Automatically Operated Neutral Blocking Device (NBD) for Transformer Geomagnetic Disturbance (GMD) and EMP Mitigation

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Abstract

The design and operating characteristics of a new transformer neutral blocking device (NBD) will be presented. This NBD design provides automatic protection for HV and EHV transformers against geomagnetic disturbances (GMDs) and electromagnetic pulse (EMP) events when GMD or EMP induced currents in a transformer are detected. The device provides a metallic path to solidly ground the transformer during normal operation and an AC effective grounding path for the transformer for only short periods (i.e. a few hours) when a solar disturbance or EMP event is impacting the earth. Power grid modeling and studies show neutral blocking in a grid provides significant reductions in reactive power (VAR) consumption and GIC harmonics as well as protection against relay mis-operations. Additionally, NBDs enhance the protection of GSU transformers at hydro-generation facilities which can provide important black-start resources for a power grid. The design, operational benefits and a summary of recent substation operating experience of the SolidGround™ NBD will be presented. A fully protected electromagnetic pulse (EMP) SolidGround™ will also be presented.

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]. The expected frequency of large solar super storms impacting the earth has been studied and published in four separate publications in recent years [2-5]. Geomagnetic Disturbance (GMD) events saturate transformers that then induce voltage harmonics in power systems which can cause damage to power system components. 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 detonated above 80 kilometers altitude [6]. During the last several years NERC has developed Reliability Standards for Geomagnetic Disturbances in compliance with FERC Order No. 779. An extensive EPRI report published in 1983 [7] concluded "A capacitor in the neutral of transformers was determined to be the most effective and practical blocking device." This paper describes an upgraded EMP protected version of a fully automated neutral blocking device which was described in a previous paper published in November 2017 [8].

Reasons to Install SolidGround™ NBDs in a Power Grid

The primary benefits of applying the SolidGround™ NBD [9] to a power system's HV and EHV transformers (GSUs, Auto-Transformers and HVDC Converter Transformers):

- Enhances the stability and reliability of the electric power grid
- Automatically Blocks GIC and EMP E3 induced DC currents
- Prevents half cycle saturation and harmonics in GSUs and HVDC converter transformers (reduced in auto-transformers)
- Prevents GIC related damage of GSU, HVDC converter transformers and auto-transformers

HydroVision Published Date: June 26, 2018

- Provides a solid metallic and effective AC ground with continuous DC current neutral blocking mode available – "Passive Mode")
- Reduces VAR losses and the added cost of replacement VARs
- Allows transformers to operate through solar storm events at their full efficiency
- Reduces risk of voltage collapse due to a severe GIC event
- Reduces the cost of power generation by eliminating much of the need for uneconomic dispatch (i.e. utility sales, purchases and power transfer adjustments) during GMD events
- Prevents damage to and mis-operation of transformers, SVCs, generator rotors, and AC breakers caused by GMD or EMP induced currents
- 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 induced harmonics from common low-level solar storms
- Scalable to help protect the entire grid against 100 year Solar Super Storms and Nuclear EMP E3
- No adjustment of protection to relay settings required
- SCADA controls with continuous monitoring: DC currents, GIC induced harmonics, EMP E1 pulse
- Major components are industry standard, high quality, provided by ABB and Schweitzer

GMD Modeling of a Typical Northern USA Power Grid

Power flow studies which include geo-magnetically induced currents generally show the largest induced GIC currents are found in the lines with the highest HV and EHV voltages and longest distance transmission lines. This fact is consistent with the highest voltage lines having the lowest DC resistance and also the largest induction loops for the Faraday induction of geomagnetic currents (GICs). This finding shows that our most critical power generation and transmission assets are also our most vulnerable when considering GMD and EMP events. To emphasis these findings power flow studies were performed on a typical northern power grid using the PowerWorld™ simulator software. These studies show a significant voltage decreases in winter power flow conditions for a northwest to southeast geo-electric field of only 10.5 V/km as shown in Figure 1.

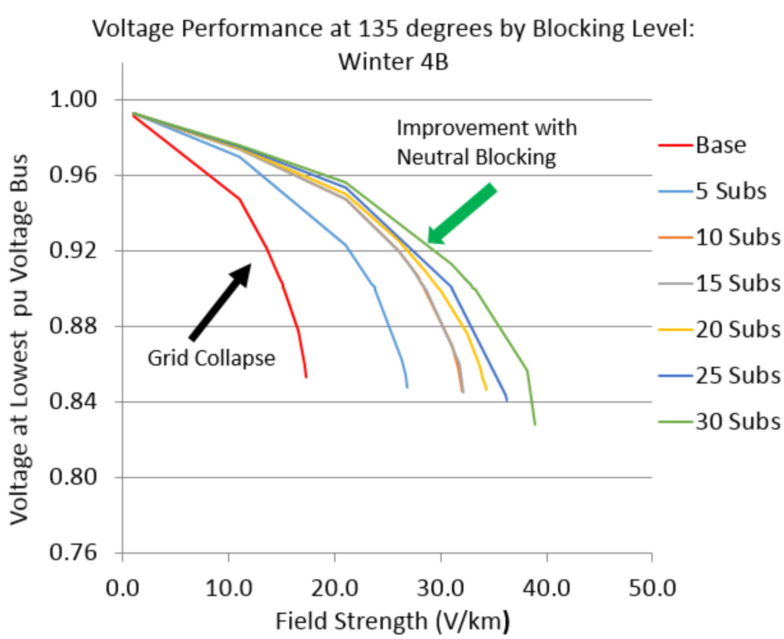

Figure 1: System Voltage Collapse Modeling vs Worst Geo-Electric Field Angle (NW to SE) as Neutral Blocking Devices are Applied at Specific Sub-Stations

These power flow simulations were also used to assess the effectiveness of applying NBD devices in a typical northern power grid. An example of these modeling results an improvement in voltage collapse for various geomagnetic field strengths also shown in Figure 1. The graph shows significant improvements in the voltage collapse scenarios as multiple NBDs are applied at five (5) and ten 10) substations selected as those with the largest induced GIC currents. Included in these ten (10) substations are two large 345 kV power generation facilities. These results show that by applying NBD devices at these most critical locations, which include one hydro and one oil fired power plant, a large improvement to the grid reliability can be realized. Important to note that an EMP event or 100 year solar super storm could be significantly higher than 21 V/km as will be discussed in a later section in this paper. Further protection against voltage collapse can be realized with the placement of additional NBDs beyond what is shown in figure 1.

These power flow studies also show the ten highest Neutral GIC current flows (Blue Bars) for a 20 V/km field shown in Figure 2 as the base case. This figure also shows the Neutral GIC currents (Orange Bars) after 5 NBD devices are applied at substations #2, #3, #4, #5 and #7. It should be noted that substations #2 and #3 are generation sites which only have two-winding Generation Step Up (GSU) transformers and because of their configuration (Delta – Wye) an NBD will block all the GIC flowing in these type of transformers.

The PowerWorld™ modeling shown in Figure 2 assumed peak power operation scenario with no contingencies. A GMD geoelectric field of 20 V/km was used to represent a Carrington (one in one hundred year) storm located directly over the USA. Therefore 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.

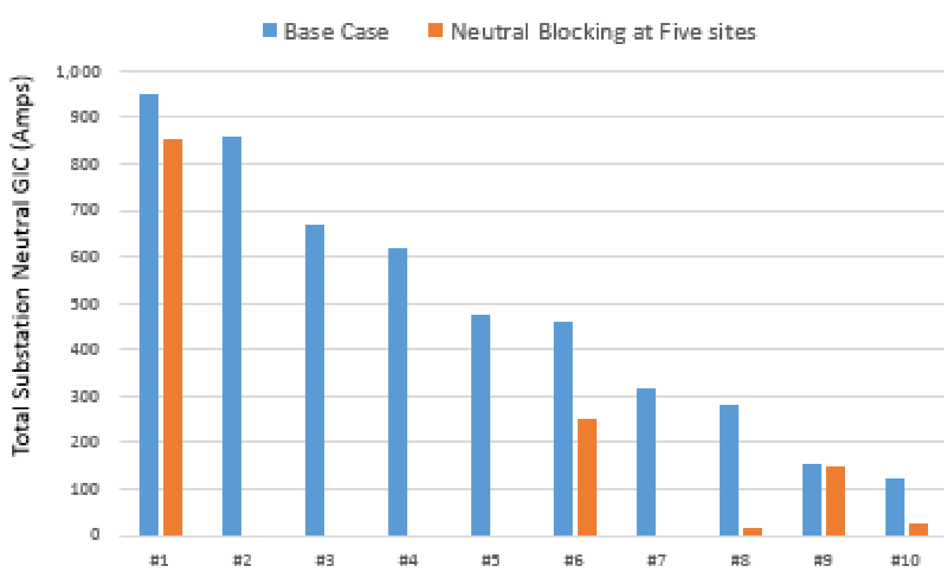

Figure 2: Typical Northern Power Grid Modeling of GIC Before (Blue) and After (Orange) Neutral Blocking added at five Sites (#2, #3, #4, #5 and #7) for a severe GMD (20 V/km) at Worst Angle (NW to SE). Neutral blocking at five sites shows a 73% decrease in Total GIC of the top ten GIC sites (#1 thru #10. No GIC "Whack-a-Mole" seen in the above modeling result.

Effective Placements of Neutral Blocking Devices (NBDs)

The PowerWorld™ modeling of numerous power grids clearly show the most effective locations for installing Neutral Blocking Devices (NBDs) to reduce GIC currents and induced harmonics as well as improve the power grid stability [8]. These most critical locations are generally the following:

A. Generation Step-Up Units (GSUs) and First Down Stream Transformers

The modeling usually indicates the generation step-up transformer units (GSUs) which are connected to the longer transmission lines with large induction loops are the most susceptible. Therefore the geomagnetic induced currents (GICs) at GSUs are usually found to be the largest in a particular region [8]. Additionally, the first down-stream transformers on these lines will likewise experience high GIC currents. Additionally, GSU transformers are two winding transformers which means that when the GIC current in the neutral connection of the transformer is blocked by an NBD, the GIC current in that transmission line is completely eliminated in the first power grid transmission leg. Furthermore, power grid modeling of GIC currents will usually identify the GSU and first down-stream transformers as the starting place to place NBDs to improve grid stability and resiliency against GMD and EMP events. Secondly, it should also be noted that in case of a very large power blackout the recovery will most likely depend on hydro generation facilities in nearby regions of the blackout.

B. Nuclear Power Plant Generation Step-Up Units (GSUs)

A second set of important transformers that should be protected from GMD and EMP events are the GSUs at nuclear power plants. These GSUs are important for several reasons. First, they are usually large, expensive and difficult and costly to replace. And the nuclear generators are a very large contributor to our electrical power needs. For example in the USA nuclear plants typically provide 20% of our energy requirements each year.

C. HVDC Converter Transformers

A third category of important power transformers that should be protected from GMD are the large HV converter transformers located at converter stations in HVDC transmission systems. The converter stations (i.e. converting AC to DC and the DC to AC) of these systems are sensitive to induced harmonics when GMD events occur. Low level GMDs can cause large reductions in transmitted power (MVAR losses) as well as harmonics. Large GMDs can damage not only the converter transformers themselves but also the converter modules of these systems. By installing NBDs at both ends of these HVDC lines, GIC currents and harmonics can be avoided to ensure a robust, reliable and high capacity transmission system. Converter transformers are similar to GSUs since they are two winding transformers which means that when neutral GIC current is blocked by an NBD, the transformer GIC current is completely eliminated.

GMD Induced Harmonic Studies

Geomagnetic Disturbances (GMDs) are known to cause GIC induce voltage harmonics in HV transformers which can cause damage to power system components. Recent published papers 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) [10, 11]. Power grid measurements as well as modeling studies show that induced GICs currents as low as 4 to 5 Amps/phase can result in THVD levels that exceed the IEEE 519 standards [10, 11]. And in a recent important breakthrough paper on harmonic modeling in power systems results show that induced harmonics at generation and at HV transmission stations can result in ever increasing large THD harmonic levels as they are propagated downstream to lower voltage transmission systems and approach the load [12]. This finding is most likely a critical link which relates annual low level GMD disturbances to customer equipment damage and business interruption claims.

It should be noted that the newly announced NERC GMD Power Grid Study, June 13, 2018, now includes a study task on the impacts of GMD induced Harmonics [13].

Insurance Studies of Losses Related to GMD Events

The presence of ongoing low-level solar storms each year that produce GICs which invade the power grid and generate harmonics has been statistically correlated to electrical power customer equipment damage and business losses. Insurance studies published in 2014 and 2015 show there is significant negative impact to electrical equipment each year which can be statistically attributed to these common low-level solar storm effects [14].

Recent EMP Commission Report Sites Large EMP E3 Heave Wave (85 V/ km)

The EMP Commission reports of 2004 and 2008 have warned that the USA was not prepared nor protected against a nuclear EMP threat [15]. In May of 2018 an updated EMP Commission report disclosed previously classified EMP E3 “Heave Wave” threat information [16]. This new EMP E3 field of 85 V/km, recently declassified by the U.S. Department of Defense (DoD), indicates a threat level which is about 3.5 times larger than the assumed field sited in a recent EPRI paper which examined E3 induced power grid voltage collapse for a number of target locations within the US 48 states [17]. These modeling results showed voltage collapse for 5 to 7 locations out of total of eleven (11) target locations examined for an E3 field of 24 V/km. These voltage collapse results will obviously be more drastic when this newly released 85 V/km E3 field is applied in future modeling studies. Furthermore, today’s modern nuclear devices may produce even higher E3 heave levels than those recorded in Soviet tests back in 1962 upon which the 85V/km is based [16].

It should also be noted that the highest GIC currents are typically found on the longest and highest voltage lines which have the lowest resistance and largest area induction loops. This indicates the most vulnerable power equipment will be the large HV generator step up transformers (GSUs), the HV power generators, and the first downstream step down transformers as shown in the power grid modeling results in an earlier section of this paper.

SolidGround™ Neutral Blocking Device (NBD) Design with EMP Upgrade

A photo of the installed SolidGround™ neutral blocking device is shown in Figure 3 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.

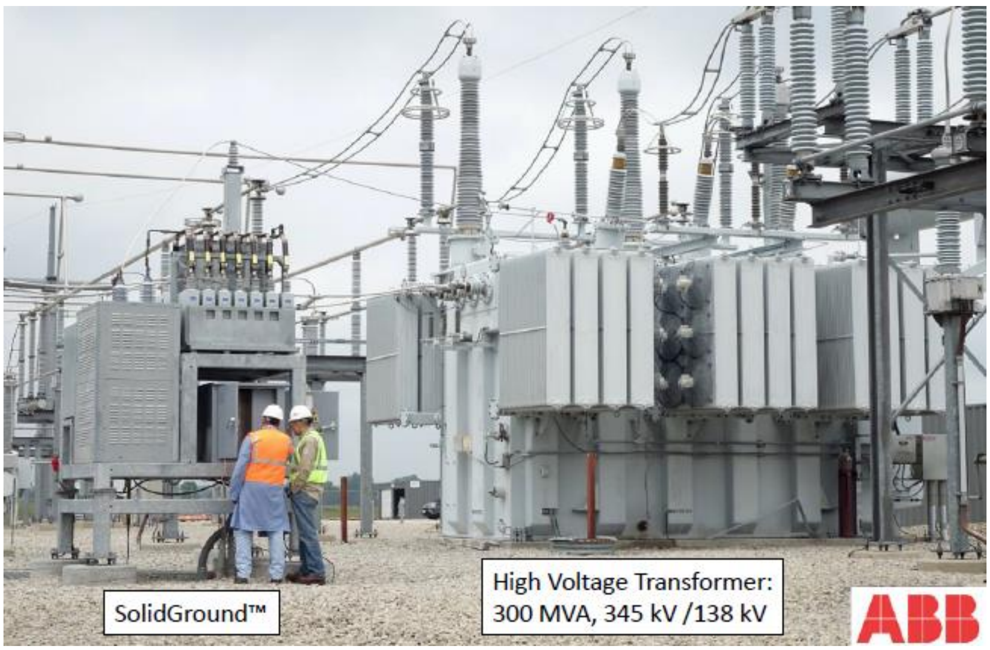

Figure 3: SolidGround™ Neutral Blocking Device Installed and Operational in Wisconsin.

Electrical Design – The SolidGround™ NBD is fully automated (with manual overrides) and continuously maintains a grounded neutral with three parallel paths for current to flow from the transformer neutral to ground. These are:

1. a solidly grounded metallic path through an AC breaker in series with a DC breaker,
2. a GIC/EMP blocking path consisting of a low AC impedance capacitor bank (less than 4 ohms) in series with a power resistor, and
3. an overvoltage protective path consisting of DuraGap™ (robust, static device comprised of three parallel spark gaps for dual redundancy)

   It should be noted that the neutral of the transformer is connected directly to the three independent parallel paths to ground to ensure a highly reliability grounding protection system. Two of these three grounding paths are hard wired without breakers which eliminates the risk of losing the transformer grounding connection.

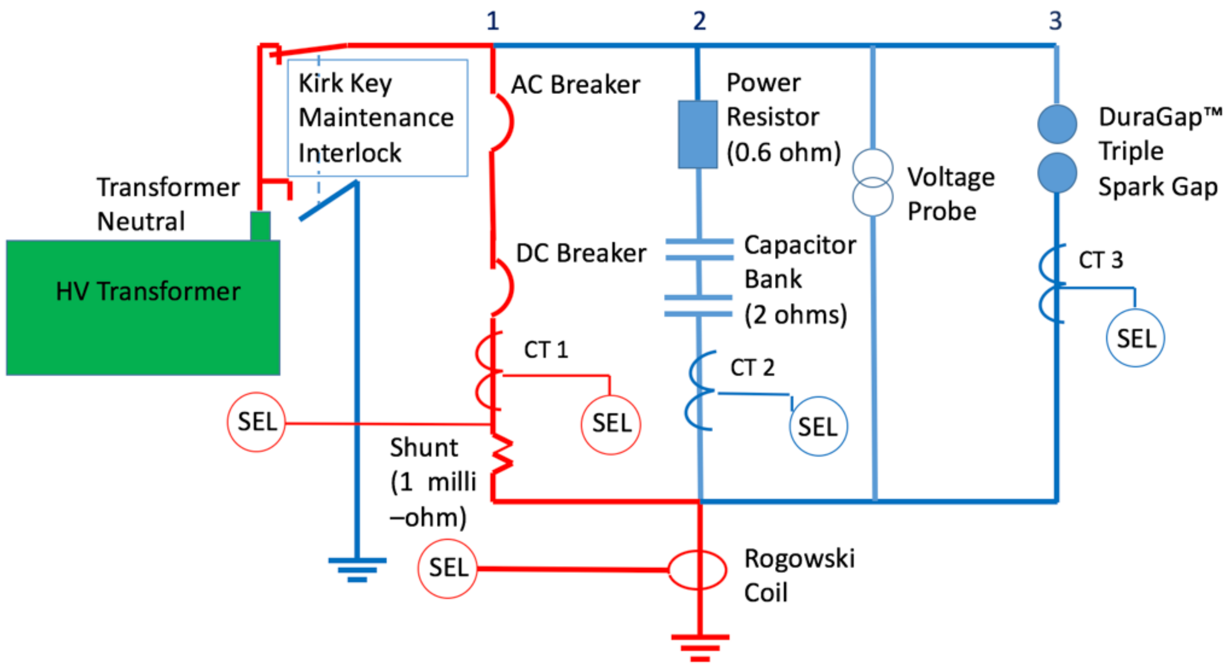

Figure 4: EMP Protected Neutral Blocking Device (SolidGround™) Circuit Diagram

The circuit diagram for the SolidGround™ NBD previously described in the MIPSYCON paper of November 7, 2017 [8] has been revised to include two (2) banks of capacitors to meet the high DC voltage associated with the EMP E3 induction threat. This duel bank of capacitors is shown in Figure 4 as connected in series to protect up to 8 kV DC continuous stand-off voltage (80 V/km on 100 km line). Modular capacitor bank add-ons provide even further protection (>20 kV DC, >200 V/km on 100 km line) against very high E3 currents anticipated for transformers connected to longer lines. This EMP design has a considerably more robust dual redundant overvoltage triple spark gap assembly (DuraGap™) which can operate repeatable and safely to beyond fault currents of 84 kA (peak) and 30 kA (RMS).

Another new feature has been added as an option for the SolidGround™ EMP upgrade. Namely, an Electro-magnetic (EM) detector, shown in Figure 5. The patented EMP.Alert™ E1 detection and triggering device is used to sense the early E1- RF pulse (10 MHz – 150 MHz) associated with a Nuclear EMP event and automatically trigger the SolidGround™ NBD into its "blocking mode" well in advance of the late E3 pulse arriving at the Earths' surface. This provides for a reliable means of operating the SolidGround™ AC & DC breakers to switch the neutral blocking device into its protective/blocking mode well in advance (1 to 2 seconds) of the induction of the EMP-E3 currents in a power system and HV transformers. The EMP.Alert™ detector, shown in figure 5, was specifically designed and developed for this EMP E1 detection/triggering application. More information regarding this device can be found on the Emprimus LLC website [18]. In order to provide reliable protection of the grid it may become necessary to incorporate an array of EMP detectors within a given state or multi-state area to ensure the detection of a nuclear event from which numerous neutral blocking devices can be triggered into their protection mode of operation. In addition to this automatic operation, the SolidGround™ NBD can be placed into its continuous passive blocking mode of operation from a central utility location if a verified threat of a nuclear event has been declared.

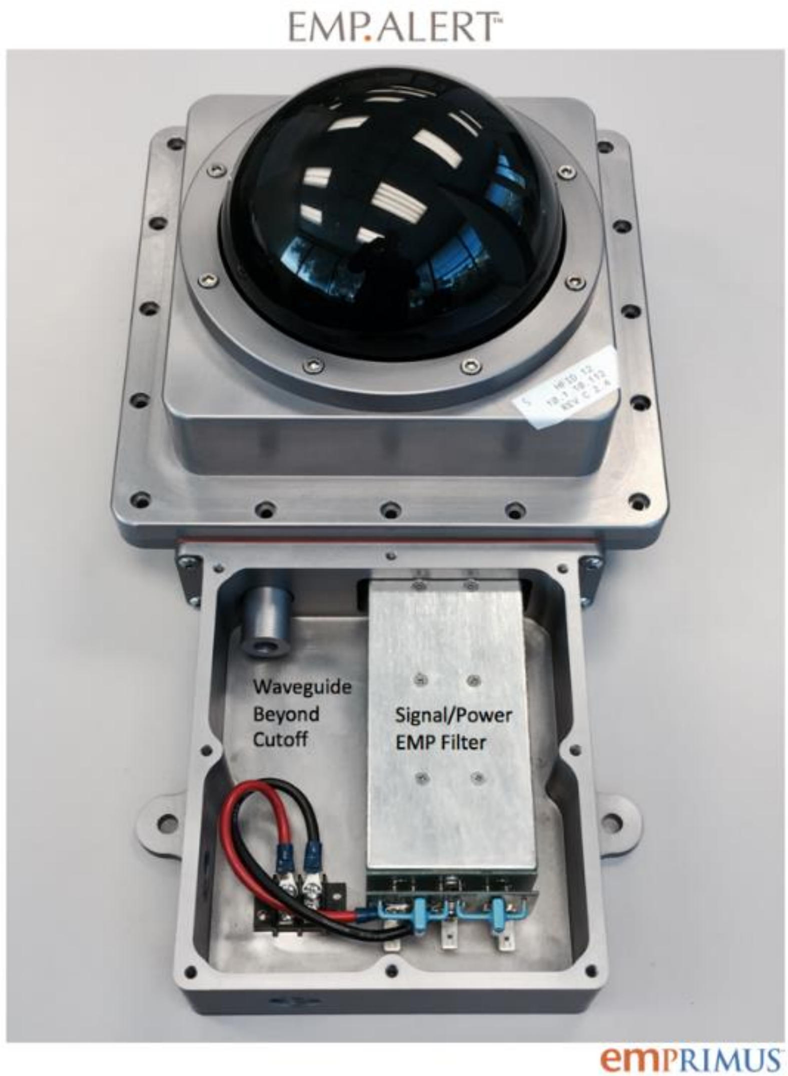

Figure 5 – EMP.Alert™ Detector for Triggering the SolidGround ™ Neutral Blocking Device into its Protection Mode of Operation, shown above with its EMP shielding and filtering of the detector electronics.

Controller Software – The software that controls the neutral blocking device has been slightly revised to provide additional monitoring capabilities (i.e. EMP E1) as well as an additional mode of operation. This new mode of operation allows the user to select a so called “passive mode”. This feature allows the user to place the NBD into continuous blocking mode 100% of the time or whenever a significant GMD or EMP event is expected. While in the passive mode SolidGround™ automatically bypasses the capacitors only when necessary such as during a ground fault.

Mechanical Design – The mechanical design of this EMP neutral blocking device remains essential the same as described in the MIPSYCON paper of November 2017 [8]. Since that time, a fully protected EMP

E1 pulse (and/or high intensity RF weapon) shielded SolidGround™ version has been designed and tested. The details of this EMP protected version will be described in a later section of this paper.

Operating Characteristics - The SolidGround™ 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 or EMPs are not impacting the earth or the specific substation. However, when GIC current, harmonics or EMP E1 are detected, the device automatically opens a breaker assembly, interrupting only the metallic AC and DC path, leaving the transformer effectively grounded through the capacitor banks as shown in Figure 4. The capacitor banks provide a two ohm AC impedance which is low enough so that relay settings on a power grid system do not require adjustment when the effective grounding path is required. This “blocking mode” will last as long as the GMD storm or EMP event continues to impact that particular substation. In the unlikely event a ground fault occurs while in 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 (DuraGap™) provides dual redundant overvoltage protection [8].

Summary of SolidGround™ Protection Operations in ATC Wisconsin Power Grid

A more detailed description of the neutral blocking operations experienced in the ATC Wisconsin Grid can be found in the November 2017 MIPSYCON Conference paper, HV Power Transformer Neutral Blocking Device (NBD) Operating Experience in Wisconsin [8]. Since the time of that published paper in November 2017 the Neutral Blocking Device has operated automatically on another six (6) occasions when GIC currents were detected at that particular transformer. A complete table of these events is shown in table I below. All totaled SolidGround™ has triggered into the GIC blocking mode more than thirty (30) times since installation in 2015 and has a perfect record of blocking GIC each and every time the GIC exceeded the preset level on the neutral of the transformer.

Table I: SolidGround™ Automatic GMD Protection Operations - February 2015 to March 2018.

Date (mm/dd/yr)	GMD Storm K-Index	Time Triggered into GIC Blocking Mode (UTC)	Duration in GIC Blocking Mode (Min.)
6/22/15	Kp = 6 - 8	18:34:00	11
"		19:51:36	10
"		20:02:12	10
"		20:17:48	10
6/23/15	Kp = 5	3:21:09	10
"	Kp = 6	3:31:17	10
"	Kp = 7	3:44:30	10
"		3:55:30	10
"		4:05:46	10
"		4:46:37	10

"	Kp = 8	5:09:58	10
"		5:20:50	10
"		5:32:02	10
"		5:51:57	10
7/19/16	Kp = 5	23:51:04	60
7/20/16	Kp = 5	1:11:32	60
3/1/17	Kp = 6	23:08:52	60
3/2/17		4:59:24	60
5/28/17	Kp = 6	3:47:00	60
7/16/17	Kp = 6	19:45:24	60
9/7/17	Kp = 6 - 8	23:01:09	60
9/8/17	Kp = 7 - 8	1:20:04	72
"	Kp = 5 - 7	12:20:18	60
"	Kp = 8	13:29:40	60
"		14:35:24	60
"	Kp = 6	15:42:44	60
11/8/17	Kp = 6	0:01:28	60
"	Kp = 6	2:37:34	60
"		3:37:56	60
2/27/18	Kp = 5	5:24:54	60
3/18/18	Kp = 6	22:43:22	60
3/19/18	Kp = 5	2:47:38	60

Note (1) SolidGround™ was initially programmed to go into GIC blocking mode ("Effectively Grounded" through capacitors) for only 10 minutes when the neutral GIC current exceeded a preset level. This was done to increase operation activity for initial testing purposes. Once all testing and experiments were done in 2015 and ATC was satisfied with the performance of the device, SolidGround™ was programmed to remain in GIC blocking mode for 60 minutes which is more consistent with GMD substorm impacts. After 60 minutes, SolidGround™ remains in GIC blocking mode only as long as the voltage on the capacitor bank remains above a preset level. If GIC drops back below the preset level, SolidGround™ automatically returns to its normal operating mode - solidly grounded.
Note (2) K-Index from NOAA (ftp.ngdc.NOAA.gov)

Automatic Protection vs Utility Operating Procedures

During the past three years SolidGround™ has been in operation in Wisconsin, the importance of an automatic protection system, rather than relying on manual operating mitigation procedures, is more clearly understood. Several specific examples are summarized below.

First it was observed that the best GMD warning systems cannot predict if, when, where or what amount of GIC a particular GMD event will create. Two identical Alerts from NOAA produce different GIC results. For example, in July of 2016 a "Kp 5, G1, 60 degrees geomagnetic latitude" GMD produced GIC at this particular substation beyond the threshold triggering SolidGround™ into the GIC Blocking Mode. The exact same alert from NOAA on December 5, 2017, a "Kp 5, G1, 60 degrees geomagnetic latitude" GMD did not produce GIC at this location sufficient to trigger SolidGround™. It was also observed numerous times that GIC was present at this substation which triggering SolidGround™ into its Blocking Mode before NOAA issued an Alert that a specific Kp/G threshold was reached.

During the past three years there have been 100's of NOAA 'Alerts' per year where a threshold of at least Kp = 5/G1 was reached. For example, there were 52 Alerts in September 2017 alone of which only 6 produced GIC at this Wisconsin substation sufficient to trigger SolidGround™ into the GIC Blocking Mode.

The SolidGround™ monitoring and operating experience has shown that automatic protection is needed and is a reliable solution for blocking GIC and preventing the generation of damaging harmonics which cause large equipment and productivity losses from common low level GMDs every year as described in a previous section of this paper [14].

And finally, automatic protection is even more important for the unpredictable variables and cascading effects associated with large GMD events. Important to note that utility operating procedures, when a large GMD event is anticipated, do not reduce the amount of GIC in the network or reduce GIC related harmonics [19]. Therefore, operating procedures do not reduce the potential for mis-operation of relays, transformer damage, generator rotor damage or customer equipment damage. GIC, wherever it arises, must instantly be detected and automatically blocked to ensure the stability and reliability of the grid. And with the threat of an EMP event, automatic protection becomes vital.

SolidGround™ Neutral Blocking Device – EMP Shielding and Filtering

The description of the EMP upgrade to the SolidGround™ transformer neutral blocking device (NBD) was presented in an earlier section of this paper. In this section the additional EMP/RF shielding and electrical filtering equipment to provide an EMP protected system is described. Below in Figure 6 is the protective cabinet for the AC breaker in the SolidGround™ electrical circuit. This cabinet has been fully tested and certified at an independent testing laboratory to meet the expected EMP RF radiation levels of a modern nuclear weapon.

Figure 6 – SolidGround™ EMP Shielded Cabinet for the neutral grounding AC Breaker electronics

Shown in Figure 7 is a second shielded and electrically filtered container designed and tested for EMP–E1/RF protection of the Schweitzer electronic controller of the SolidGround™ neutral grounding device. The filtering of the power and various signal lines is provided by a number of EMP filters as shown below in the photo (one shown). Note the back view shows a number of openings to be filled with filters for the various signal and power lines entering the cabinet. The filtering of the communications lines are provided by an Ethernet filter and a waveguide beyond cutoff which are also shown in the photo below. This container, like the cabinet above, has been fully tested and certified, at an independent testing laboratory, to meet the expected EMP RF radiation levels of a modern nuclear weapon.

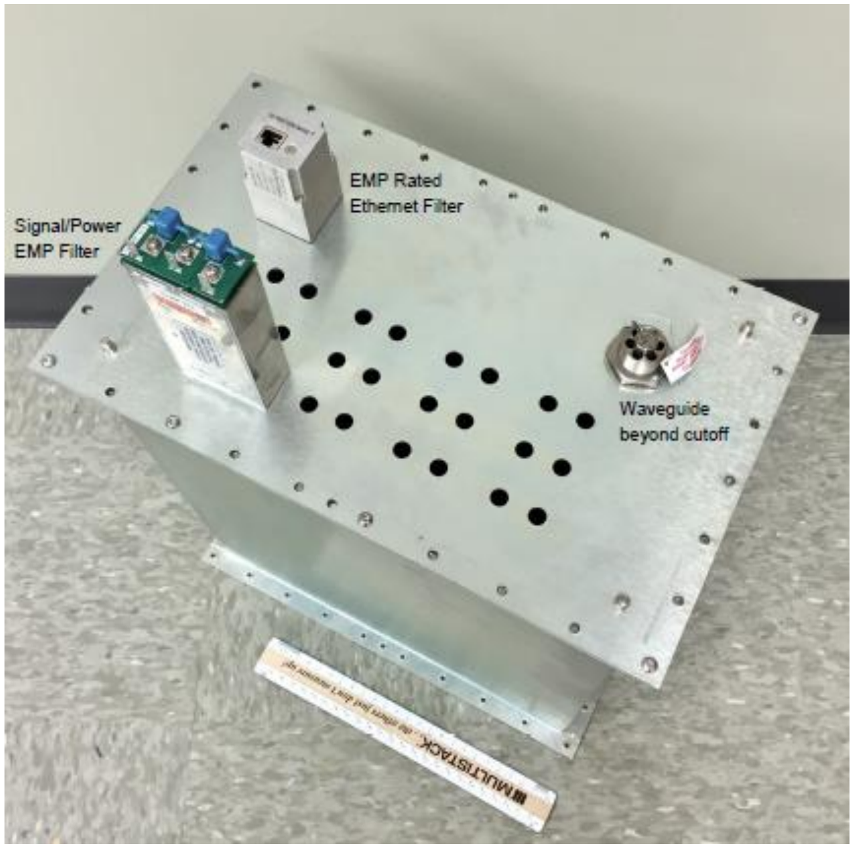

Figure 7– EMP Shielded Container for the SolidGround™ Controller Electronics (Back view)

Summary

A low-maintenance electromagnetic pulse (EMP) protected fail-safe transformer neutral blocking device (NBD) to improve power grid stability and protect against geomagnetic disturbances (GMDs) and electromagnetic pulse (EMP E3) events is described and presented in this paper. SolidGround™ was initially put into service in February 2015 and has automatically operated more than thirty (30) times blocking GIC as designed without issues during nine (9) solar storms (GMDs). The NBD operates automatically and provides several monitoring signals to the SCADA recording system. After more than three (3) years of operating history on the grid this device continues to show no signs of unintended consequences introduced into protective relays or other power system components. The device blocks GIC, prevents the generation of harmful harmonics in transformers, reduces reactive (VAR) power demand and helps prevent voltage collapse during GMD and EMP events. This paper also presents the additional EMP E1 detection, shielding and signal line filtering required for the SolidGround™ EMP upgraded version that provides an effective and low-cost solution available to the electric utility industry to protect the grid from an EMP event [9].

Acknowledgments

The production ready NBD described in this paper is a result of the input and study by many individuals and organizations. We would like to thank Randy Horton at EPRI, Luis Marti at Hydro One, Frank Koza at PJM, Russell Neal at So. Calif. Edison, Prof. Tom Overbye at PowerWorld, Chris Reinbold, Werner Hofbauer, Craig Stiegemeier, Dr. Ramsis Girgis and the rest of the ABB team, Terry Volkmann and Bill Volna for valuable suggestions. We appreciate the numerous meetings and suggestions from NERC, FERC and the following organizations: ATC, ABB, PJM, TVA, BPA, Con Edison, AEP, Dominion Energy, Southern Company, EPRI, Southern California Edison, University of Manitoba, KEMA Labs and Exelon. The support provided by Mike Rooney and Prof. George Baker at DTRA/DoD and Scott McBride is also greatly appreciated. Two individuals, who passed away recently, deserve special note. Those individuals are Dr. Arnold Vitols who worked for ABB in Mt. Pleasant, PA, and Prof. Vernon Albertson who was on the electrical engineering staff at the University of Minnesota. Their knowledge and zeal was instrumental in the development of this neutral blocking device. Finally, a special thanks to George Anderson for his passionate guidance, engineering and financial support over the last 10 years.

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