Addressing the Operational Impacts of Trapped Charge caused by islanded Inverter-Based-Generation on Medium Voltage Equipment

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***Abstract*—Utilities, generators, and other operators of medium voltage (MV) equipment are adopting plans to keep their equipment safely in service for the longest period possible. The removal of "capacitive trapped charge" in MV cables improves plant safety, availability, and reliability. In addition, the prevention or removal of "trapped space charge" also increases plant safety, availability, and reliability. The prevention and removal of both increases MV cable longevity. This paper discusses how a fast-acting bonding and grounding device with an integrated circuit breaker, such as an EMA VDH/GSMI or similar single-phase device, may remove or prevent either type of trapped charge on cables, cable accessories, and connected equipment. In addition, such a device reduces the incident energy, and reduces resulting hazards due to arc flash, electrocution, and shocks to workers.**

Islanded inverter-based generation, which is installed in solar or battery energy storage systems, including paralleled string inverters exporting power, may accelerate the aging of MV cables. Research into cable failures shows Temporary Overvoltage (TOV) induces a deep trapped space charge in cross-linked polyethylene insulation, where along with poor power quality the service life of the MV cable is reduced. This paper reviews current research on cable aging and on how a fast-acting grounding and bonding device may reduce the rate of MV cable aging if connected to islanded inverters.

Keywords—trapped charge, deep trapped charge, oxidation, grounding and bonding, fast acting grounding switch, Bulk Electric System, BES, grid following, grid forming, distribution, load rejection, relay, ride through, protection, wye, delta, ungrounded, breaker grounding, bonding, open line, overvoltage, PRC-024-2, IEEE 1547-2018, proposed IEEE P2800.

NOMENCLATURE

IDM	Island Detection Method
TOV	Temporary Overvoltage
XLPE	Cross Linked Polyethylene
HVDC	High Voltage Direct Current
HVAC	High Voltage Alternating Current
MV	Medium Voltage
LV	Low Voltage
HV	High Voltage
AC	Alternating Current
DC	Direct Current
EPC	Engineer Procure Construct
BES	Bulk Electric System
BESS	Battery Energy Storage System
NREL	National Renewable Energy Laboratory
GFO	Ground Fault Overvoltage
LRO	Load Rejection Overvoltage
EV	Electric Vehicle
GSU	Generator Step Up Transformer
ET	Electric Tree
PD	Partial Discharge
CB	Circuit Breaker
PSCAD	Dynamic Simulator (See PSCAD.com)
RLC	Resistive Inductive Capacitive
R	Resistive
C	Capacitive
DER	Distributed Energy Resources
PCC	Point of Common Coupling
PoC	Point of Connection
EPS	Electric Power System
Hi-Pot	High Potential
HVRT	High Voltage Ride Through
s	Seconds
OSHA	Occupational Safety and Health Administration

I. INTRODUCTION

Utilities and other operators of medium voltage (**MV**) equipment are adopting plans to run their equipment until failure or to make it safely last as long as they can. This paper discusses the removal of capacitive trapped charge in **MV** cables to improve plant safety and reliability and the prevention or removal of trapped space charge to increase cable longevity.

This paper provides background on inverter-based generation and explains how bonding and grounding devices is projected to extend the life of **MV** cables and cable accessories by quickly shutting down inverter islands while the inverter is exporting power, thereby reducing dielectric stress. Trapped charge studies usually discuss or include a separated cable between two open switches or circuit breakers with a residual charge, resulting in unsafe voltage. If the cable remains in this state, a direct current (**DC**) charge may persist for days **[1], [17].** A grounding and bonding device that bonds the sheath of the **MV** cable to the inner conductor would prove beneficial and would improve safety because it would discharge the capacitive trapped charge from the cable.

However, in addition to the "capacitive charge," there is another type of trapped charge called the "space charge" or the "deep trapped charge" that can exist in defects, voids, or electric trees (**ETs**) within the cross-linked polyethylene (**XLPE**) insulation of **MV** cables. This paper also explores the benefits of installing a fast-acting grounding or bonding device on an **MV** power system to determine whether a grounding and bonding device would be beneficial for the safety, reliability, and longevity of the power system in terms of the accelerated aging of **XLPE** insulation in **MV** cables connected to inverter-based power systems when an inverter or string of inverters is islanded **[3]**.

The insulation operating conditions of **MV** cables can be severe, and inverter island detection methods (**IDMs)** can delay shut down, thereby producing higher than fundamental frequency temporary overvoltages (**TOVs)** and stressing the cable's insulation. An **MV** cable fault can take the entire system out of service. Regarding the "trapped space charge" and "**ETs**", the reason to study the **ETs** in the insulation is to determine how **ETs** relate to dielectric breakdown with **TOV** in mind. According to the literature, "*The dielectric breakdown in such insulation, such as polymers and synthetic resins, used in electrical equipment insulation systems such as cables, circuit breakers and bushings, is due to the appearance of electrical trees…. Therefore, it is necessary to study the behavior of electrical trees in solid dielectrics in order to understand the phenomenon and predict the useful lifetimes, or in other words, the time to breakdown*" **[2]**.

Concerning island inverters that attempt to export their power when disconnected from their power systems, some sources report that high frequency **TOVs** are observed. For example, in his 2015 **NREL** report Hoke states:

"*When a single line to ground fault occurs, the fault often causes an upstream breaker or recloser to open, isolating the faulted part of the circuit from the rest of the grid. If there is distributed generation in the isolated (islanded) section, the generation will briefly power any load within the island until the generator's controller recognizes the island and ceases power exportation. This can result in **TOV** via two mechanisms, mentioned above. The mechanism of primary concern to this report is **GFO**, in which a three-wire generator can cause a zero-sequence voltage to appear when feeding a four-wire circuit during a single phase to ground fault. The second **TOV** mechanism, **LRO**, occurs if the generation to load ratio within the island is greater than unity*" [**4**].

Such overvoltages are clamped by surge protection. In addition, new cables do not have enough defects to fail. Therefore, installations commissioned with the bugs worked out run problem-free; however, as the installation ages, operators see that both the surge protection device becomes less effective and that cables age. The surge protection does not clamp the voltages as well as in the past, and defects in the insulation of the **MV** cable increase. Over time, **ETs** will eventually exceed insulative capability, and the cables will fail. With the above in mind, the question is "How long until failure, and what can be done to slow the aging of the cable, cable accessories, and connected equipment?"

Reports provide over the entire length of several feeder circuits, which includes customer equipment; when the feeder is exposed to several load rejection overvoltage events, over a 3 year time window, at 32 sites totaling 131 events presented fundamental overvoltage lasting 1 to 6 cycles with peak voltages clamped by an overburdened arrestor up to 1.59 pu. [4].

With the above reference in mind, the inverter voltage appears as clamped by surge arrestors, and high-frequency ringing in the voltage signal is also observed **[4]**. As systems age, some surge arrestors fail, are removed, and are sometimes not replaced, or more generally, the aging power system becomes less effective at clamping the surge and impulse voltages **[5].**

Consequently, arrestors allow higher overvoltages for the given amount of islanded power. This allows the island voltages to increase, which damages the insulation. Dielectric strength is reduced due to **ETs**, which decreases the insulative capability of the **XLPE**. Therefore, the **MV** cables will eventually fail. Transmission and distribution planners and engineer procure construct (**EPC**) specialists designing and constructing plants, including battery energy storage systems (**BESSs**), conduct technical reviews about protection requirements for interconnection. Some have concluded that it is more beneficial to use a reliable anti-islanding device, such as a fast-acting grounding switch integrated with a circuit breaker (e.g., an EMA VDH/GSMI or other very similar product).

Measurement results show that, the overvoltage has a disturbing effect on the performance underground power cable where reports provide power system frequency overvoltages has a disturbing effect on under ground cables and significantly insulation loss [34].

Given the plausibility that islanded inverter generation may accelerate the aging of the electric power system. Engineers and planners should review the benefits of adding a fast-acting bonding and grounding switch to existing circuit breakers, keeping the following questions in mind:

a. Does the discharge of an ordinary trapped charge solve the problem of removing a deep trapped charge in the insulation of the **MV** cable?

b. Does adding a fast-acting grounding switch supplement the operation of a typical **MV** circuit breaker and also supplement state-of-the-art island detection methods for one or multiple string inverters?

c. With inverter-based-resources (**IBRs**) and **IDMs**, does a fast-acting grounding device reduce the formation of a deep trapped charge over time and improve the service life of cables and equipment?

d. Does a fast-acting grounding switch make insulation coordination studies more predictable?

II. Background

There is a need for better insulation coordination for solar plants, **BESSs**, hybrids, etc., relating to the discharge of a trapped capacitive and space charge. References herein provide space charges may be discharged by heating the insulation of **MV** cables; however, this approach is not easily implemented; where a better approach is to install a fast-acting bonding and grounding device which may preemptively prevent or slow the formation of ET and deep trapped space charge. The sources cited herein discuss how the removal of a trapped space charge may be accelerated by heating the cable's insulation. **However, heating MV cables may be impractical and may also accelerate the aging of the cable.** Instead, this paper relates how new ideas, such as having circuit breakers coupled with a fast-acting grounding and bonding switch, can work with state-of-the-art **IDMs** for inverter-based generation, such as in solar and wind plant **BESSs** and hybrids. Such support also includes high voltage (**HV**), **MV**, and low voltage (**LV**) cable insulation in transmission and distributions systems (single- or three-phase), including but not limited to the charging and discharging of electric vehicles (**EV**s) via **EV** bi-directional chargers. All the above techniques together can possibly prolong the service life of insulation and connected equipment enduring the stress caused by inverter-based generation.

Sources provide inverter-based-generation, such as solar plant's, **BESS's, or hybrid's [6], [7], [14] accelerate the aging of MV** power cables and equipment, resulting in less effective insulation throughout their service life. Typically, **MV** circuit breakers open under power when islanded generating inverters export their power. Without a fast bonding and grounding device, inverters may not shut down fast enough. The result is long-term **TOVs**, where anti-**IDMs** may delay shutdown for 40–200 ms and up to 2 s. Concerning distributed energy resources (**DERs**), IEEE 1547 states "*For an unintentional island in which the **DER** energizes a portion of the Area [electric power system] **EPS** through the [point of common coupling] **PCC**, the **DER** shall detect the island, cease to energize the Area **EPS**, and trip within 2 **s** of the formation of an island (see IEEE 1547 (2018) Sec. 8.1 Unintentional Islanding*." This is too long, comparatively, a fast grounding and bonding device can shut down an island in 12 ms [11], thus better protecting the inverters.

The long-term **TOV** results in accelerated aging and damaged or destroyed surge protection and insulation. In other words, increasingly higher voltage spikes and increasingly weaker insulation eventually cause a cable fault or a fault in expensive equipment, such as a generator step-up transformer (**GSU**) **[8], [9]**.

A. Several Causes of Insulation Failures other than Inverter Islanded Temporary Overvoltages

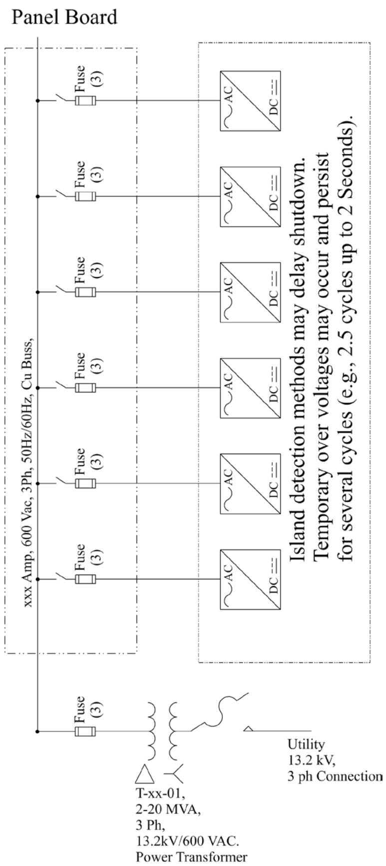
Reports on insulation failure state that given the increasing asset age of the **MV** distribution network, more failures are being observed **[10].** This type of degradation is common to all types of polymeric insulation, including polyethylene, ethylene-propylene, rubber, and butyl rubber **[13]**, **[14]**. As stated in the literature, "*Despite significant advances in modern technology for assessing the condition of power grids, the reliability of MV power connections is a global problem due to frequent failures*." **[13]**. As one report states, "*While the evolution in cable construction, materials, and manufacturing processes intended to produce continual increases in reliability with associated reductions in total cost of ownership, the process did not always yield the expected results*" **[12]**. However, such reports do not explicitly state **TOV**s are caused by inverter islanding and exporting power. As an example of evolving **EPSs** with bidirectional inverter power flows, bulk electric system (**BES)** hybrid vehicle-solar-grid (VSG) integrations use the batteries of **EVs** in conjunction with the inverters and net metering connections of solar photovoltaic (**PV**) systems at night when **PV** systems are unused to provide ancillary services to the grid to earn a financial return that can serve as an incentive for ownership of **EVs** and **PV** systems **[29], including both three-phase and single-phase systems.**

B. IBR Delayed Shutdown

IDMs may delay inverter shutdown. For string inverters (see Fig. 1), the time can range from several cycles or approximately 40 ms up to 120 cycles or approximately 2 s.

Over the years, manufactures have introduced several **IDMs**. However, each has their own detection time, and ride-through requirements may delay such detection methods in shutting down the inverter.

During islanding, both **LV** surge arrestors (usually installed internally in each string inverter) and **MV** external surge arrestors work together to clamp the **TOVs** on islanded **EPSs**. **If the surge protectors are maintained and the island energy or power that dissipates or is conducted through the surge protective devices is within the specified duty of each arrestor, such surge protection is projected to protect components connected to the EPS. However, there is a likelihood that inverters will island several times per year. This may age both internal and external surge protection, and over time the clamping capability of the affected surge protection may be less than what the EPC engineers had anticipated.** The sources cited herein suggest the increasing voltage spikes will weaken the insulation over time. **Table 1** provides some details about reports from NREL concerning several inverter manufacturers. The reports indicate **IDMs** are programmed on string inverters **[30]**, **[31]**, **[32]** (Fig. 1) and relates them to the probability that the island detection on each inverter will delay shutdown due to interconnection operating specifications. Each **IDM** needs time to determine if the inverter on the faulted **EPS** should remain on-line. This delay can cause unwanted **TOVs** if the islanded inverter is generating near-maximum power.



Interconnection Diagram
Solar String Inverter
without grounding
& bonding device.

Fig. 1

C. *Accelerated Aging*

Reports indicate that after 10,000 impulses, **XLPE** insulation shows dramatic deterioration and **ET** formation **[14]**. However, an inverter is much more powerful than the lab equipment used by Cao, et al. [14]. Concerning **HVRT**, if extrapolated to inverter generator operation, each islanded inverter exporting power is allowed up to (60 Hz*2 pulses per cycle *2 sec=240 pulses) 240 pulses per a long HVRT island event; where the number of islands needed to exceed 10,000 pulses is likely less than 41; where given high power, poor power quality during an island, the number of TOV events is projected to be much less if there are a string of inverters connected to the same cable. As an example, Sandia [33] reports in the year 2018, **1227 inverter failures or faults of which 109 events are grid related**. While Sandia did not track island events or **GFOs**, where 5% are grid related (Fig. 2); the significant number of events at least warrant investigation to see if a fast-acting grounding and bonding device would reduce the number of failures [33].

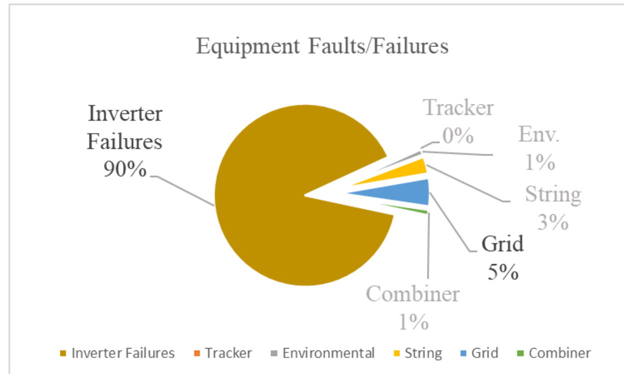


Fig. 2

However, considering that **IDMs** may prevent long- term islanding, the energy and power in the pulses in a real-world island event are much larger, and research suggests the degradation of insulation would take less time, which is not good. This agrees with the presumption that installations will initially perform well, however if allowed to island without protection such a plant may not realize the service life expected. This report explores techniques to extend the service life of the **MV** cable. Generally, temperature and poor power quality act to accelerate aging of insulation. Reports also indicate that at elevated temperatures from 50° Celsius to 90° Celsius **ETs** form in **XLPE** cable insulation within a range of voltage between 9 kV and 18 kV. Partial discharge (**PD**) activity is monitored simultaneously. Researchers have also found that temperature and voltage level have a pronounced effect on the process of **ET** formation. An important finding is higher temperatures result in reduced "initiation" of **ETs, however, if ETs are pre-existing, they may grow faster.** As expected, the injection current increases at high voltage levels. However, the most important takeaway from the research is impulse magnitude and the number of pulses appear to accelerate the aging of **XLPE** cables **[14].**

Table 1

String Inverter Supplier	**Power [kW]**	**Island detection methods?**	**Can IDM delay shutdown? e.g., < 2.5 cycles (40 ms) to 120 cycles (2 s)**	**Can temporary overvoltage exist during islanding?**
NREL[2], Sungrow [30]	125	Yes	Yes	Yes
NREL[2], Huewei [30]	45	Yes	Yes	Yes
See [31], [32] Notes 1 & 2.	Varies	Yes	Yes	Yes

1. See NREL report on inverters [30],[31],[32]: Apparent Inc., Enphase Energy, SolarEdge Technologies, and SMA.
2. NREL National Renewable Electric Laboratory

D. Pure DC Voltage and Treeing in XLPE MV Cables

Table 2

Sources report electric tree (ET) inception at continuous pure direct current (DC) voltages (Source [15])		
Voltage Level kV	Positive DC	Negative DC
	Percentage of Samples in which **ET**s Initiated (%)	Percentage of Samples in which **ET**s Initiated (%)
25	0	0
22	20	0
28	20	0

In testing **DC** voltages **[15]** and given the information in Table 2, the results show pure DC voltages, where 20% of the samples-initiated **ETs** for a purely positive **DC** voltage. However, experimental results concerning **PD** are different when superimposed with characteristic harmonics on **PD** activity and **ETs** (see Fig. 3) within **DC XLPE** dielectric test samples. Generally, **ETs** and the activity of the associated **PDs** depend on the wave shape and harmonic contents. The possibility of **ET** inception is higher in the case of **DC** voltage, suggesting that a dynamic electric field increases the stress in **XLPE** insulation, and **PDs** and **ETs** are among the major insulation-degrading phenomena that can lead to power cable breakdown **[15].**

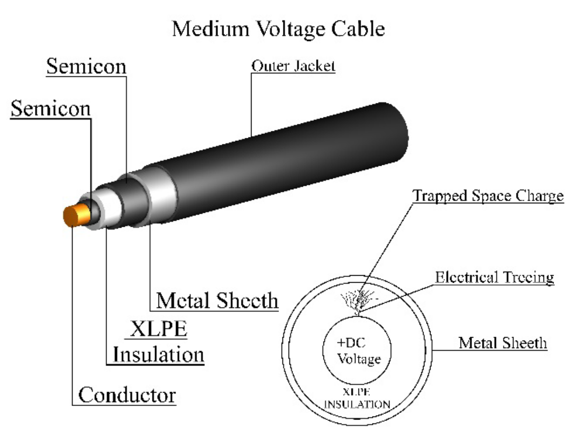


Fig. 3

E. Insulation Failure and Inverter Islanding

Generally, **GSU** transformers have paper insulation or more expensive and reliable epoxy resin. The marks of transformer quality are reliability, consistent performance, and a long service life. In engineering terms, this means it can handle the heat, has the required dielectric strength, and can withstand short circuits. During inverter-based generation in **BESS** and wind, solar, or hybrid plants connected to a **GSU** transformer, an inverter generator exports power. From time to time, a circuit breaker located on the high side of the transformer connected to the inverter opens while the inverter is running (sometimes the remote trip or the "shut down signal" is delayed). Generally, during the resulting island the inverter power quality is poor, is impulsive, exceeds specified insulation levels, and can take up to 2 s to shut down. While islanding and depending on arrester strength, the voltages may exceed the declining dielectric strength of the equipment, such as the **GSU** or **MV** cable insulation, causing them to fail before their presumed 30-year service life.

F. Space Charge, Trapped Charge, AC and DC ETs

Concerning charge detrapping, [**16] and [27]** provide space charge measurements under **DC** fields with periodically grounded **DC** tree experiments (*i.e., the sample was pre-stressed under a constant* ***DC*** *voltage for a while and then grounded for a short time*) of a sample to initiate the **ET** and to promote its growth. The apparatus used to remove the trapped charge in the laboratory is like a fast-acting grounding and bonding device. The experiment carried out demonstrated that there is a correlation with the effect of temperature on space charge detrapping and the grounding of a **DC** tree in **XLPE** (see Fig. 4). As stated in the literature: "*From the experimental results and discussions presented above, the following conclusions can be drawn. (1) The apparent trap-controlled mobility of space charge becomes larger, and its decay rate becomes smaller in the initial phases of depolarization with the increase of temperature. These outcomes indicate that charge detrapping becomes easier at a higher temperature*" (Fig. 4). **However, keeping the cable from getting too hot during operation is the accepted practice. The example in Fig. 4 is provided to show a deep trapped charge may have lower mobility at cooler temperatures and adding a fast grounding and bonding device is a better solution to reduce overall stress, which may result in a reduction in accelerated aging of the MV cable.**

Another industry example illustrating the problem of a residual space charge is negative charges caused by **DC** high potential (hi-pot) in the cable. Once the **AC MV** cable is energized, charge carriers in the defect locations become **polarized and create an area of high stress, and the MV cable fails**. The defects in the MV cable's insulation are called "trapped space charges" because following the DC hi-pot testing, such locations in the insulation and the affected charge carriers do not have the mobility to move and dissipate throughout the cable **[16], [17], [27].**

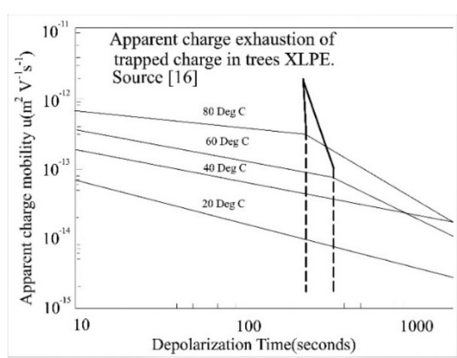


Fig. 4

Note: The trapped charge in an AC system while the circuit breaker is open, and the inverters are shut down is like a DC source or potential. Research on "DC" charge may provide insight into the dielectric stresses in isolated AC cables [16],[27].

With the trapped charge tree experiment in mind, a fast grounding and bonding device is as effective as an "anti-trapping device" or a "detrapping device" to either remove the trapped charge or to prevent a deep trap in the first place. For example, concerning a trapped charge in **ETs** in cables and with the inverter-related **TOV** in mind, a fast-grounding and bonding device such as an EMA VDH/GSMI helps by preventing **TOV** injection of a deep trapped charge in the first place. Studies on the Weibull distribution show that a higher applied voltage enhances the rate of tree propagation, thereby reducing the life of cable insulation [**18**], whereas the device in **[11]** would both prevent the stress or slow the aging of the cable.

It has been said that **ETs** in insulation are caused by the partial breakdown of polymers due to the strongly divergent electric field. **ETs** in insulation materials are directly related to cable failure. The **ET** growth process can be generally described based on the three stages—the initiation, propagation, and runaway stages [19]. The application of **DC** voltage to **XLPE** insulation leads to space charge formation due to the dielectric polarization and relaxation phenomenon. A space charge is generally formed due to the imbalanced injection and extraction of the charge carriers (electrons) at the anode and the cathode. In **AC** systems, a **DC** charge—either positive or negative—may be injected into the **ETs** or defects and remain after de-energization, where with bonding strength in mind, charge carriers will exhibit different conduction values due to various mobilities.

A deep trapped charge may not dissipate as fast as a capacitive charge measured in a dissipation test (e.g., Tan theta). For example, an **HV** coil on a polyphase transformer changes polarity and causes repeated **TOV** stress on the trapped charge in the **ET** in the winding or cable's insulation, where the deep trapped charge readily flows and heats. According to **[28],** "*DC voltage application leads to the flow of current due to polarisation (i.e. polarisation current) of the insulation. When the DC supply is switched-off and insulation is shortcircuited, depolarisation current flows. The difference between polarisation and depolarisation currents is called as conduction (or absorption or leakage) current, which is directly proportional to the conductivity. Higher the conduction current more will be the conductivity and more likely is the degradation of insulation. Space charge and conduction current existence causes it's aging and reduces the time to breakdown"[**internal references within [28] omitted, & cited reference is without using the common spelling of depolarization**]*

G. Isolated Cables and Trapped Charge

A suggested experiment beyond the scope of this paper is to bond both sides of an **MV** cable and inject current, where flowing charge traverses the length of the cable, where charge flows in and out of the cable to "sweep up the deep trapped charge" or space charge faster. If only one side of an **MV** cable is electrically connected to its sheath, a path is provided to charge and discharge the cable. However, the charge carriers only go back and forth and charge like a capacitor, rather than traversing the length of the cable. The purpose of the test is to determine if flowing charge through the entire length of the cable is better at reducing internal dielectric stress in cable insulation.

Concerning a power system dynamic simulator **PSCAD™** a simulation *provided later in this paper* and to illustrate the persistence of a trapped charge and with the preceding in mind, a significant scenario is given, as follows. An **MV** cable is connected to either an ungrounded or a grounded **MV** winding of a **GSU**, where the proposed sequence of events are as follows. First, the **MV** cable experiences a near simultaneous fuse opening at the **MV** bushing of the **GSU,** and on the other side of the **MV** cable a circuit breaker opens (and does not provide a shorting path for the conductors). Second, the string of inverters export near-maximum power through the step-up transformer, causing a **TOV** on the **MV** cable. Third, the circuit breaker opens, and a very short time later the fuse opens, where one of the phases is near or at the top of the voltage wave on the **HV** winding of the transformer. Fourth, not simulated but taken into account is that the **MV** cable has existing **ET** defects in the **XLPE** insulation, and the charge of a given polarity remains trapped in this **MV** cable's insulation in the **ET**. Fifth, a short time later the operator closes the breaker at the peak of the wave of the opposite polarity, where the dielectric stress in the **ET** is now at the extreme, thereby increasing the likelihood of a cable failure.

Also, in the PSCAD simulation, if a grounding switch is provided, a shorting path is established for the cable conductors to significantly decrease the depolarizing current's charge time and decrease the dielectric stress in the **MV** cable's insulation with defects. The next scenario repeats this; however, a fast-acting grounding and bonding device is added, and the simulation is repeated.

Please keep in mind the references cited herein usually use a power supply in testing that is much smaller than an inverter moving a charge via the MV winding of the 2 MVA step-up transformer.

The application of **DC** voltage to **XLPE** insulation leads to space charge formation due to the dielectric polarization and relaxation phenomenon. A space charge is generally formed due to the imbalanced injection and extraction of the charge carriers (electrons) at the anode and the cathode. [**21**]. Consider the "string inverters" and the step-up transformers as the injectors of imbalanced charge carriers. In sources **[16]** and **[27]**, periodic grounded DC tree experiments were performed at 20 °C, 40 °C, 60 °C, and 80 °C, respectively, using periodic pre-stressing and grounding. The sample was subjected to a constant **DC** voltage for 160 s and then grounded for 2 s, a cycle that is repeated 15 times. For **MV AC** cables, the charge may persist for longer than 160 s or 2 min 40 s when a cable conductor is separated and when each end is open at the same time. When protective devices open and isolate cables, successive restrikes may occur, which equalizes the potential between the load and the supposedly de-energized side or cable [**22**].

H. Calculating DC Isolated Cable (Capacitive) Trapped Charge

A common mechanism responsible for trapped charge accumulation is cable isolation after a restrike (see Fig. 5), which, without a significant discharge path, may remain on the cable for a period of hours or even days [**23**].

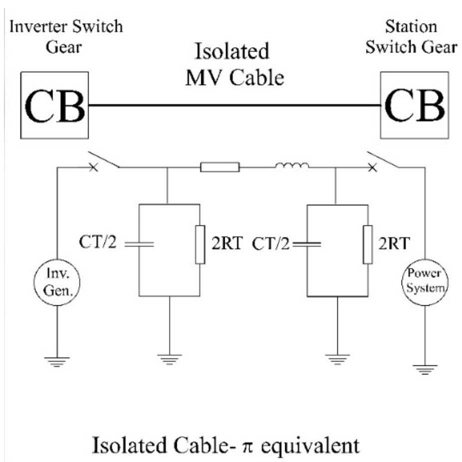


Fig. 5

Therefore, the case is the following: the initial conditions are 140% AC rated and that "peak" voltage is the value included in this calculation with an optimistic crest factor of $\sqrt{2}$ on the islanded **MV** cable and the switch.

$$V_{peak} = \sqrt{2} \cdot 1.4(Arrester\ Clamped\ TOV) \cdot V_{AC\ Rated} \ (1)$$

The cable insulation resistance (**R**) and cable insulation capacitance (**C**) are shown in Table 3. The **RC** time constant is represented by the following expressions in equations 1 through 5. The calculation of the **RC** time constant is illustrated in the Figure 6 **[23].**

$$R = K \cdot log\left(\frac{D}{d}\right) \cdot \left(\frac{1}{L}\right) \cdot \left(\frac{1}{n}\right) \qquad (2)$$

$$C = 7.35 \cdot \left(SIC/log\left(\frac{D}{d}\right)\right) \cdot L \cdot n \ \ (3)$$

During TOV, if both circuit breakers are tripped simultaneously or if there is a restrike at the time when one of the three phase voltages is at its peak amplitude and the cable is isolated, the initial peak capacitance charged voltage (phase-ground) due to an isolated trapped charge on a disconnected and isolated **MV** cable is calculated with a crest factor of 1 as follows, keeping in mind 1.4 is the projected TOV:

$$V_{peak} = 1.4(TOV) * \frac{\sqrt{2 * 34500}}{\sqrt{3}}. \qquad (4)$$

The equation used to predict the voltage over time is given in equation 4 and is shown in the figure 6 and the **RC** time constant in equation 7; the calculated time constant τ is 158 s (see Fig. 6).

Table 3

Cable Description	**1000 MCM**	**350 MCM**	**Cable 2/0**	**Unit**
Diameter Over Insulation (D)	1.9770	1.5020	1.2530	inch
Diameter Under Insulation (d)	1.0600	0.6160	0.3760	inch
Cable Length (L)	500	500	500	feet
Parallel Cables (n)	1	1	1	N/A
Volume Resistivity (Rho) (K)	1.0000E+13	1.0000E+13	1.0000E+13	Ohms - meter
Dielectric Constant (SIC)	2.15	2.15	2.15	N/A
Calculated Resistance	5.4140E+12	7.7418E+12	1.0455E+13	Ohms
Calculated Capacitance	2.9188E+04	2.0412E+04	1.5114E+04	Pico farads
RC Constant	158	158	158	s

Sources: Southwire, Okonite Company; Abdallah Hedi, conférence de la Société Française d'Electrostatique, Degradation Mechanisms of Cross-linked Polyethylene Insulation by Thermal and Electrical Aging, 2018

$$V(t) = V_{peek} \cdot e^{\frac{-t}{R*C}} \qquad (5)$$

$$\tau = R \cdot C \qquad (6)$$

However, source [**24**] shows there are other factors that increase **R**, such as the change in rho increasing by a factor of 10 as **XLPE** ages. In this case, the **RC** time constant would be 1580 s. If there are any hidden circuits to ground, such as loads or measuring devices, this will decrease R, and the discharge of the **MV** cable is much faster.

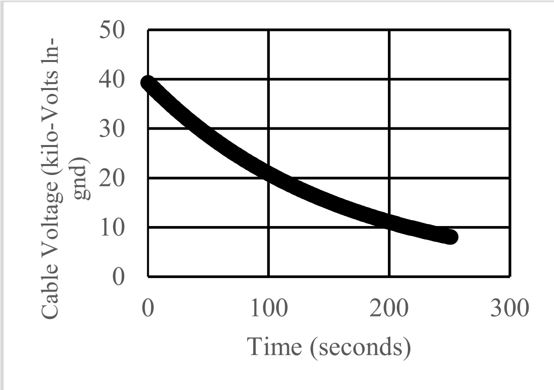


Fig. 6

Figure 6 shows the projected discharge time of an isolated **MV** cable where aging or other external factors could change the discharge time. However, if a fast bonding and grounding device is installed on the power system and on the cable and is operated with a circuit breaker, the discharge would be in the milliseconds, and the removal of the **DC** charge would make the power system safer.

I. *PSCAD Simulation DC Trapped Charge Breaker Only*

A PSCAD simulation (see Fig. 7) was performed to illustrate the problem of a trapped DC charge. The RC time constant is lower, so the cable discharges faster to illustrate the discharging of the cable. The **PSCAD** model uses an inverter generator exporting power on a 34.5 kV system. In this case, a circuit breaker is used to replace a **GSU** fuse. A 500-foot 34.5 **MV** cable is modeled with a frequency dependent (phase) model, which is basically a distributed **RLC** traveling wave model that incorporates the frequency dependence of various parameters. This model represents the frequency dependence of internal transformation matrices in **PSCAD**. The cable spacing is set at approximately 7 inches, and the sheath is used as a return.

The simulation sequence of events is accelerated to illustrate the effect of a DC trapped charge. The sequence could happen over minutes to hours, depending on how long an operator cycles the breaker while trying to determine what failed.

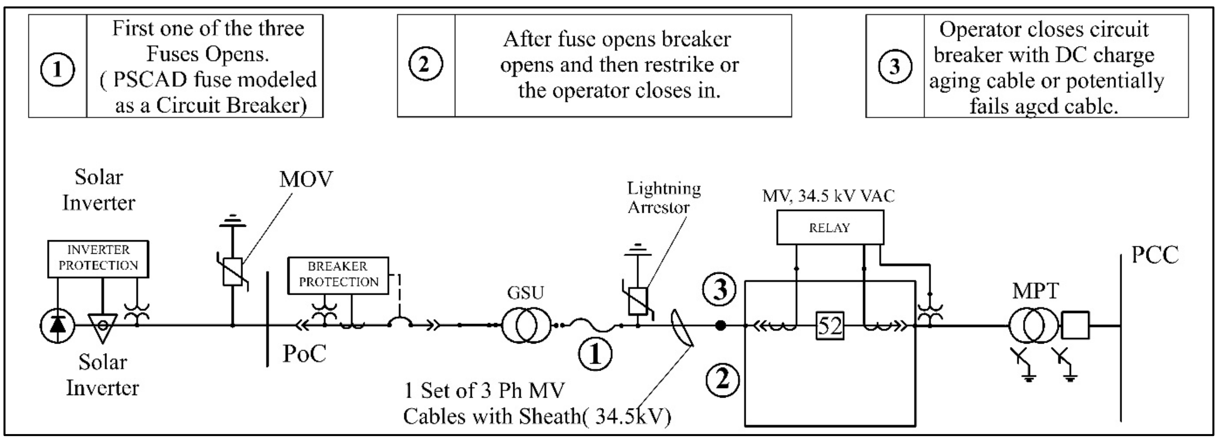


Fig. 7

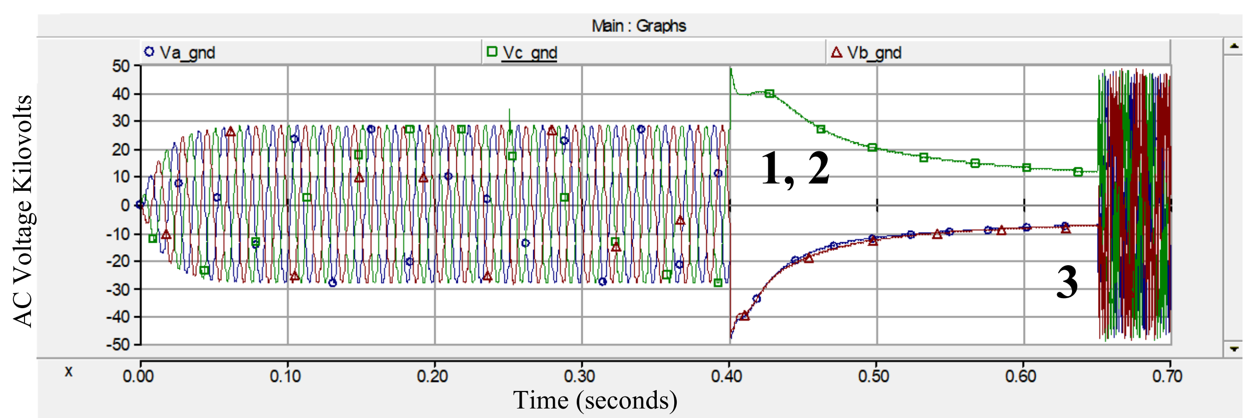


Fig. 8

The sequence in PSCAD begins, and at 0.4 s, the circuit breaker opens, and then a hypothetical fuse opens just after 0.4 s (*Note: Concerning the three separate cables, this is an illustrative example only for cable isolation; it is possible and likely that only one fuse opens and that the fuse is simulated using a circuit breaker model*), thus creating a very short-term island with the inverter exporting power. The voltage increases, the surge arrestor clamps the voltage, and the DC charge remains on the isolated MV cable. The discharge **(Important note: The *RC time constant is lowered in this simulation to accelerate cable discharge to illustrate this example. Most likely, a well-isolated cable will take a lot longer to discharge.)*** of the cable begins, but the circuit breaker closes before the cable is discharged (3), causing the voltage to spike and rapidly oscillate (**most likely, the inverters would shut down, and there is a possibility the breaker would close in against residual DC charge, which could cause the cable to fail**). The resulting spikes and high-frequency poor power quality would at the very least age the insulation of the MV cable. The results of the simulation are shown in Fig. 8.

J. Injury due to Energization and Trapped Charge

The Occupational Safety and Health Administration (OSHA) provides fatality and catastrophe investigation summaries. The summaries provide a description of the incident, generally including events leading to the incident and causal factors. However, when searching for the source of the cause of the injury OSHA is not found to report details as to the type of specific source of generation.

The continuing modification of both distribution and transmission systems include more and more “inverter-based-battery charging systems” and “inverter based solar systems” which may cause unwanted energization. Currently OSHA is without specifically delineating the “source” of generation in its reports. With the addition of inverter-based generation BACKFEEDING into distribution systems, identifying the source of energization may prove useful.

According to OSHA, an electrical hazard can be defined as a serious, workplace hazard that exposes workers to Burns, Electrocution, Shock, Arc Flash/Arc Blast, Fire, and Explosions. In this paper, we are concerned with protecting workers during construction and subsequent operation of backfeeding inverter-based generation. Where it is proposed that such protection consists of a breaker which first clears the inverter-based equipment from the transmission or distribution system, then subsequently and immediately within 12ms operates with a mechanically interlocked bonding and grounding device that effectively connects all phase conductors which are fed power from inverter-based generation together and to ground. Such a device like the VDH/GSMI does more than just simple grounding and is designed to immediately bond conductors together after its breaker opens. The VDH/GSMI is intended to conduct safely any current likely to be imposed by islanded equipment. The grounding and bonding function is designed to make a “permanent” connection between phase conductors and ground so that islanding currents supplied by inverter-based generation flow when the grounding portion of the VDH/GSMI is closed, causing the voltage on the islanded electrical system to be much lower. In addition, with such a device connecting phase conductors together and to ground the resulting higher currents quickly discharge the trapped charge in the cable’s shunt capacitance.

The National Electric Code Article 100 defines “bonded” (Bonding)— connected to establish electrical continuity and conductivity; however, concerning OSHA and its regulations 29 CFR § 1910.399 (definitions) provide a different definition of the term “bonded”; where we find the term “Bonding (Bonded)” —The permanent joining of metallic parts to form an electrically conductive path that ensures electrical continuity and the capacity to conduct safely any current likely to be imposed.

Where the VDH/GSMI’s VI grounding switch is designed to provide a “permanent” bond when the grounding switch vacuum interrupters (**VI**) are closed [emphasis added]; thereby connecting the phase conductors and ground together to ensure electrical continuity within the VI’s designed capacity to conduct safely any current likely to be imposed. Here we take care that OSHA and the National Electric Code have different definitions for the word and term bonding, and care must be taken in each design case to see what word or term applies.

OSHA requires compliance with 29 CFR § 1910.399, 29 CFR § 1926.449 and NFPA electrical safety standards (NFPA 70E) and workers are trained on the Four Hazards, known as: 1. fall, 2. caught in between, 3. struck, and 4. electrocution; where herein we are discussing electrocution, along with shock, and injuries from Arc Flash/Arc Blast.

In addition, and to point out OSHA’s unique terms and definitions of “voltage to ground”, for grounded circuits, the voltage between the given conductor and that point or conductor of the circuit that is grounded; for ungrounded circuits, the greatest voltage between the given conductor and any other conductor of the circuit (29 CFR § 1926.449). Here we take special care to point out that this special definition of “voltage to ground” is without an ordinary meaning.

Concerning the resulting “voltage to ground” on conductors included in islanded inverter-based generation, the “insulation level” and or “working space” of or around such equipment, may not be sufficient because the trapped charge and voltage on such conductors may be greater than anticipated. Consequently, engineers may need to revisit their assumptions as to the level of islanded “trapped charge” and resulting “voltages” seen on electrical equipment. However, if a device that clears the inverter-based generation from the distribution system, then immediately and subsequently “connects” or “bonds” the phase conductors together and also grounds is installed on the electric power system, the resulting trapped charge depending on the equivalent circuit may be reduced to safe levels within less than a cycle.

To remove trapped charge and cause inverter-based energization to quickly cease on both transmission and distribution systems a "clearing" and subsequent bonding and grounding device is needed. Engineers may use such a device such as a VDH/GSMI™, TPGR™, SPGR™ to significantly reduce the exposure of arc flash and arc blast energy to workers during construction and subsequent operation of electrical equipment; thereby saving lives.

As an example of injuries to workers caused by either arc flash, energized equipment or general shocks, a search was performed on OSHA's website, the following was found:

1. When searching for reported injuries by OSHA on their website, https://www.osha.gov/pls/imis/AccidentSearch, with the search term "arc", from the years 2016 through 2022 there are reported 188 incidents and injuries due to presumably arc flash where 10 are fatal.

2. When searching for reported injuries by OSHA on their website, https://www.osha.gov/pls/imis/AccidentSearch, with the search term "energized" from the year 2016 through 2022 there are reported 101 incidents and injuries due to energization where 44 are fatal.

3. When searching for reported injuries by OSHA on their website, https://www.osha.gov/pls/imis/AccidentSearch, with the search term "shock" from the year 2016 through 2022 there are reported 222 incidents and injuries due to shocks where 44 are fatal.

These reports include workers working on single phase, and three phase systems, with either low voltage or medium voltage applied, the reader is encouraged to perform their own search.

A "clearing" and subsequent bonding and grounding device is needed to reduce the energy available during a fault, and during an island to provide a path across phase conductors or ground to discharge trapped charge and remove unwanted energization.

Such a device increases the likely hood that lives will be saved when mistakes are made by workers or when equipment does not operate correctly. For example, a scenario concerning trapped charge is given: the capacitive energy available in a 100 ft, 2 AWG cable with 5 micro farads of capacitance between the conductor and outer sheath; initially a fuse opens on one side of the cable and then a breaker opens on the other at the voltage peak, resulting in 30,000 DC volts (peak) and over 2,000 Joules of energy stored, This stored energy easily exceeds safe limits and recommendations provided in IEEE Std 80 (Approx. 13 joules over 0.083 milliseconds through the workers body may cause ventricle fibrillation).

IEEE Standard 80 reports, workers are very vulnerable to the effects of electric current at frequencies of 50 Hz or 60 Hz. Currents of approximately 0.1 A can be lethal; and in certain cases, the human body is able to tolerate very high currents due to lightning surges. The International Electrotechnical Commission provides curves for the tolerable body current as a function of frequency and for capacitive discharge currents [See IEC 60479-2 (1987-03).

Where concerning trapped charge, such a device like the VDH/GSMI can both reduce the amount of time of lethal exposure to workers due to both trapped charge and energization and as a result can save lives. A PSCAD simulation is given showing just how fast this equipment can intervene and save lives; however, relay settings are critical and not discussed in this paper.

*K. **PSCAD** Simulation **DC** Trapped Charge Breaker and Fast Grounding and Bonding Device*

A **PSCAD** simulation is provided to illustrate how a grounding and bonding device discharges an **MV AC** cable (see Fig. 9, see next page). Note that the grounding and bonding device (ANSI Device Number: 57) is added; however, keep in mind that an added grounding and bonding device may not directly discharge a bound or deep trapped charge in the MV cable's "aging" defect. However, because it reduces the length of time the **TOV** is applied the added grounding and bonding device may prevent the trapped space charge from occurring in the first place. The **PSCAD** model uses an inverter generator exporting power on a 34.5 kV system. In this case, a circuit breaker is used to replace an inverter step-up transformer fuse. A 500-foot 34.5 kV **MV** cable is modeled as a frequency dependent (phase) model, which is basically a distributed **RLC** traveling wave model that incorporates the frequency dependence of various parameters. This model represents the frequency dependence of internal transformation matrices in **PSCAD**. The cable spacing is set at approximately 7 inches and uses the sheath as a return.

The sequence in **PSCAD** begins, and at 0.4 s both circuit breakers open, and then a hypothetical fuse opens just after 0.4 s (*Note: Concerning the three separate cables, this is an illustrative example only for cable isolation; it is possible and likely that only one fuse opens and that the fuse was simulated using a circuit breaker model*), thus creating a very short-term island with the inverter exporting power. Approximately 12 milliseconds later, the mechanically interlocked grounding and bonding device closes. As a result, the voltage collapses, and the charge is removed from the **MV** cable. The results are shown in Fig. 10 (See next page.).

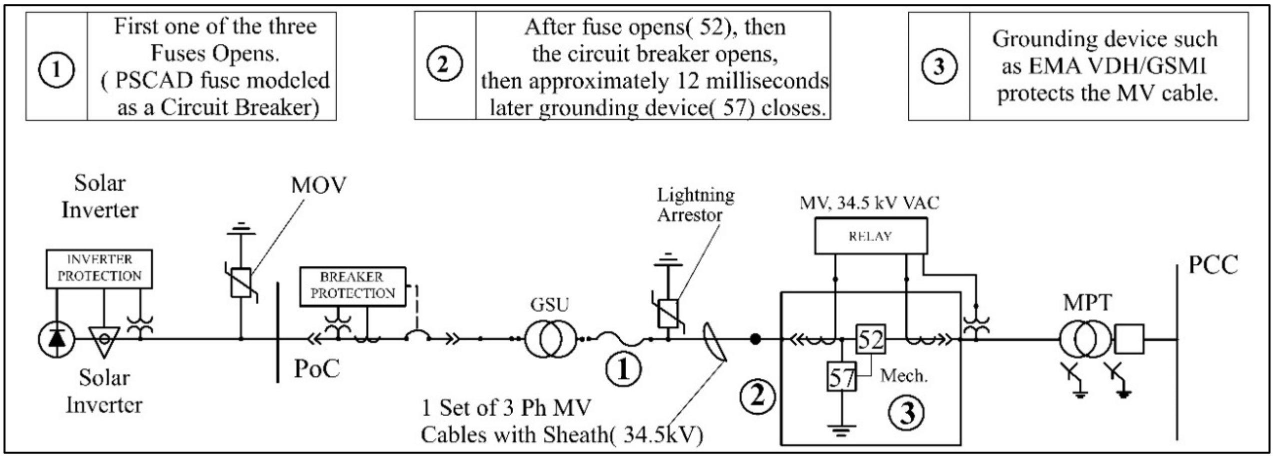


Fig. 9

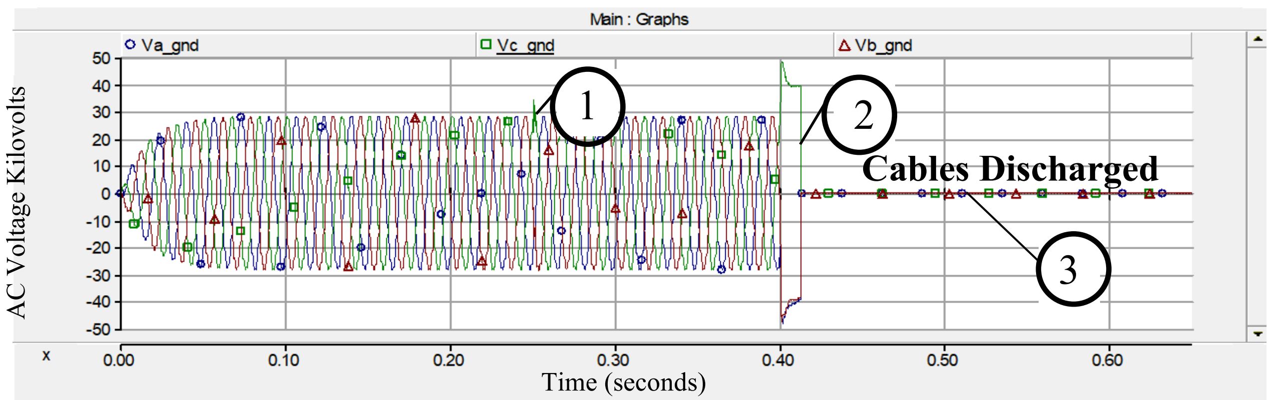


Fig. 10

III. Discussion

A. Introduction

Whether it is one inverter or a string of inverters, inverter **IDMs** allow for **TOVs** to persist while the inverter is attempting to export power within an islanded power system. The insulation can be stressed for up to 2 s by **TOV** impulsive waveforms and poor power quality. Figure 11 shows ride-through requirements; the voltage within the enclosed area is random and illustrates that the island voltage is an estimate and depends on many factors. Generally, if including all operating requirements for a string of inverters the island voltage is unknown, unless a specific case is given with many known parameters.

Figure 12 shows the projection of the voltage on the island power system with the addition of a bonding and grounding device. Figure 10 shows the ordinary trapped charge is clearly and rapidly discharged from the cables, and the cables and the voltages as measured by the inverter are low enough for the inverter to sense it needs to shut down. However, the mobility of a deep trapped charge is very low and has a stronger bond within the cable's insulation. The sources referenced in this paper provide experimental results that show the trapped energy level increases with the aging process, and the non-averaged electric field is a necessary condition for charge migration [**16**], [**25**], [**27**]. Where the question remains, can a string of islanded inverters maintain a zero DC bias while islanding?

IDMs and other ride-through standards will impact how long an inverter remains operating while islanding, each requires study. Standards such as, proposed IEEE 2800, Underwriters Laboratories (UL) Standard 1741, HPUC Rule 14H, Hawaiian Electric Companies tariff for Interconnection of Distributed Generating Facilities with the Company's Distribution System (Rule 14H) **[31]**, IEEE 1547 or PRC-024 are all different. For example, rule 14H is clearly different than IEEE 1547 and defines a total of 11 grid supportive functions where **LV** ride-through may be 50% instead of 15 % or 0%. However, during islanding, the **TOV** that may occur can quickly be remedied by a fast-acting bonding and grounding device.

Deep traps cause the electrons to be captured and to accumulate in the **MV** cable's insulation. With age, the deep traps also increase, which inevitably leads to an increase in the number of electrons remaining in each cycle [**25**]. A prolonged island and **TOV** cause more charge to accumulate in the deep traps, which ages the cables. A fast-acting grounding and bonding device would decrease this time and may reduce deep trap charge accumulation. Even with islanding, a fast-acting bonding and grounding device would prevent or reduce the "prolonged

TOV" and impulsive waveforms, which may relieve the insulation of severe dielectric and mechanical stresses. **Therefore, we can conclude that a fast-acting grounding and bonding device added to a circuit breaker may very well decrease charge accumulation caused by islanding inverter-based resources.** This answers questions a and c in the introduction section**.**

A fast-acting grounding and bonding device added to a circuit breaker is supplemental to the state-of-the-art **IDMs** for one or multiple string inverters, although it does not necessarily replace **IDMs**. However, it sends a clear signal to shut down. The several **IDMs** proposed can use such a device to not ride through (**ride-through is an inverter requirement that the inverters remain operating and conditionally export real and reactive power depending on an interconnection requirement**), and thus the insulation is relieved of stresses. This answers question b in the introduction section of this paper.

Insulation coordination studies are more predictable when integrating a fast-acting grounding and bonding device as a supplement to a breaker. The length of time the TOV is applied is predictable based on the relay setting on the MV power system. This makes it easier to calculate or simulate the energy burden for the lightning arrestors or other surge protective equipment. This answers question d in the introduction section.

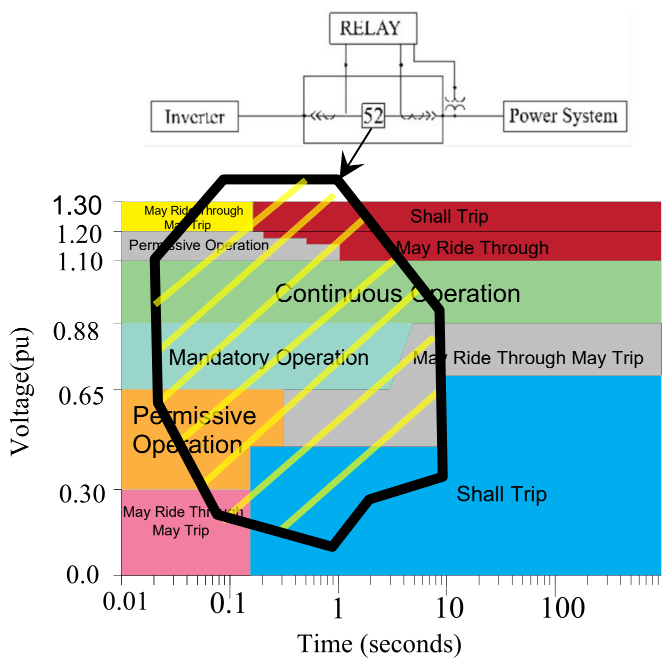


Fig. 11

With just a circuit breaker and depending on island conditions, the island voltage can go anywhere.

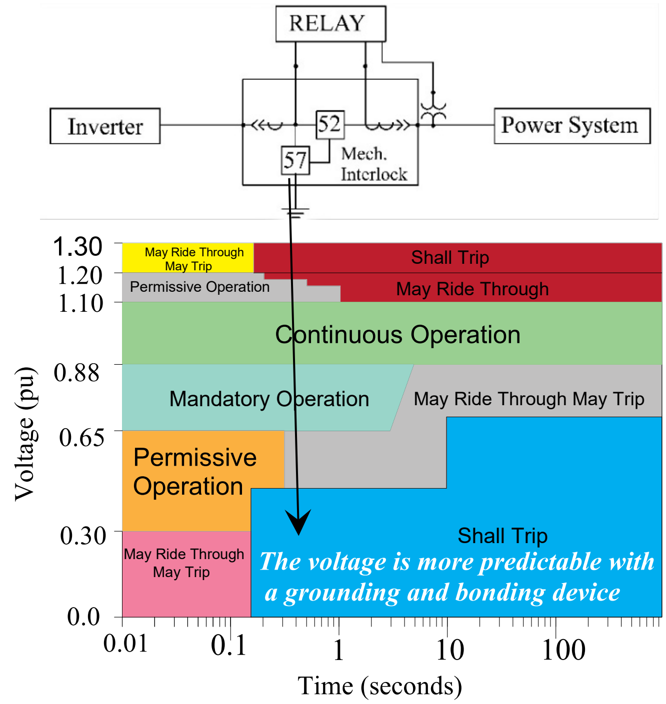


Fig. 12

The EMA VDH/GSMI is a combined mechanically interlocked circuit breaker grounding switch, a fast-acting grounding and bonding device for inverter-based generation that removes or prevents trapped charges.

B. Discussion: The Two Types of Trapped Charges

The literature referenced herein discusses two types of trapped charges. One is the charging current of a cable or its capacitance between the central conductor and the concentric sheath. The other relates to the cable dissipation factor where charges become trapped in the defects of the cable's insulation. Both types of trapped charges are concerns related to inverter-based generation and safety.

C. Space Charge and Capacitive Charge

When testing a cable's dissipation factor, the physics show that perfect insulation with no defects has 90° of a phase shift between voltage and current, and therefore a sample **MV** cable looks like a capacitor and appears to be in good condition. This is capacitive charge, and engineers are concerned with removing this charge on isolated cables, which is discussed in previous sections of this paper.

As the cable degrades, the defects or **ETs** grow, and the charge becomes trapped locally. The **MV** cable simply heats up (e.g., resistive, dissipative), and the angle moves down from 90°, indicating a real power loss component. Concerning the dissipation factor, what is measured with respect to the **MV** cable's insulation is real-power and reactive-power.

Qualitatively speaking, if the measurement is purely resistive, a new cable will be needed.

These tests are limited to single types of cables, as different cables have different dissipation factors; therefore, background information is needed to better understand the test results. However, a good way to determine a cable's status is to increase the voltage on the cable and identify whether the dissipation factor on a specific cable is getting worse relative to other cables. If it is, this is indicative of the aging of the cable relative to other similar cables in service and of how the defects have grown. Cables can be rated as "highly degraded", "moderately degraded", and 'acceptable' or as "action required", "further study required', or "no action required" [**17**].

D. Space Charge and Accelerated Aging

Concerning accelerated cable aging, the benefits of a fast-acting grounding or bonding device (such as EMA's VDH/GSMI) are that it reduces the time of a DC trapped charge and the time of applied distorted **HV** waveforms causing oxidation stress in **XLPE** cables. Inverter-based generation plants can be part of the cause of high-frequency impulse overvoltages that can accelerate the aging of **MV** cables. Research into cable failures shows that a deeper trapped charge in **XLPE** insulation accelerates cable aging.

IDMs allow **TOVs** to persist while the inverter is attempting to export power within an islanded power system. This may accelerate insulation aging because surge arrestors on the **MV** islanded power system quickly change their state to clamp the inverter-induced **TOV**. As a result, the **MV** cable experiences **HV** impulses and distorted voltages, thus stressing the insulation.

According to the research on insulation, "During the operation of high-voltage cables, the insulation materials may be subjected to the distorted voltage waveform, such as a **DC**-pulse, **DC**–**AC**, and **DC**-harmonic composite voltages, which may trigger electrical trees" [**16**]. A trapped charge may be bound in this **ET**, and the insulative ability of the **XLPE** is thus reduced **[26**]. While there is no unified theory to explain the degradation and breakdown behaviors of insulation materials in high-voltage direct current (**HVDC**) and high-voltage alternating current (**HVAC**) cables, reducing the time of applied **TOV** may reduce the "rate of aging" in **MV XLPE** cables [**26**].

E. OSHA fatalities and Safe limits

In this paper we discussed Occupational Safety and Health Administration (OSHA) fatality and catastrophe investigation summaries. Also discussed as a solution to reduce injuries and fatalities is installing a breaker, first clearing inverter-based generation from a distribution or transmission system, then subsequently and immediately a mechanically interlocked bonding and grounding device bonds the "inverter side" phase conductors together and grounds, which is shown to reduce trapped charge within milliseconds. where without such a device in certain cases trapped charge can remain for several minutes to hours and the capacitive energy available easily exceeds safe limits as provided by IEEE Std. 80. We also show that such a device such as, a VDH/GSMI™ SPGR™, TPGR™ within 12 milliseconds can reduce the dangers of unwanted energization and trapped charge or shock hazards to workers.

IV. Conclusion

Isolated cable systems with an inherent capacitive charge, a space charge with capacitance discharge profiles, and discussions concerning a space charge have been presented in this paper with and without the application of a fast-acting bonding and grounding device. The studies referenced herein show that without a grounding and bonding device, it may take hours to reach a safe level of voltage due to a protracted discharge rate. A fast grounding and bonding device with a mechanically interlocked circuit breaker, such as EMA VDH/GSMI [**11**], or a similar single-phase device for distribution systems will make this voltage disappear instantaneously; however, a space charge may remain. As the research has indicated, heating the cable may mobilize the charge carriers in **XLPE MV** cables.

In addition, a fast-acting bonding and grounding device reduces the time of applied poor power quality and **TOV** to **MV** cables and connected equipment when inverter-based generation is islanded. Contemporary research into the causes of a space charge and **ETs** within the **MV** insulation shows that the insulation is relieved of prolonged **HV** and high frequency stress. Future research on the benefits of a fast-acting bonding and grounding device is needed, as such a device attenuates the accelerated aging of the **MV** cable's insulation and the growth of **ETs** when coupled with islanded inverter-based generation exporting power.

Last and most important, the VDH/GSMI or similar device is shown to reduce trapped charge and unwanted energization within milliseconds and cause the trapped charge or "voltage to ground" to quicky reduce to safe levels that in certain cases do not exceed IEEE Standard 80.

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Thomas Wilkins works with and for ELECTROMECHANICS (EMA) and was paid to prepare this and other reports, including the PSCAD simulation by EMA.

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VIII. Biographies

A technical biography and photograph for each author may be included if necessary.

XI Changes/Errata

1. Removed NREL Ref. [4] included Reynolds, Mamadou Diong, Philip VanSant, Load Rejection Overvoltage of Utility-Scale Distributed Solar Generation at Ref [4]
2. Changed name to Thomas Wilkins
3. Introduction changed can to is projected.
4. Added reference [34] Power System frequency overvoltage has disturbing effect cable insulation.