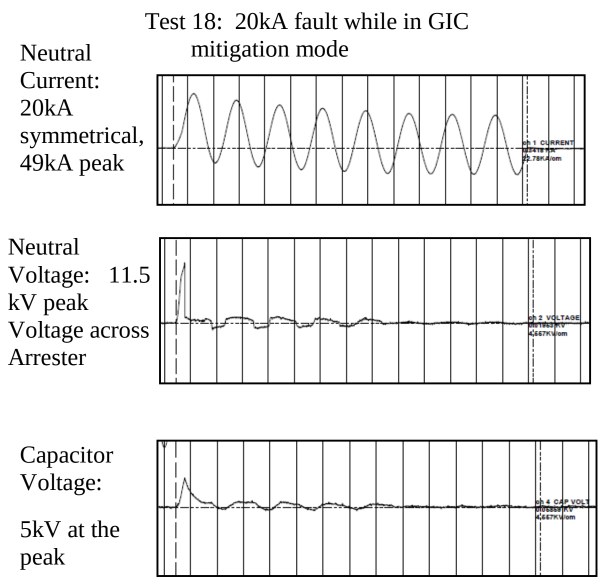

Figure 4. Typical System Protective Mode Ground Fault Current and Voltage Plots. The plots show eight (8) cycles. The peak current in the top graph was 49 kA, the peak voltage in the second graph was 11.5 kV and the peak voltage in the third graph was 5 kV.

The neutral blocking system live power grid experiments were conducted at the Idaho National Laboratory in Idaho Falls, ID in September, 2012. The grid experiments were funded and conducted by the Defense Threat Reduction Agency (DTRA) an agency within the United States Department of Defense. Figure 5 is a photo of the installation area. This government owned facility offered an almost isolated 138kV test loop that was about 13 miles long. The system was connected to the combined neutrals of two HV transformers. The transformers were 15 and 3.75 MVA both with a high side voltage of 138kV. The simulated GIC was provided by a bank of batteries and the DC current (0 to 62 amps) was injected into the neutral connection in small (~2+ ampere) increments until the neutral blocking control electronics triggered the system into the protective mode.

Numerous grid experiments were performed over a one week period. In the first set of experiments the neural blocking system was applied to the neutral of both HV transformers. It was observed that an injected DC current of 6 amps produced a 2% harmonic content on the 138 kV line. A typical data chart from these grid experiments is shown in figure 6. Here the simulated GIC current rises until transformer saturation is observed after about 0.5 seconds. The system electronics is shown by the next line which detects the DC current at 6 amps after 1.2 seconds. The third line shows that after a preset delay of 0.8 seconds a signal is sent to the DC switch on the transformer neutral to open. The GIC current is then rapidly blocked (less than 0.8 seconds) with only a small overshoot.

In every case the control electronics was triggered by the DC current measurement in the shunt resistor and not the line harmonic measurement because the harmonic build-up had not yet occurred. The system effectively blocked the DC current and as a result transformer vibrations and the generation of harmonics were eliminated.

In a second set of experiments the neutral blocking system was connected to the neutral of the 15 MVA transformer but not the 3.75 MVA transformer. In these experiments the neutral blocking system protected the smaller transformer but not the larger one. These experiments were conducted with neutral DC currents ranging from 0 to 30 amps and the system performed as expected. A limit of 30 amps was imposed by the INL operators to avoid the potential of high currents and the generation of harmonics outside the INL transmission loop. The grid experiments over the one week period met all objectives and the neutral blocking system performed as expected. A detailed publication on the results of these live grid experiments is being prepared by DTRA.

Figure 5. DTRA Power Grid E3 Test-bed Located at Department of Energy's Idaho National Laboratory

(Photo taken from EUROEM 2012 Conference Book of Abstracts, Paper # M. R. Rooney and W.J. Scott, July 2-6, 2012, p. 94)

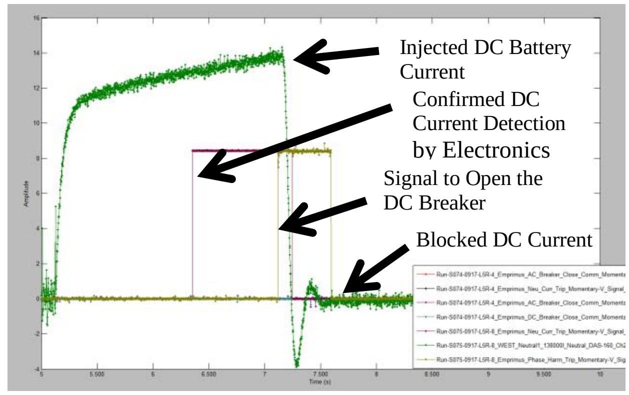

Figure 6. System operational data taken at the Idaho National Labs while connected to a live power grid. The injected DC current shown in green is detected and confirmed followed by an eight tenth (0.8) second built-in delay before the system is placed into its GMD protection mode.

System & Operational Considerations

A. Transformer Interactions –

Normal Operational Mode: The system will not give rise to voltages that will exceed the rating of the transformer to which it is connected. Multiple tests with 22,000 amperes rms and 58,000 amperes peak were conducted during the ground fault testing at the KEMA laboratories. All components passed. The neutral to ground voltage measured across the shunt was 22 volts (i.e. 22kA through the 0.001 ohm shunt resistor). This would prevent the other non-faulted phases from overvoltage. Essentially the neutral is grounded with only one milliohm of resistance added to the neural ground path.

GIC Blocking Mode: The same fault currents were used. These tests indicated the MOV went into the pressure relief mode in 3 milliseconds. The maximum voltage across the MOV was 11.5 kV for less than 1 millisecond. With low level faults when the neutral to ground voltage will not cause the MOV to operate, the capacitors and resistor handle the fault current. This leaves a 1 - j1 ohm (resistive / capacitive) impedance in the neutral. An industry rule of thumb indicates that up to 5 ohms of impedance in the neutral to ground connection can be tolerated before relay setting changes are required. The neutral is effectively grounded during a ground fault after only a short (0.1 to 2 seconds) built-in adjustable time delay in the sensing electronics. All components passed and operated as expected. This would prevent the other non-faulted phases from damaging overvoltage.

Additionally, the neutral blocking system does not create voltage spikes that could exceed or damage a transformer. Ground fault voltages on the transformer neutral connection will not exceed the high conduction voltage of the MOV of 11.5 kV [33]. When a ground fault occurs the neutral voltage rises to 11.5 kV at which point the MOV enters its pressure relief mode. The neutral voltage then rapidly (within a few micro-seconds) is clamped to a few hundred volts, the voltage of the arc current on the Jacobs ladder. PSCAD simulations as well as HV testing show there is no voltage or current (in-rush) spiking as a result of this rapid clamping of the voltage. The ground fault testing shows the capacitor voltage decays from a high of 5.5 kV to near zero with a time constant of 2.65 milli-seconds as predicted by the RC time constant of the circuit. Therefore the largest voltage experienced by the transformer neutral is 11.5 kV which occurs about 1/6 of a cycle after the initiation of the ground fault. This voltage is well below the 110kV BIL rating of a typical transformer.

The only rapid, step function, change in voltage created by the system occurs when the MOV enters the pressure relief mode. This rapid decrease in voltage observed on the transformer neutral does not give rise to voltage or current spikes that can exceed the ratings of the transformer. The current recorded in the KEMA testing did not show any evidence of an induced spiking. Furthermore, analysis shows that the inductance of the transformer coil will prevent an induced current spike when the MOV enters into a high current conduction condition.

B. Multiple Transformers Application

To significantly reduce installation cost and reduce the space requirements it may be possible, at generation sites and specific sub-stations, to apply one neutral blocking system to several transformers. In such applications it would be advantageous to use a much larger MOV (or a Thyrisitor) that can conduct larger ground fault currents, on the order of 16,000 amps for 6 cycles, without entering into its pressure relief mode. Extended neutral buses may be required to bring the transformer neutral connections together at the neutral blocking unit. One or several sets of control electronics could be used with these multiple transformers to trigger the system into its protection mode. This application approach could reduce the overall cost substantially and significantly reduce the required installation foot print at specific sites. An analysis supporting this claim is presently being developed. Additionally, this was successfully demonstrated at the Idaho National Labs live grid testing when two HV transformers neutrals where connected to the neutral blocking system.

C. Power System Interactions –

1. *Potential for Resonances –*

The neutral blocking system should not create unwanted resonances when used as a transformer neutral blocking device. In the normal mode of operation the capacitor bank is shorted by the switch assembly therefore no new induced resonances are possible. When the system is in the GIC blocking (protective) mode, the one ohm resistor in series with the capacitor bank has been shown to effectively dampen potential resonances that might be caused by the addition of the capacitance in the neutral connection. Additionally, the MOV that is used to protect the capacitor bank has also been shown to provide further damping of potential resonances. PSCAD simulations and HV live grid testing have confirmed that initial resonances after entering the protective mode are damped out within a few cycles. Some preliminary frequency scan studies using PSCAD/ EMTDC and a typical power system network show the impact of neutral grounding capacitors on the harmonic frequencies (f > 60 Hz) is negligible when the capacitance is above 1,000 micro-Farads.

The potential for a sub-synchronous resonance interaction with either a mechanical resonance or electrical resonance with another component in the power system has been raised. Analysis shows that a typical potential resonance caused by the interaction of the system capacitor bank with the associated transformer and line inductance would result in a resonant frequency in a range of 10 to 20 Hz. The compliment of this resonance when 60 Hz provides the forcing function would therefore be in the range from 50 to 40 Hz. Therefore, when implementing a neutral blocking system, it is recommended that all nearby equipment that could have either a mechanical (i.e. turbine generator) or electrical resonance in this 50 to 40 Hz range should be identified. However, the fact that the neutral blocking system is not connected into the high voltage phases but rather on the transformer neutral indicates that it will be difficult to couple sufficient energy into a sub-synchronous resonance condition. Furthermore, the one ohm damping resistance in series with the capacitor bank offers significant damping for a potential sub-synchronous interaction. It may be possible to provide additional protection from a sub-synchronous resonance event by adding a relay capable of detecting such resonance and bypassing the capacitor.

2. Potential for Blocked GIC to Find another Path –

If a GIC blocking device is used in the neutral of a two winding transformer, such as a generator step-up (GSU) transformer, the GIC will not have another path to flow. These types of transformers do not have a direct DC path from their primary to their secondary. So when determining where to install neutral blocking devices, top priority should be given to the GSUs in the network.

In the case an auto-transformer, there is a direct DC path from primary to secondary. In this case when the neutral DC current is blocked the GIC can still flow through the transformer. The effective quasi-DC current flow in the transformer will be reduced which reduces heating in the auto-transformer. The current flowing out of the secondary will increase or decrease, determined by the downstream lines resistive paths and their orientation to the geo-electric field gradient.

As neutral blocking devices are placed into service, the total GIC in the local grid will be reduced. However, the GIC in parallel or down-stream lines may experience increased GIC current levels. This indicates that a sufficient number of neutral blocking devices will be needed to reduce the risk of grid instability and/or voltage collapse. To determine where neutral blocking devices should be installed it is recommended that GIC/Power Flow modeling be performed on the area of interest within a specific power grid. Such modeling can not only simulate GIC and Power flows for various geo-electric field conditions but also predict the field levels for system voltage collapse. In addition, these models can predict the improvements in GIC flow, reactive losses, and geo-electric fields for voltage collapse as neutral blocking devices are added to the model [34]. It is therefore recommended that modeling of networks be performed to determine the best location for neutral blocking devices.

3. Potential that Protective Relays will Require Re-Setting –

The blocking impedance of a system is less than 2 ohms (i.e. one ohm resistive and one ohm capacitive). This is small compared to the impedance of a typical transformer. For example, a 345 kV transformer has a typical impedance of 17 to 24 ohms inductive and one (1) ohm resistive (reflected to the 345 kV winding). By adding this protective system to the neutral the resultant positive and negative sequence impedance will not be changed. The system capacitance and resistance will add only 3 – j3 ohms of impedance to the zero sequence network impedance. This change should be small in comparison to the inductive impedance of the transformer windings. And the capacitance reduces the zero sequence impedance of the combination transformer winding and capacitor bank. This small change should not necessitate a change in protective relay settings.
Studies conducted by the University of Manitoba show that resonances as well as malfunctioning of directional relay elements can be avoided if the neutral grounding capacitance is larger than 1,000 μ Farads. For a typical power system there was no significant difference in the fault current levels between a metallically grounded (solidly grounded) system and a capacitor grounded system when the capacitance was 2,650 μ Farads and the directional and distance relays operated correctly for all test cases simulated.

4. Potential for Multiple MOV Replacements –

When a large ground fault current is experienced, the nearby neutral blocking devices will likely contribute to the fault current. But the magnitude of these nearby currents will depend on their proximity and the local network impedance characteristics. Specific network simulations should be conducted to evaluate the potential for multiple nearby MOVs entering the pressure relief mode for large ground faults.

5. Potential for a Non-Expendable MOV –

A much larger and more expensive MOV arrays could be designed into the system. By stacking on the order of 100 MOV units in parallel, all with matched electrical (Volt – Amp) characteristics, a MOV array that can carry large ground fault currents without the need for replacement. This type of stacked MOV might be a design variation that some industry adapters might prefer.

Another option is the use of a power Thyristor (SCR) instead of an MOV. A properly designed Thyristor can withstand numerous ground faults and never require replacement during the life of the neutral blocking system.

6. Potential for Conducting Large Ground Fault Currents –
The system, while in its normal mode of operation, can handle 25,000 amperes of current for short periods (one second). And when the system is in its GIC protective mode a ground fault current will first be conducted by the MOV as it enters into its pressure relief mode and within 65 milliseconds (i.e. less than four cycles) there after the AC switch will be closed thereby providing a ground path for the fault current. The AC switch was rated to close on 63 kAmps and was tested at KEMA to 56 kAmps.

7. Potential Consumable Components –
In the unlikely event of a large ground fault while the system is in the GIC protective mode, the MOV protecting the system capacitors may go into its pressure relief mode, which results in a low impedance shorted condition. The grounding switches will automatically be closed and locked in the closed position (i.e. locked by means of a lock-out relay) until the MOV is replaced in a maintenance operation. It is stressed that this is an unlikely event, and even if it does occur, results in a solidly grounded transformer neutral. This is a localized condition which will not affect the overall operation of the grid.

8. Potential for Transformer Insulation Damage –
The potential for transformer insulation damage when a MOV rapidly collapses the neutral voltage, as shown in figure 4 (second graph), has been analyzed by a group at the University of Manitoba and also be experts at ABB Inc. The findings by both groups indicate that this rapid change in voltage on the transformer neutral connection will not result in damage to the insulation on the transformer windings.

9. Potential for Zero Sequence Impedance Issue –
When a neutral blocking device is applied to a HV transformer an analysis should be performed to ensure that the device meets the appropriate effectively grounded requirements for example the appropriate IEEE standard for the neutral grounding of electrical utility systems [35]. These requirements are typically the following: the ratio of the zero sequence reactance to positive sequence reactance be positive and less than three (i.e. $3>X_o/X_1>0$) and the ratio of the zero sequence resistance to positive sequence reactance be positive and less than one (i.e. $1>R_o/X_1>0$). For typical systems/networks we find that these above requirements are met and therefore the impedance grounding of the SolidGround™ system, when in the GMD protective mode, will not present an issue for most installations. In some cases it may be determined that the power resistor in the neutral blocking system may need to be reduced below one ohm in order to meet the above second requirement.

10. Potential Switching Over Voltages Issue
Switching over voltages was addressed in a preliminary study by A.D. Rajapakse at the University of Manitoba using a typical power system network. Worse case conditions were assumed for this study. Simulations were conducted for two transformer grounding cases namely; a metallic ground and an impedance grounding (one ohm capacitive reactance plus a one ohm power resistor). The simulation studies showed no appreciable differences between the two cases studied.

11. Potential Increased GIC Flow to Neighbor Control Areas-
If a portion of the grid adopts neutral blocking systems but connected neighbors do not it has been speculated that neighbors may experience increased GIC current flows when the neutral blocking devices are in their protective mode of operation. However, recent modeling studies performed by S. Dalman at PowerWorld LLC show that these GIC current flows to and from the neighbor control areas are actually not appreciably changed as more neutral blocking devices are added to the protected grid.

IV. Neutral Blocking Installation requirements

1. Installation of First Unit or Units –

The installation of the first unit or units depends on whether the objective is to minimize risk of specific transformer damage and reduced lifetime or the reduction of reactive losses to minimize the risk of voltage collapse. It is recommended that the transmission network GIC and power flow simulation studies be performed to help determine the best location(s) for the first installation(s). Such studies can determine the levels of GIC that can result in system voltage collapse. The study can also model the insertion of neutral blocking devices at the locations of highest GIC currents. Repeated iterations can then be performed as additional neutral blocking devices are added to the network until a desired reduction of risk for voltage collapse is achieved. Such modeling software products are offered by Power World, Siemens (PSSE), GE and possibly others.

2. System Connection to Transformer(s) –

The conductor that grounds the neutral is physically removed and reconnected via a bus to the maintenance bypass switch located on the SolidGround™ unit. The maintenance switch assembly is Kirk key interlocked such that the neutral of the transformer is always connected to ground. When multiple transformers are involved for either a three phase bank or for two separate three phase transformers, the neutrals are connected to the unit maintenance ground via a bus. The maximum continuous neutral current can be up to two hundred amperes using the appropriate size bus. This current is limited by the one ohm 40 kW power resistor in the neutral blocking system.

V. Industry standards:

Applicable Industry Standards for this Development –

- Assembly: National Electric Safety Code C2
- Capacitor: IEEE Standard 18-2002
- AC Switch (breaker): EN 6094: Common Specifications for high Voltage Switchgear, EN 62271-100
- DC Switch (Breaker): IEC60947-2 for Direct Current applications
- Surge Arrester: IEEE/ANSI C62.11, IEC 60099-4

VI. Industry Organizations position Relative to GMD Mitigation

The October 18, 2012 proposed FERC GMD rulemaking [36] points out that operational responses to satellite solar storm warnings, which can be as short as a 15 minute warning, are ineffective in dealing with the threat. FERC also recommends in the proposed rulemaking that remedial solutions such as neutral GIC blocking be installed where appropriate. Permanently installed, immediately ready, neutral GIC blocking equipment is automatic and instantaneous in its response to GIC and harmonics, eliminating the need for human decision making and intervention, with attendant potential for error and uncoordinated response.

VII. Future Directions

In the future the electronics that will control the SolidGround system will be a special unit manufactured by Schweitzer Electronics Laboratory (SEL). The various parameters such as quasi-DC current trigger level, harmonic amplitude trigger level, harmonic detection bandwidth, and trigger delay times will be adjustable by reprogramming the SEL control software.

An optional protection feature that could be included in the system is the addition of a spark gap in parallel with the MOV or in some models a Thyristor. The breakdown voltage of the spark gap would be selected such that it would prevent the MOV from ever entering its pressure relief mode. This additional protection would then prevent any potential for an MOV to end up in an open circuit (non-conducting) state and have a simultaneous malfunction of the switch reclosing controls. That is, the spark gap would ensure a grounding path if the MOV ended up in a non-conducting state (open circuit) and the switch assembly failed to close after a ground fault was detected. The development of an appropriately rated and reliable spark gap for this application is in development at Emprimus LLC.

VIII. Conclusions

An automatic fail-safe power grid stability protection system against GIC was designed, simulated, fabricated and extensively tested. The system can be used to protect HV and EHV transformers of wide range of sizes as well as static VAR compensators. The system was shown to reliably and effectively block GIC currents when detected. The grounding design is fail-safe with three parallel paths to earth ground for AC currents. High voltage ground fault testing and live power grid experiments showed the system operated reliably and in agreement with earlier PSCAD simulations. The electrical components in the system are all accepted commercial items with many hours of field service experience. The production unit is now available as a factory assembled system.

IX. Acknowledgments

The authors would like to thank George E. Anderson of Emprimus LLC for his continual encouragement and critical reviews of the project. The authors would also like to thank the following people for their encouragement and helpful comments during the development of the Emprimus Solid Ground neutral blocking system; George Baker Professor Emeritus, James Madison University, Bill Chiu of So. Calif. Edison, Frank Lembo and Bob Sanchez of Con Edison Corp., Steven Naumann of Exelon Corp., and David Wojtczak of American Transmission Corp.

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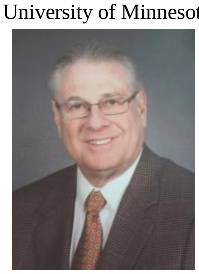

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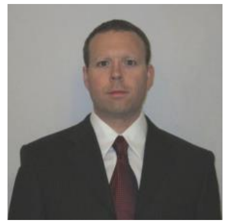

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