HV Power Transformer Neutral Blocking Device (NBD) Operating Experience in Wisconsin

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Abstract

This paper describes the design and operational performance of a neutral blocking device (NBD or neutral insertion device, NID) designed to protect HV and EHV transformers from geomagnetically induced currents (GIC) when geomagnetic disturbances (GMD or solar storms) impact power systems. Standard power flow modeling, including induced quasi-DC GIC, is applied to guide the application of NBDs to prevent voltage collapse, transformer/generator rotor damage and HV breaker malfunction during intense GMDs. This modeling also shows that potentially damaging GIC induced harmonics can be significantly reduced when NBDs are employed. A summary of the design and on-going operational experience of a SolidGround™ NBD on American Transmission Company's (ATC) power grid in Wisconsin is described.

Reasons to Employ Neutral Blocking Devices in a Power Grid

The following are some of the benefits of applying NBDs to a power system's HV and EHV transformers to block quasi-DC GIC caused by GMDs or electromagnetic pulse (EMP) events:

- Enhances the stability and reliability of the electric power grid by preventing (1) half cycle saturation related VAR losses and harmonics and (2) GIC related damage of GSU and auto-transformers
- Allows transformers to operate through solar storm events at their full efficiency
- Prevents voltage collapse due to severe GIC
- Reduces the cost of power generation and transmission by eliminating the need for uneconomic dispatch (utility sales, purchases and power transfer adjustments) during GMD events
- Reduces VAR losses and the added cost of replacement VARs
- Prevents damage to and mis-operation of transformers, SVCs, generator rotors, and AC breakers caused by GIC or EMP induced currents during GMD or EMP events
- Reduces existing GIC stress on equipment from common low-level solar storms
- Reduces or eliminates customer equipment damage, business interruptions and relay mis-operations caused each year by GIC related harmonics from common low-level solar storms

Index of Terms

ATC – American Transmission Company
Axion – SEL Real-Time Automation Controller
DTRA – Defense Threat Reduction Agency
EHV – Extra High Voltage
EMP – Electromagnetic Pulse (E1, E2 and E3)
EPRI – Electrical Power Research Institute
FERC - Federal Energy Regulatory Commission
GIC – Geomagnetically Induced Current
GMD – Geomagnetic Disturbance
GSU – Generator Step-up Unit
HV – High Voltage
INL – Idaho National Laboratories
KEMA – High-current testing lab in PA
Kirk Key – A power equipment interlock switch
MHD-EMP – Magnetohydrodynamic EMP
MOV – Metal Oxide Varistor
MISO – Midcontinent Independent System Operator
NBD – Neutral Blocking Device
NERC – North American Electric Reliability Corporation
NOAA – National Oceanic and Atmospheric Administration
PLC – Programmable Logic Controller
Rogowski Coil – Precise AC current sensor
RTAC – Real-Time Automation Controller
SEL – Schweitzer Engineering Laboratory
SCADA – Supervisory Control And Data Acquisition
SVC – Static Var Compensator
THVD – Total Harmonic Voltage Distortion
VAR – Volts Amps Reactive

Introduction

Geomagnetically Induced Currents (GIC) caused by solar storms (i.e. GMD) have been a recognized concern in electrical power systems for over seventy-five (75) years [1]. This phenomenon was first studied and published in several papers in the mid 1960s and 1970s [2-5]. Solar storm damage to large power transformers and line disconnect failures caused by accumulated degradation due to moderate intensity storms has been reported in the U.S., Canada, Sweden and South Africa [6-9]. In March 1989 the Quebec grid collapsed when a mid-intensity (roughly 2 V/km) solar storm hit the earth [9]. The largest recorded solar storms to impact the earth occurred in August 1859 and May 1921. These two solar storms referred to as the 1859 Carrington and the 1921 NY Railway storms fortunately occurred many years before modern electrical power grids were developed [10–11]. A solar storm of their magnitude today could result in significant long-lasting damage to our economy and country. Even common low-level solar storms produce GICs which invade the power grid and generate harmonics causing customer equipment damage. Recent insurance industry studies indicate that there is significant negative impact to electrical equipment each year due to these common low-level solar storm effects [12].

The expected frequency of large solar super storms impacting the earth has been studied and published in four separate publications in recent years [13-16]. Three of these four studies [13-15] agree that the probability of the next solar super storm hitting the earth is about 12% during the next decade and 50% in the next 50 years. It is important to note that NOAA recorded a solar super flare ejection from the sun in July of 2012 which was on the same order of intensity as the Carrington flare of 1859. Fortunately, this massive flare was ejected from the back side of the sun and therefore missed the Earth [17]. Because the Sun rotates on its own axis within a period of 25 days, this 2012 flare would have directly impacted the Earth if it ejected just a few days earlier.

Geomagnetic Disturbance (GMD) events saturate transformers that then induce voltage harmonics in power systems which can cause damage to power system components. Papers published in 2001 and 2015 indicate that even low levels of geomagnetically induced current can cause GSU and other types of HV and EHV transformers to exceed the IEEE 519 standard for Total Harmonic Voltage Distortion (THVD) [18, 19]. Depending on the MVA rating of the transformers in question and the strength of the transmission system to which they are connected, GIC in the range of 10 to 15 Amps can result in THVD levels that exceed IEEE 519 standards [20]. Even moderate GMD events have induced GIC currents in power systems that were capable of producing large THVD disturbances [21].

The induction of quasi-DC current in power systems can also be caused by the "Blast" and "Heave" portions of the electromagnetic pulse (EMP E3) from a nuclear device exploded above 80 kilometers altitude [22]. A series of nuclear tests in the late 1950s and early 1960s over the Pacific Ocean clearly showed electrical power systems are vulnerable to an EMP E3 pulse in a manner similar to that of a GMD [23]. Therefore, mitigation options against GIC in power systems are also suitable for mitigation against nuclear EMP E3 events. The 2008 EMP commission report states "steps taken to mitigate the E3 threat also would simultaneously mitigate this threat from the natural environment" [24]. An EMP model of the SolidGround™ NBD which is capable of protection against higher EMP E3 levels (with electronics shielded and filtered against the high EMP E1 fields) has been designed, tested and is available. The GMD model NBD described in this paper can be upgraded to an EMP model at any time. Additional detailed information on the EMP version of this NBD is available online [25].

During the last several years NERC has developed Reliability Standards for Geomagnetic Disturbances in compliance with FERC Order No. 779. The NERC standard requires utilities to conduct studies to determine the grid's susceptibility to GMD [26]. Additionally, NERC has also been ordered to study and develop a similar standard for EMP impact to the power grid [27]. As a result, effective low-cost mitigation solutions for protecting power grids are being investigated by electric utilities around the globe.

An extensive EPRI report published in 1983 [28] concluded "A capacitor in the neutral of transformers was determined to be the most effective and practical blocking device." Following this study two prototype transformer neutral blocking devices were placed into live grid prototype testing, one in northern Minnesota in 1991 and the second in Quebec in 2000 [29, 30]. In both of these designs, capacitors were placed in the neutral path to ground 100% of the time. Both devices were reported to have performed adequately but further production models were apparently not developed or pursued by the industry.

This paper describes a fully automated neutral blocking device that continuously maintains a grounded neutral with three parallel paths for current to flow from the transformer neutral to ground. These are: a solidly grounded metallic path, a GIC blocking path consisting of a low AC impedance capacitor bank in series with a power resistor and an overvoltage protective path through a spark gap. This device automatically opens the metallic path directing all neutral AC current through a low AC impedance capacitor bank only when needed, thereby blocking the quasi-DC currents induced by GMD or EMP E3 events. This process allows utilities to maintain a solid metallic grounded neutral under normal operating conditions, roughly 99% of the time. This NBD concept was developed by Emprimus LLC and has been studied by the University of Manitoba [31] and EPRI [32] to assess potential risks associated with its use. These studies concluded that there are no unintended consequences from using a neutral blocking device (NBD) of this design [33-34]. The NBD described in this paper was first tested at the KEMA high-current testing laboratory in Chalfont, PA. It was later field tested by the Defense Threat Reduction Agency (DTRA—an agency within the Department of Defense) at the Idaho National Laboratory (INL) in Idaho Falls, ID [33-34]. This testing simulated the MHD-EMP E3 (the quasi-DC induced current) impact on a high voltage power transformer. The NBD device met all performance requirements, successfully blocking all injected DC currents. This NBD was designed to be fully code-compliant with industry accepted and tested components. The device has been in service in the Wisconsin ATC power grid since February 2015.

GMD Modeling of the Wisconsin ATC Power Grid

Power flow studies to assess the impacts of GIC on ATC's power grid were performed using the PowerWorld^{TM} simulator software. These studies showed significant voltage decreases approaching voltage collapse for an east to west geo-electric field of 19 V/km (Figure 1). Note: this figure assumes a best case power grid scenario of peak power with no contingencies.

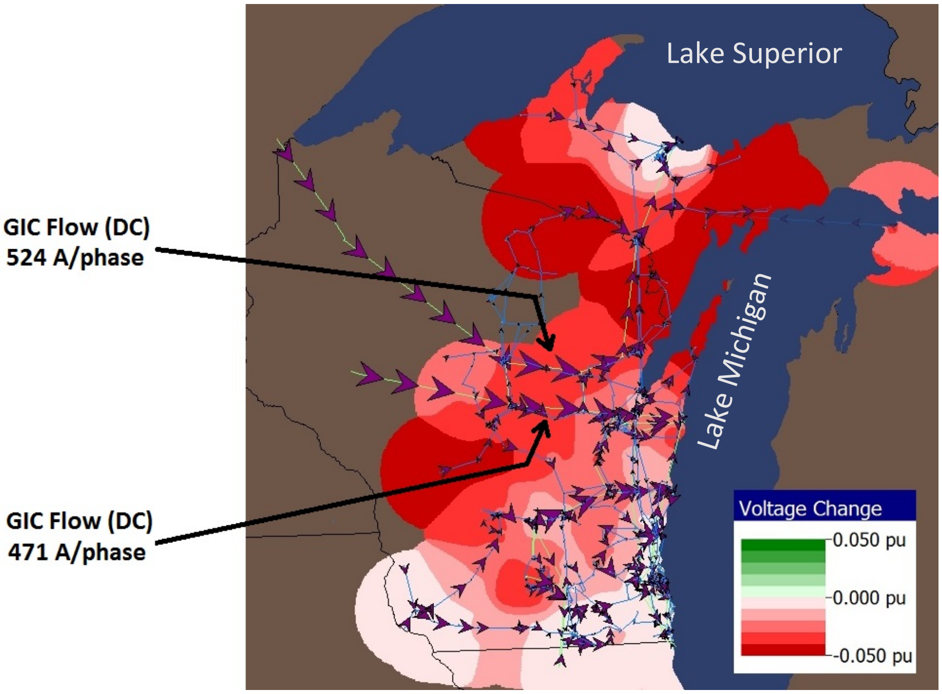


Figure 1: ATC WI and Upper MI Voltage Decrease Map for a 19 V/km Geo-Electric East-West Field.

NBDs were then added to these power flow simulations to assess the effectiveness of applying NBD devices at the most effective sites in ATC's power grid for reducing the risk of voltage collapse during a severe GMD. An example of simulation results where the system voltage collapse is plotted for various geomagnetic field strengths is shown in Figure 2. The graph shows significant improvements in the voltage collapse scenarios as multiple NBDs are applied at five (5) and twenty-five (25) substations. Important to note that a 100 year solar super storm could be higher than 21 V/km [35]. Further protection against voltage collapse can be realized with the placement of additional NBDs.

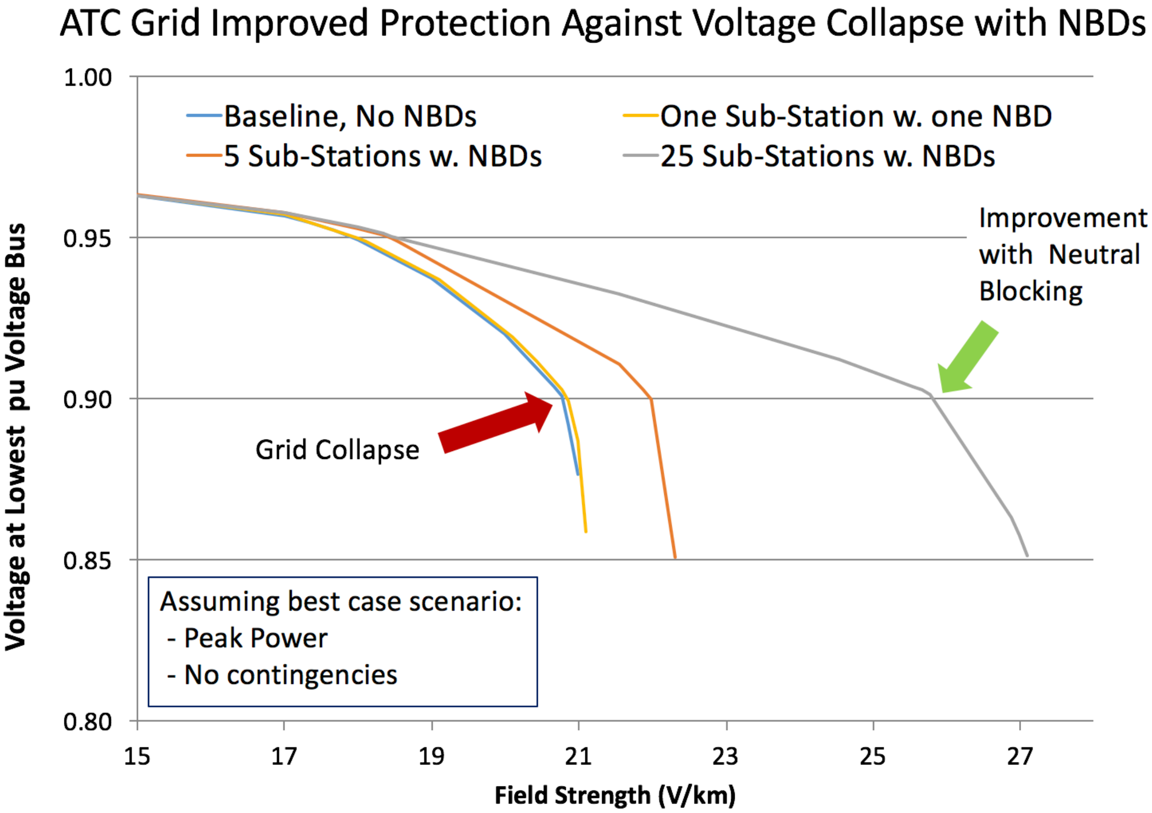


Figure 2: System Voltage Collapse Modeling vs Worst Geo-Electric Field Angle (W to E) as Neutral Blocking Devices are Applied at Specific Sub-Stations

Studies also examined the impact of several power system scenarios which might cause system voltage collapse at lower geo-electric field values. Figure 3 shows three power system scenarios that were considered: 1) Peak power with no contingencies, 2) a shoulder load of 80% with high power transfers and no contingencies, and 3) a loss of generation at one site with high power transfers. Models of these three scenarios show voltage collapse field strengths are reduced from an initial 21 V/km for case #1 down to 16.5 V/km for case #2, and down to 12 V/km for case #3. These results clearly show that it is important to consider the potential impacts of generation outages, high transfers and other contingencies when evaluating the GMD vulnerability of a power system.

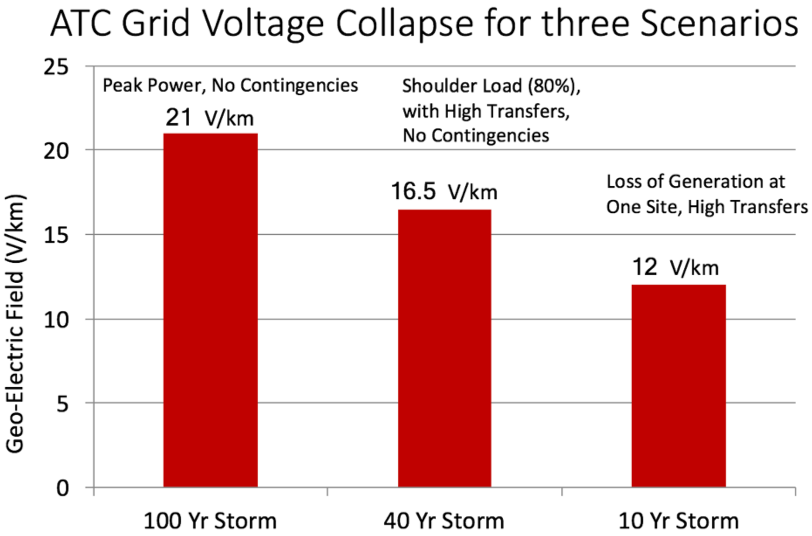


Figure 3: ATC Grid Voltage Collapse Modeled for Three Power System Scenarios

Figure 4 shows the ten highest GIC currents simulated on the grid for a 19 V/km east to west geo-electric field corresponding to a severe GMD storm. This field (19 V/km) is just below that for voltage collapse in the ATC power grid as calculated using the PowerWorld^{TM} modeling assuming peak power with no contingencies. The earth conductivity adjustment factor for soil in Wisconsin was used and because the center of this storm is assumed to be located directly over the USA a latitude adjustment factor was not applied. Furthermore, it was assumed that the area of impact of the storm was large enough that spatial averaging of the geo-electric field did not apply.

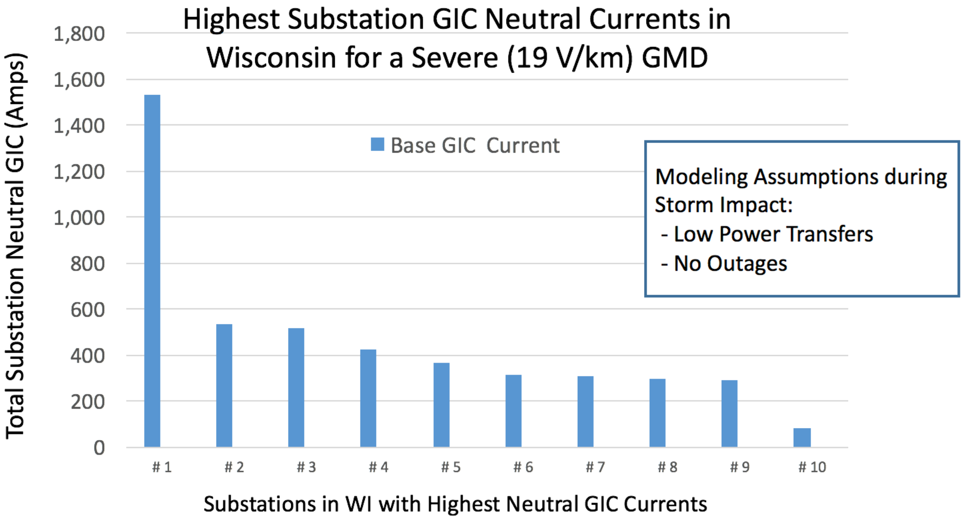


Figure 4: Modeled Base GIC (Blue) for a Severe (19/ V/km) GMD at Worst Field Angle (W to E).

The ATC grid model was also used to determine if the installation of NBDs would increase GIC at any other transformers (i.e. the "whack-a-mole" effect). Results showed that if an NBD was installed on just one transformer at a substation the GIC would move and increase the GIC on other transformers in that same substation. It was therefore apparent that all transformers at a given substation would require neutral blocking devices to avoid this impact. Next, the effect of placing additional NBDs at a nearby substation was modeled. Figure 5 shows the GIC currents, in orange, at each substation after NBDs are strategically applied at one primary site (#1) and at one nearby substation (#10). Note: when a specific site is selected for applying NBDs it is assumed that NBDs will be applied to all transformers at that site. These results show that with neutral blocking installed at two sites, the neutral GIC at those two sites will drop to zero and the GIC at other substations is essentially the same as before the NBDs were installed (i.e. little to no local "whack-a-mole" effect in the Wisconsin Grid). It should also be noted that blocking these large GIC currents reduced potentially damaging transformer saturation generated voltage harmonics as well.

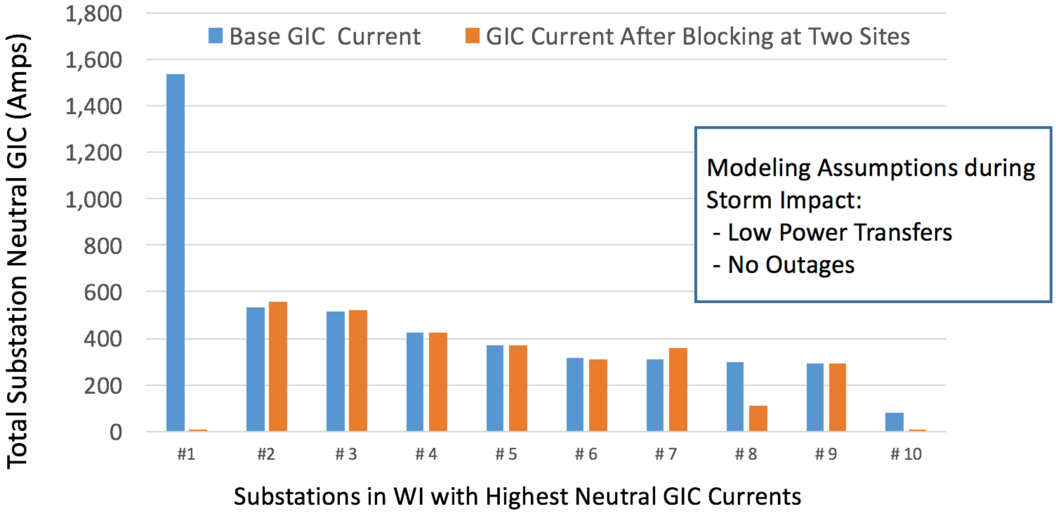
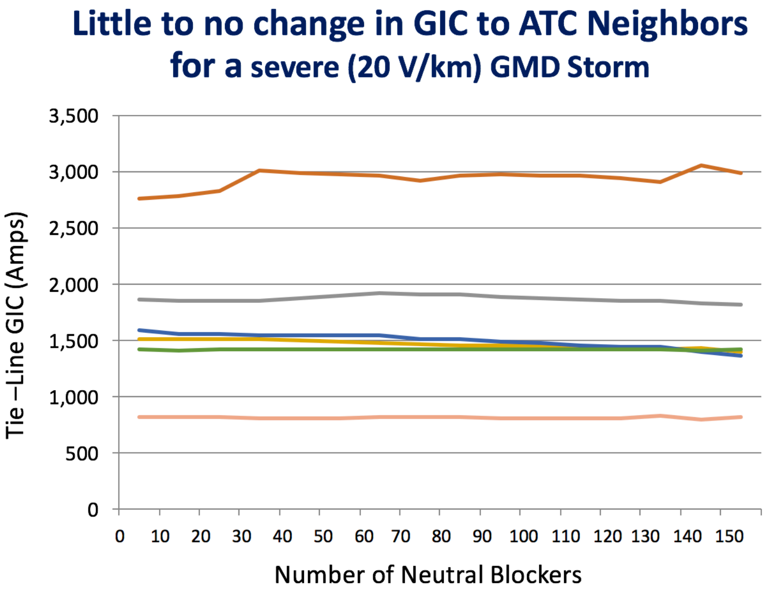


Figure 5: Modeled GIC Before (Blue) and After (Orange) Neutral Blocking added at Sites #1 & #10 for a Severe (19 V/km) GMD at Worst Field Angle (W to E). Little to no GIC "Whack-a Mole."

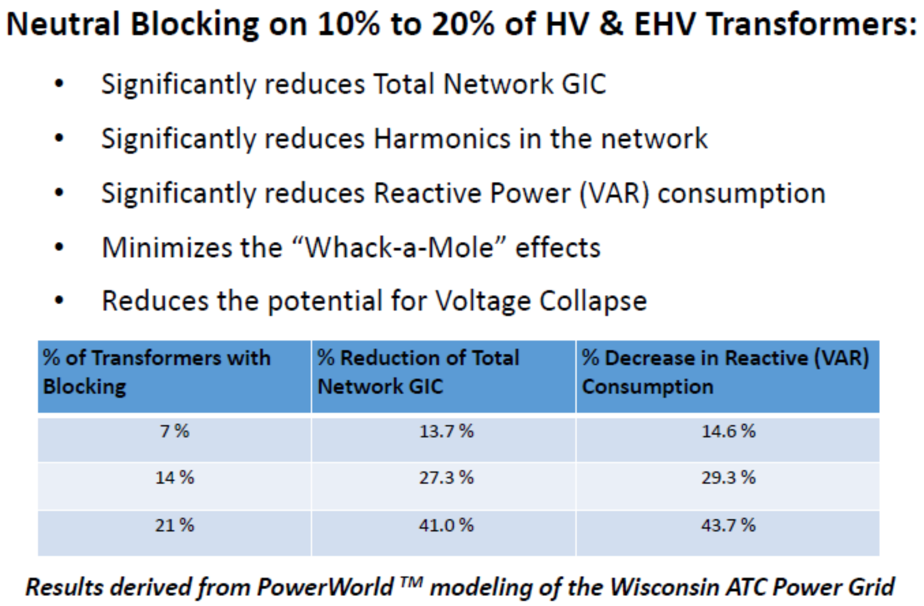
Finally, we examined the "whack-a-mole" impact on six neighboring utilities as more NBDs were applied to the Wisconsin grid model. The results (Figure 6) show little to no change in the GIC current flowing to ATC neighbors. The various models show that the issue of whack-a-mole can be addressed with the proper placement of NBDs. As NBDs were added, the ATC grid became more stable without adversely affecting neighboring utilities.



Results derived from PowerWorld ™ modeling of Wisconsin Grid

Figure 6: ATC's Top Six Tie-Line Currents as Additional Neutral Blockers are Applied. Models Show Minimal NBD "Whack-a-Mole" Effects in Wisconsin.

Another benefit of applying neutral blockers to HV and EHV transformers is the reduction of reactive power (VAR) consumption. Models of the ATC system indicated that the placement of NBD devices on just 20% of large transformers would reduce total network GIC and total network VAR demand by over 40% (Figure 7). This reduction in VAR demand significantly improves transmission efficiencies.



Neutral Blocking on 10% to 20% of HV & EHV Transformers:

- Significantly reduces Total Network GIC
- Significantly reduces Harmonics in the network
- Significantly reduces Reactive Power (VAR) consumption
- Minimizes the "Whack-a-Mole" effects
- Reduces the potential for Voltage Collapse

% of Transformers with Blocking	% Reduction of Total Network GIC	% Decrease in Reactive (VAR) Consumption
7 %	13.7 %	14.6 %
14 %	27.3 %	29.3 %
21 %	41.0 %	43.7 %

Results derived from PowerWorld ™ modeling of the Wisconsin ATC Power Grid

Figure 7: Benefits of Reducing Total Network GIC on the Wisconsin ATC Power Grid.

Automatic Protection vs Operational Procedures

Relying on warning systems to inform operating decisions may not be effective due to errors or time lags in present warning protocols. Better warning systems can be developed. However, even with a warning of 30 minutes (the best that can be expected from the nearest satellite) operating measures may prove ineffective due to unpredictable variables associated with any particular GMD event.

Utility operating procedures when a GMD event is anticipated, do not reduce the GIC in the network or reduce GIC related harmonics [20]. Therefore, operating procedures do not reduce the potential for mis-operation of relays, transformer damage or generator rotor damage. GIC must be blocked or significantly reduced to ensure the stability and reliability of the grid.

To address the necessity for rapid and reliable protection, the NBD in the ATC grid automatically triggers into GIC blocking mode when the first GIC impact on the network is detected.

Selection of Neutral Blocking Device (NBD) Location in Wisconsin

ATC, which operates the majority of the high voltage power grid in Wisconsin, decided to purchase, install and operate the first "SolidGround™" NBD described in this paper at a substation that provides bulk electric power to the Upper Peninsula of Michigan.

The location of this installation was selected for several reasons. First, it is remote from generation, limiting the potential impact of the NBD's operation on GSUs in the area. Second, it connects to a long radial EHV transmission line that has historically had significant GIC flows during solar storms. This is due to the high soil resistivity along its route and to its more northerly location, which is closer to the higher strength electrical fields caused by solar storms. Third, there is only one transformer at this substation, eliminating the concern for potential negative effects of shifting the GIC current to a parallel transformer at the same substation during GIC blocking mode operations.

A photo of the installed neutral blocking device is shown in Figure 8. It is located approximately 25 feet from the only transformer at this site, a 300 MVA, 345 kV to 138 kV autotransformer. The transformer neutral is connected to the NBD device which in turn is connected to a buried ground grid.

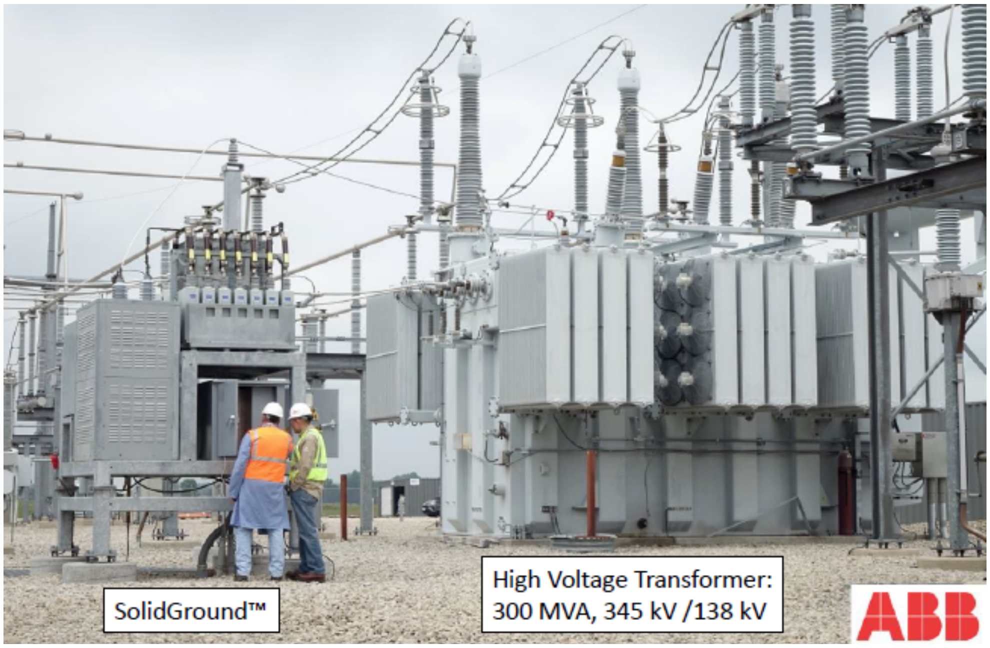


Figure 8: SolidGround™ Neutral Blocking Device Installed and Operational in Wisconsin.

Design of the Neutral Blocking Device (NBD)

Electrical Design – The circuit diagram for the NBD is shown in Figure 9. The device has three parallel paths to ground: namely, a solidly grounded path through an AC breaker in series with a DC breaker, a GIC blocking path consisting of a low AC impedance capacitor bank in series with a power resistor, and an overvoltage protective path through a spark gap. Additionally, the NBD has a fail-safe Kirk Key bypass switch that allows the NBD to be safely taken out of service for maintenance. The NBD device is designed to minimize impacts to the transmission grid and the transformer.

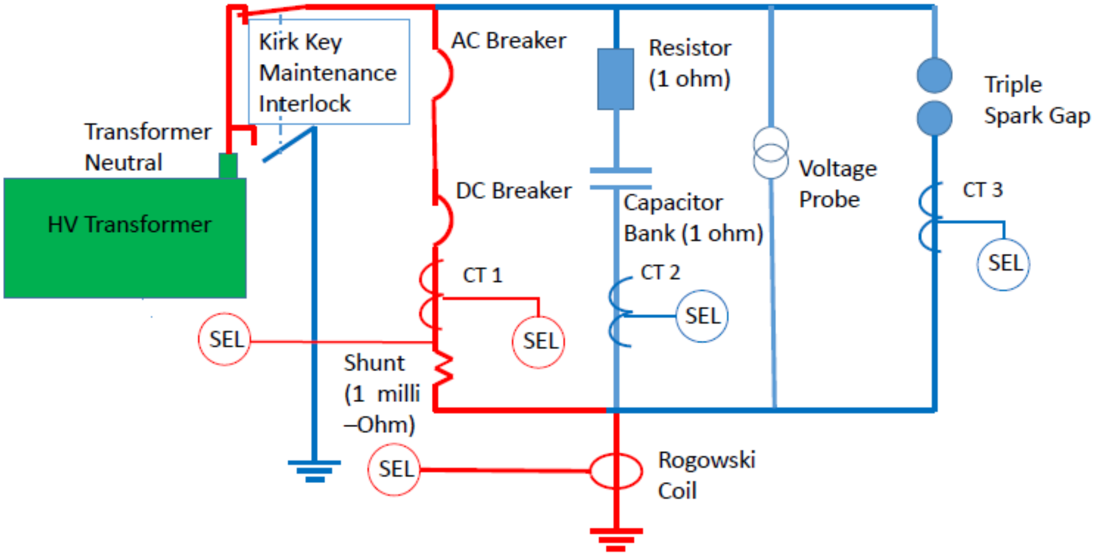


Figure 9: Neutral Blocking Device (SolidGround™) Circuit Diagram.

The NBD is configured such that the transformer neutral is normally solidly grounded through the metallic AC and DC breaker path. This normal mode of operation covers the vast majority of the time when GMDs are not impacting the earth or the specific substation. However, when GIC current is detected in the neutral (when the quasi-DC GIC current is sensed in the one milli-ohm shunt resistor), the device automatically opens a breaker assembly, interrupting only the metallic AC and DC breaker path, and the transformer remains effectively grounded through the low AC impedance capacitor bank shown in Figure 9. This "GIC blocking mode" will last as long as the GMD storm continues to impact that particular substation. If we assume (10) storms are experienced each year with GIC affecting a particular substation, for an average of 8 hours per storm, the NBD device would be in the GIC blocking mode, less than 1% of the entire year. If a ground fault happens while in GIC blocking mode, there is a risk of overvoltage to the transformer and capacitor bank. To protect the transformer and the capacitor bank during such an event a carefully calibrated and robust triple spark gap assembly provides dual redundant overvoltage protection (Figure 10).

The spark gap [36] was designed for this application and tested to be extremely reliable for multiple high-current power system ground faults. Also shown in Figure 9 are three current sensors (CTs), a voltage probe, a Rogowski Coil current sensor and a shunt resistor to monitor neutral current through the breakers. All of these sensors provide input signals to an SEL Axion RTAC Controller (PLC) located in the substation control building. Appropriate monitoring and alarm signals are metered at the substation and sent back to the Operating Center via the SCADA system.

Figure 10: Redundant Triple Electrode Pair High-Current Overvoltage Spark Gap Protection Assembly (DuraGap™).

Spark Gap Design – A durable and reliable high-current spark gap (DuraGap™) was developed and patented by Emprimus LLC to provide transformer protection against multiple high-current power system ground faults [36]. Three Jacob's Ladder configured electrode pairs, shown in Figure 10, were used to create a dual redundant, triple spark gap assembly. The spark gap assembly successfully passed rigorous independent testing at the high energy KEMA laboratories in Chalfont, PA. The electrodes were fabricated using an ablation resistant alloy. They were rigidly mounted on a high strength electrical insulator stand-off which was designed to withstand the large Lorentz forces experienced when a high-current arc, i.e. 20,000 amps for eight (8) cycles, occurs in the electrode pairs. The gap spacing between electrodes is adjustable to provide voltage breakdown protection from 5 kV to 25 kV. The spark gap testing demonstrated that the assembly could withstand over twenty (20) high-current and duration (20,000 Amps for 8 cycles) ground fault events without any observable degradation to its ground fault protection performance. The recorded arc energies were typically on the order of three (3) mega-joules for each ground fault event. This static overvoltage device does not require a cool down period between multiple reclosing events. It should be noted that neutral ground fault currents are typically smaller than line to line or line to ground faults because they are limited by the transformer impedance. Modest structural changes to this spark gap will provide protection for much larger ground fault currents if deemed necessary to meet more stringent power system requirements.

Controller Software – The software that controls the neutral blocking device was developed and tested by Emprimus LLC and later verified and certified at the ATC installation site. The controller and software were configured to monitor measurements from several sensors and transmit a control signal to open the breaker assembly to activate the NBD's GIC blocking mode whenever the neutral GIC current exceeds a preset value. The software also includes several monitoring functions to provide alarm signals to the substation SCADA system should abnormal conditions be detected.

The controller continuously monitors the following parameters: GIC neutral current, induced harmonics, neutral grounding continuity, capacitor bank AC & DC voltage, AC neutral current, the number of fault events on the spark gap, the open and closed positions of AC & DC breakers, and the supplied power to both the Axion controller and to the neutral blocking device. The AC neutral current is continuously monitored to provide confirmation that the transformer ground connection is secure.

Mechanical Design – The neutral blocking device is designed to meet substation environment and safety requirements. The capacitor bank, power resistor, AC and DC breakers, current sensing shunt resistor and spark gap are mounted on a steel frame with base dimensions of 8 feet by 8 feet. These components are mounted above a height of 9 feet 3 inches to provide electrical clearance as required by the ANSI C2 substation code for unguarded, potentially live components. The spark gap assembly is mounted near the top of the structure such that a ground fault arc plume from the electrodes is expelled above the capacitors and other NBD components. The AC and DC breakers are mounted in a NEMA 3R steel cabinet. The power resistor is mounted in another cabinet. Finally, a Kirk-Key interlock system is used to allow easy and fail-safe disconnection of the device from service for maintenance while maintaining a solid ground for the transformer. This NBD is designed to work on nearly all HV and EHV transformers designs.

No Power Grid Unintended Consequences Related to the ATC NBD Device

Concerns have been raised regarding potential unintended consequences of applying neutral blocking devices (NBDs) on HV and EHV transformers. To address these concerns the utility industry commissioned EPRI to study the potential unintended consequences of implementing NBDs in modern power grids. In 2014 EPRI published a study of two specific designs [32]; namely, a 43.2 ohm capacitive impedance NBD passive device which was considered by the industry in the early 1990's [29] and a one-ohm capacitive impedance NBD design similar to the NBD installed at ATC.

This 2014 EPRI study identified only one concern related to the one-ohm NBD device; namely, the requirement to replace the overvoltage protection MOV (metal-oxide-varistor) component each time it was consumed by ground fault current [29]. The implementation of the DuraGap™ spark gap overcomes the EPRI study concerns of using a consumable device such as an MOV lightning arrester.

The primary issue with the second passive NBD design (i.e. the 43.2 ohm NBD), which has capacitors placed in service 100% of the time is the permanent loss of solid metallic neutral ground thereby relying on an overvoltage protection device 100% of the time should a fault occur in the area. A second issue with this NBD design is that the high impedance does not meet the IEEE standard of an "effectively grounded" system. This could require adjustment of relay settings to prevent relay mis-operation [37].

Another concern, not mentioned in the EPRI report but expressed in a meeting with utility engineers, is the potential that a large portion of the power grid could be floated at a high voltage if NBDs were installed on all HV and EHV transformers over a large area. First, the NBD described in this paper has a low one-ohm impedance, meaning the transmission grid is still "effectively grounded" in the GIC blocking mode, since only DC, not AC, current is blocked. Second, the unique design of SolidGround™ specifically solves these issues by <u>maintaining a solid metallic ground</u> in normal operating mode (roughly 99% of the time) and automatically directing neutral current through a low AC impedance capacitor bank ("GIC blocking mode") only at the precise time a specific transformer location experiences potentially damaging GIC current. This allows for the safe installation of this NBD over a large portion of the power grid as the remaining majority of transformers maintain a solid metallic AC and DC ground. As more NBDs of this design are installed, total network GIC will continue to decrease meaning fewer transformers will experience GIC and more transformers will remain in normal operating mode with a solid metallic ground. Furthermore, power grid modeling indicates significant protection against GIC can be achieved with properly located NBDs on just 20% to 30% of the HV and EHV transformers in a given area. Thus, the vast majority of ground connections on transformers are still available to prevent a large portion of the grid from floating at a DC or quasi-DC voltage.

Acceptance Testing and Commissioning of the Neutral Blocking Device

An electrical model/simulator of the NBD was used to validate the software program used in its SEL Axion 2240 RTAC Controller prior to the installation of the device at ATC's substation. An extensive checklist was used to test all inputs, outputs and potential error modes to validate NBD controller functionality.

Commissioning the software and the NBD device included simulating conditions that indicated normal operation (entering and exiting the GIC blocking mode) and multiple contingencies of possible failures or unusual conditions (breakers not operating as ordered, faults, unusually high unbalance current, loss of transformer neutral). It was also verified that the system communicating status and select sensor data was properly connected to the controller and sending information to ATC's control center. After all combinations of potential events were simulated and correct operation of the NBD device was verified, the unit was certified as ready for operation in its automatic response mode.

Operational Experience in the Wisconsin ATC Power Grid

After extensive testing and validation procedures, the NBD was put into service in February of 2015 at a substation in the ATC power grid. The first automatic protection event was recorded on June 22nd of 2015. A recording of the transformer neutral GIC current and NBD capacitor bank voltage is shown in Figure 11.

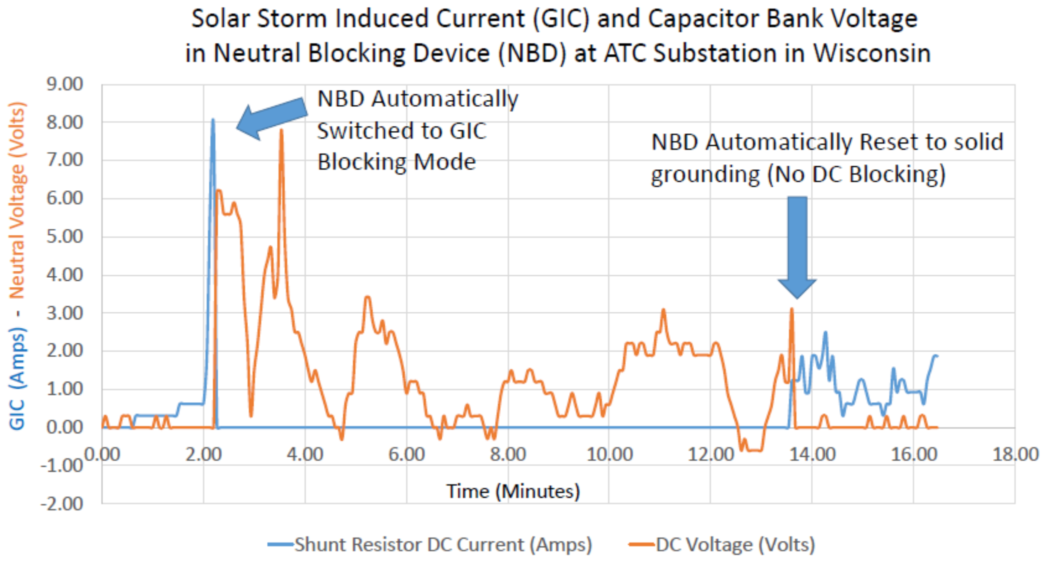


Figure 11: Recording of Neutral Blocking Device (NBD) June 22, 2015, Automatic Operation. Blue Trace is GIC Current (amps) and Orange Trace is Capacitor Bank Voltage (volts).

Figure 11 shows that when the neutral GIC current exceeded 5 Amps for more than 5 seconds the NBD triggered into its GIC blocking mode. This low level was selected to increase the chances of NBD operations to test the device functionality. The protection duration was initially set to 10 minutes as can be seen by the capacitor bank voltage and GIC current recordings in Figure 11. After a 10 minute duration the NBD automatically reset itself into the solidly grounded mode, provided the neutral-to-ground potential was less than eight (8) volts. However, if the neutral-to-ground voltage still exceeded 8 volts, which indicates the storm is still impacting the NBD, the unit would remain in the GIC blocking mode until the DC voltage went below 8 volts and stayed below this level for more than 10 minutes.

Tables I and II summarize the number of automatic operations that have been experienced and recorded during several low-level GMDs (Solar Storms) impacting the earth. Initially the length of time for the device to remain in the GIC blocking mode was set at ten (10) minutes to allow the device to actuate multiple times during a GMD storm which typically lasts two to three days. This setting resulted in multiple automatic NBD actuation—fourteen (14) times—for a K-7 storm that occurred over two days on June 22nd and June 23rd of 2015 (Table I).

Table I: NBD Automatic GMD Protection Operations - June 2015.

Date (m/d/yr)	GMD Storm K-Index	Time Triggered into Protection Mode (CST)	Protection Mode Duration (minutes)
6/22/2015	Kp=7	13:34:00	11
"	"	14:51:36	10
"	"	15:02:12	"
"	"	15:17:48	"
"	"	22:21:09	"
"	"	22:31:17	"
"	"	22:44:30	"
"	"	22:55:30	"
"	"	23:05:46	"
"	"	23:46:37	"
6/23/2015	"	00:09:58	"
"	"	00:20:50	"
"	"	00:32:02	"
"	"	00:51:57	"

Note (1) NBD was programmed to go into GIC blocking mode for 10 minutes when the neutral GIC current exceeded a preset level. After 10 minutes, the NBD remained in GIC blocking mode only as long as the voltage on the NBD capacitor bank remained above a preset level.

Note (2) K-Index from NOAA (ftp.ngdc.NOAA.gov)

Note, the first GIC blocking mode duration time was 11 minutes long, rather than 10 minutes, because the voltage on the NBD capacitor bank was still above the pre-programed set point after 10 minutes, indicating the initial GMD impact was still present.

Table II shows several GMD storms which occurred between June 2016 and October 2017. Note: after 2015 the NBD blocking time duration in the software was increased from 10 to 60 minutes. This longer GIC blocking mode duration reduces the number of automatic operations of the device and is more consistent with the expected delay between GMD sub-storm impacts.

Table II: NBD Automatic GMD Protection Operations - July 2016 to Oct. 2017.

Date (m/d/yr)	GMD Storm K-Index	Time Triggered into Protection Mode (CST)	Protection Mode Duration (minutes)
7/19/2016	Kp=6	18:51:04	60
"	"	20:11:32	"
3/1/2017	"	18:08:52	"
"	"	23:59:24	"
5/27/2017	"	22:47:00	"
7/16/2017	"	14:45:24	"
9/7/2017	Kp=7	18:01:09	"
"	"	20:20:04	72
9/8/2017	"	07:20:18	60
"	"	08:29:40	"
"	"	09:35:24	"
"	"	10:42:44	"

Note (1) NBD was programmed to go into GIC blocking mode for 60 minutes when the neutral GIC current exceeded a preset level. After 60 minutes, the NBD remained in GIC blocking mode only as long as the voltage on the NBD capacitor bank remained above a preset level.

Note (2) K-Index from NOAA (ftp.ngdc.NOAA.gov)

There have been periods when this ATC substation has been out of service to allow for upgrades to equipment unrelated to the neutral blocking device (NBD). During these outages several GMDs occurred which were not recorded. Taking the NBD in and out of service was found to be a simple, straightforward and safe process without the need for any adjustments to relays or other equipment in the network.

Summary

A low-maintenance fail-safe transformer neutral blocking device (NBD) to improve power grid stability and protect against geomagnetic disturbances (GMDs) has been installed and is operational in Wisconsin. SolidGround™ was initially put into service in February 2015 and has operated and blocked GIC as designed without issues during six (6) low-level solar storms (GMDs). The NBD operates automatically and provides several monitoring signals to the SCADA system through the substation control house. The experience to date has shown no signs of unintended consequences introduced into protective relays or other power system components. The device blocks GIC, prevents harmonic generation, reduces reactive (VAR) power demand and helps prevent voltage collapse during GMD events. This operational experience shows that an effective and low-cost electromagnetic pulse (EMP) protective version of this device can be made available to the electric utility industry [38].

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