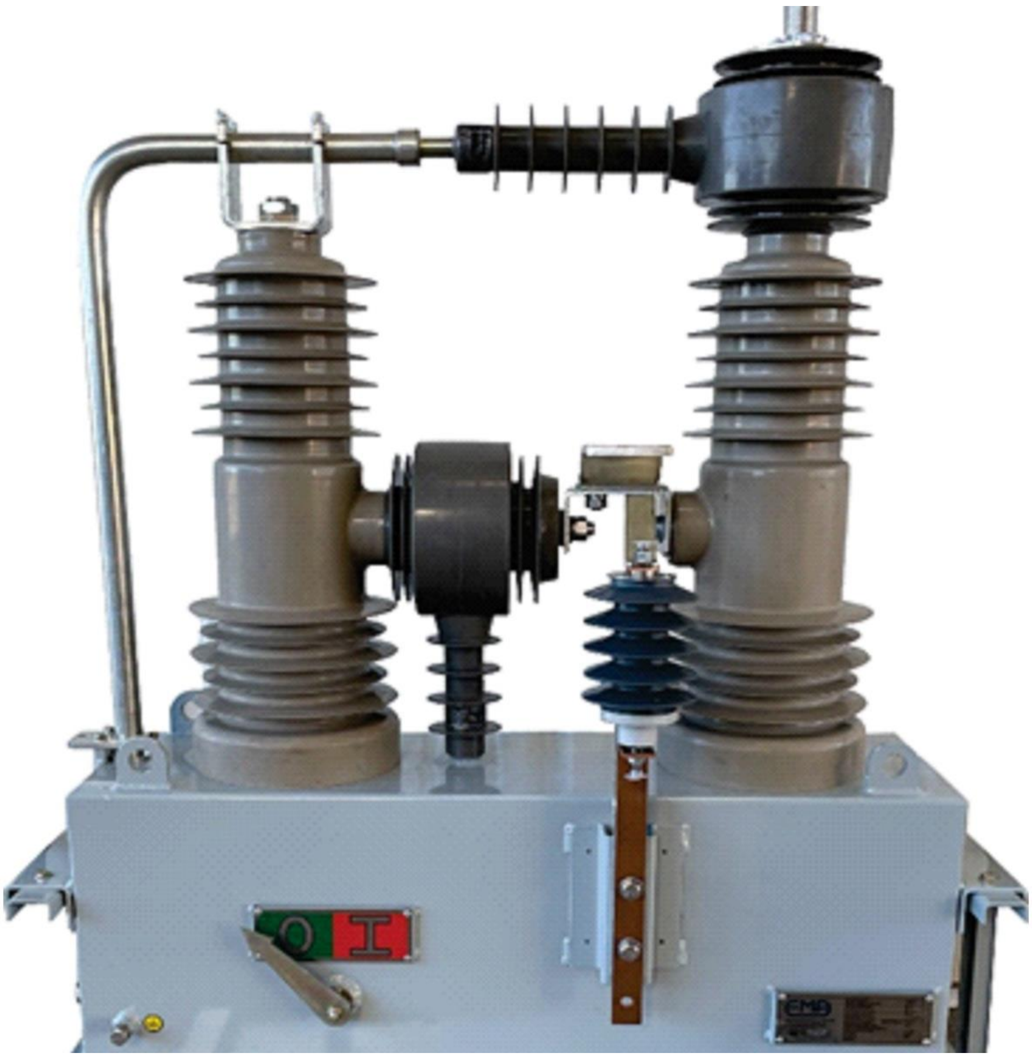
EMA Grounding Recloser Protects DER RPF[1] Distribution Systems Day and Night



[1] DER: distributed energy resources: RPF: reverse power flow (e.g., backfeeding inverter-based power)

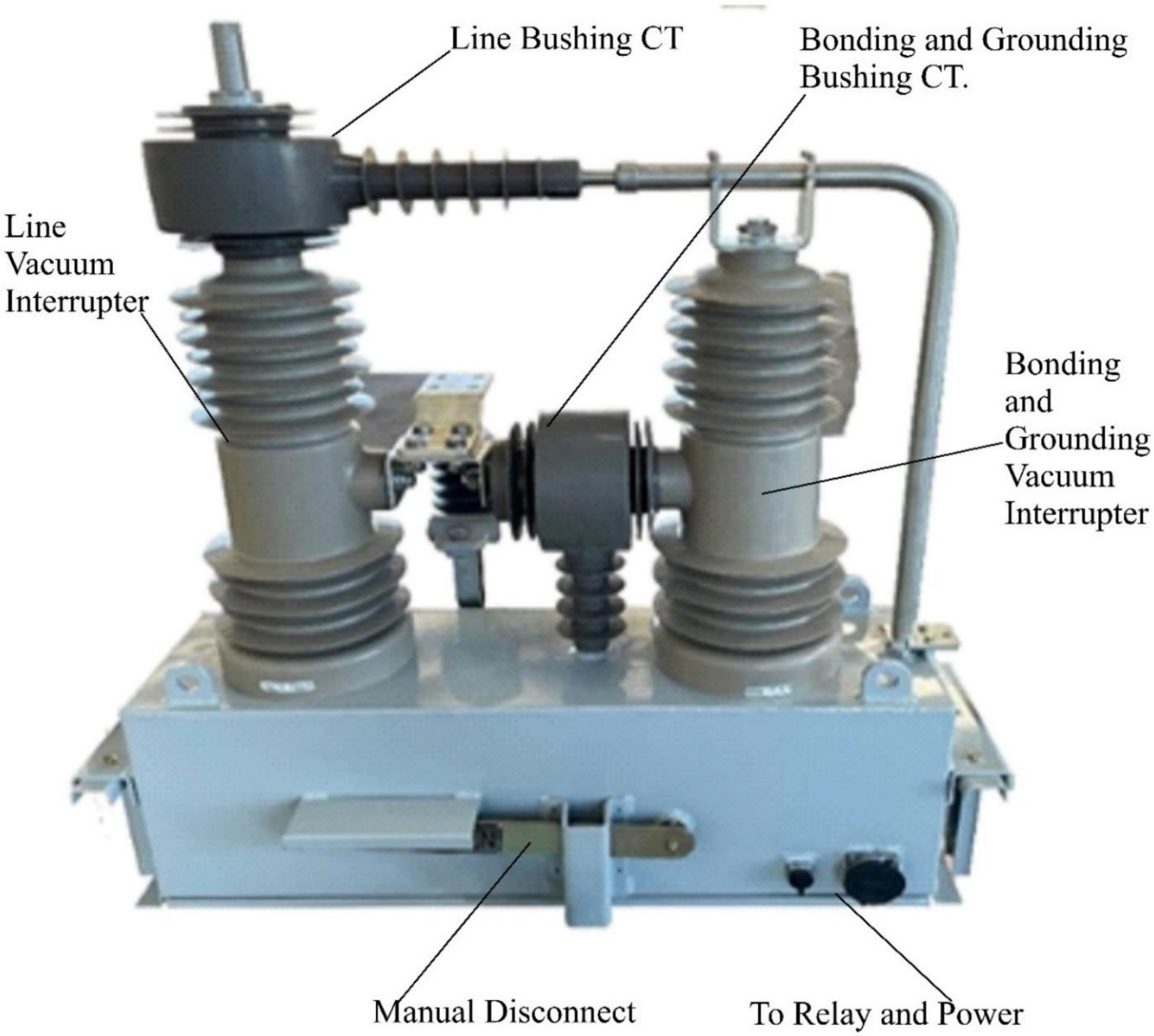


Fig. 1. Grounding Recloser, Back(Relay Not Shown).

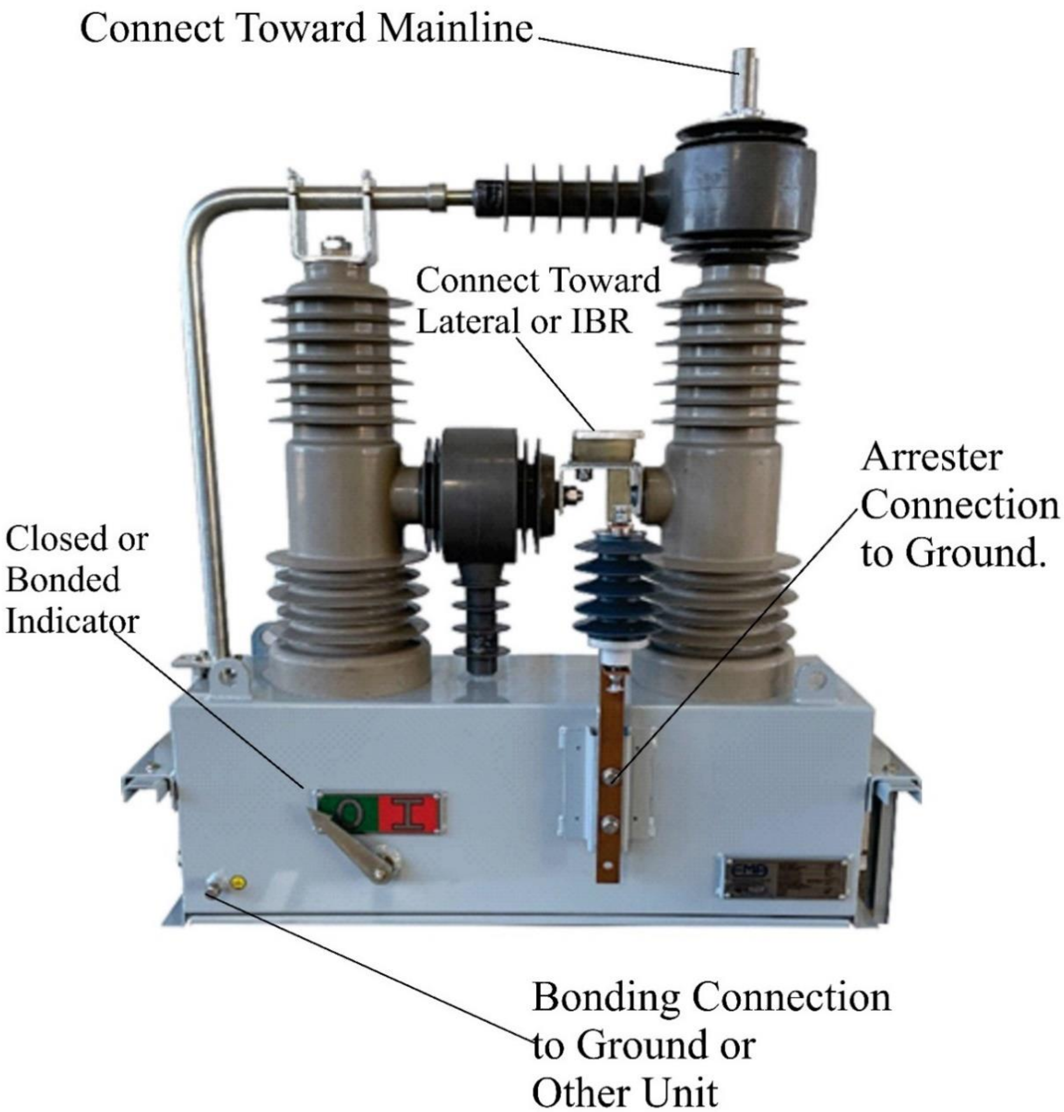


Fig. 2. Grounding Recloser, Front(Relay Not Shown)

***Abstract*—This PSCAD simulation indicates that a grounding recloser provides protection for both distribution customers and inverter-based resources (IBRs) from prolonged temporary overvoltage (TOV) during lateral connected IBR load rejection (backfeeding) overvoltage (LRO) caused by an open line on the mainline. This PSCAD simulation indicates (*when "islanded" IBR causes a reverse power flow on an affected distribution circuit*) the following results: (1) the EMA grounding recloser is a fast reliable method to shut down IBR (*See IEEE 1547*), (2) reduce TOV duration, and (3) restore service to the customer.**

A grounding recloser protects the insulation of either grounded or ungrounded distribution systems with interconnected IBR from prolonged TOV. The grounding recloser is similar to the larger EMA grounding breaker (VDH/GSMI) used in transmission systems. The grounding recloser is designed for distribution systems, where it provides bonding between phase conductors and a "bolted" ground to shut down islanded IBR and then reclose. This simulation indicates that when the grid following IBRs suffers a load rejection overvoltage (LRO), the grounding recloser during the simulated open line (mainline) is effective for sending a clear low voltage signal to the IBR on the lateral, causing the IBR to quickly go offline. Which can be a signal on the power line to remote trip IBR. In this simulation, because the fault is permanent, the grounding recloser does not reclose and remains in lockout, where the lateral phase conductors remain bonded and grounded. The grounding recloser is used in wind, solar, or battery, and provides protection both day and night, without using direct transfer trip for IBR.

Keywords—grid following, grid forming, distribution, load rejection relay, recloser, ride through, protection delta, ungrounded, breaker grounding, bonding, open line, overvoltage, ANSI 59-1, ANSI 79, IEEE 1547-2018.

I. INTRODUCTION

The three-phase 38 kV VDH/GSMI performs well and has done so for several years in transmission systems by bonding each phase together and to the ground during a feeder disturbance in wind and solar transmission power plants. Now, EMA has developed a distribution grounding recloser based on the same concept as the 38 kV VDH/GSMI (Fig. 1 and Fig. 2).

This paper discusses the grounding recloser on distribution systems and simulates with PSCAD the grounding recloser connected to an ungrounded distribution system. This paper also discusses the grounding recloser and what protection it provides. The integration of solar or battery generating systems installed on distribution systems in increasing numbers creates a need for the added elements of both bonding and grounding along with reclosing. The EMA grounding recloser provides these added elements.

IEEE standard 1547-2018 [3] requires distributed energy resources (DER) to support the grid during steady-state and abnormal conditions. In this paper, with PSCAD, we look at the protection of DER resources interconnected to an ungrounded distribution system through a lateral using an ANSI 59-1 overvoltage element to see how a grounding recloser protects an ungrounded feeder or lateral. The lateral is connected to a 4.8 kV mainline connected to a 10 MVA distribution substation transformer, where the low side of the transformer is configured delta (Fig. 3 and Fig. 10).

A. Similarities and Differences Between IEEE 1547 and the Bulk Electric System.

IEEE1547-2018[3] applies to DER and provides for “system design planning levels” in the aggregate. In this paper, we show that DER may not always meet requirements at the point of common coupling (PCC) or Point of Coupling (PoC) per section 4.2 of IEEE 1547; therefore, DER without a grounding recloser may be without full compliance with all requirements of IEEE 1547. As a result, planners may need the grounding recloser as a supplemental BES or EPS device either for a single unit or in the aggregate to meet Bulk Electric System requirement and/or local electric power system (EPS) requirements.

IEEE 1547-2018[3] defines the PCC as the point of connection between the area EPS or facilities that deliver electric power to a load. IEEE 1547-2018[3] defines the PoC as the point of distributed energy resources connection (point of DER connection–PoC) as the point where a DER unit is electrically connected in a local EPS and meets the requirements of this standard exclusive of any load present in the respective part of the local EPS.

The NERC BES I4 definition [5] states that dispersed power producing resources that aggregate to a total capacity greater than 75 MVA (gross nameplate rating), and that are connected through a system designed primarily for delivering such capacity to a common point of connection at a voltage of ≥100 kV. Thus, the facilities designated as BES are the individual resources, and the system is designed primarily for delivering capacity from the point where those resources aggregate to >75 MVA to a common point of connection at a voltage of ≥100 kV.

The point being if a planner of a distribution EPS wished to aggregate its inverter-based resources (IBRs) at the PCC to meet either the NERC’s I4 definition or the IEEE 1547 (2018) EPS definition, planners would need equipment to meet the relevant FERC requirements (e.g., FERC order Nos. 743, 773, etc.) and local EPS requirements. The grounding recloser assists planners in meeting IEEE 1547 and NERC BES I4 requirements.

B. EMA Grounding Recloser

EMA manufactures a single-pole dead tank automatic grounding vacuum interrupter (VI) recloser with a control relay. Grounding recloser applications are for both overhead and underground medium-voltage distribution feeders. The automatic grounding recloser is Rated Max Voltage:15.5 kV; Rated Lightning Impulse: 125 kV BIL; Rated Continuous Current 800 A; Rated Symmetrical Interrupting Current Main Breaker: 25 k; Rated Symmetrical Interrupting Current Ground Breaker: 12.5kA; Line Charging Current 2 A, Cable Charging Current 10 A, Dry Withstand 60 Hz 1 min 50 kV, Wet Withstand 60 Hz 10 Sec; opening Time 30msec, closing time 55msec. The automatic grounding recloser is designed with the following references in mind: ANSI C37.60, C37.61, C37.90.1, and C62.41.1. EMA manufactures a single-phase pad or pole-mounted grounding recloser with phase bonding and grounding protection. This unit is designed to provide protection during reverse power flow on affected distribution laterals and feeders with inverter based generation such as battery or solar (Fig. 3 and Fig. 4).

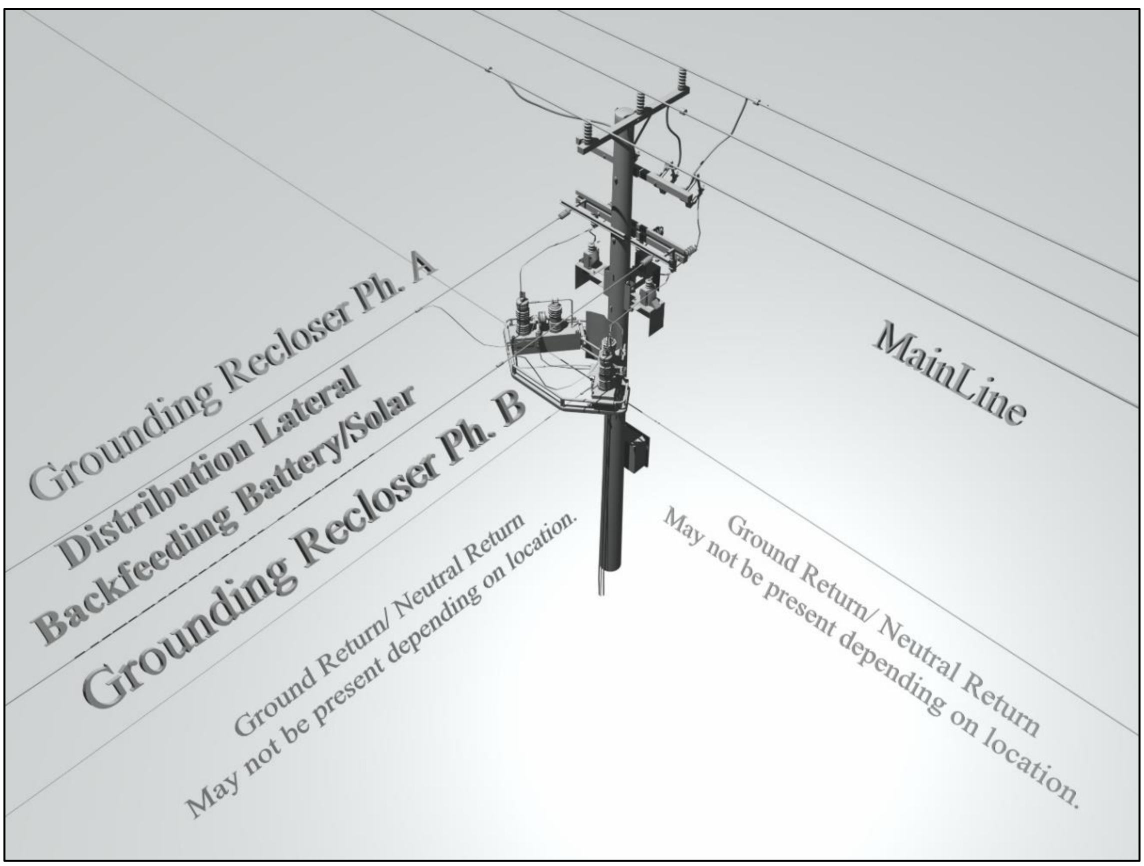


Fig. 3 Phase-to-Phase Installation by Using Two Units [Note. One unit is for phase-to-ground.]

The dead tank, 60-Hz automatic grounding recloser, is manufactured with VIs encapsulated in a solid dielectric insulator. The compartment is NEMA 3, with a charging motor inside. Sealed multipins "through the bulkhead" round threaded connectors are provided for power, signal, and control (Fig. 1 and Fig. 2).

Fig. 4 Lateral To Homes, Industrial Locations, and Commercial Locations for Battery or Solar

C. *Reverse Power Flow Problem*

Concerning small solar installations (Fig. 3 and Fig. 4), when DER islands from the grid, and during a reverse power flow, load rejection overvoltage (LRO) occurs for either grounded or ungrounded systems. The overvoltages occur because the inverters do not shut down, and there is enough energy in their PV arrays, battery banks, DC bus, and capacitors to continue to operate beyond the requirement of 0.16 s (see IEEE 1547) and cause overvoltage on the separated lateral. According to the IEEE, load rejections and transient overvoltages can reach 159% [1] of the rated voltage and even higher. The islanded TOV can persists for long periods: ≥1, which may destroy connected equipment and is a safety hazard. Studies have indicated that surge arresters, feeder design, power system maintenance, protection coordination, and inverter power electronics influence the severity the TOV during a load rejection.

D. Direct Transfer Trip and Reverse Power Flow

A common method for protecting islanded distribution systems is direct transfer trip (DTT), which is a protection system that sends a trip command to remote circuit breakers. DTT uses a dedicated communication link. Usually, DTT is used when an upstream device opens, and the DTT device(s) then sends a signal to open downstream devices. However, IBR backfeeding its power(kW) within the distribution system, which then islands, will cause a TOV to occur on the islanded portion. During this condition, upstream and downstream protection intermittently reverse, thus necessitating new devices and methods to protect the distribution system, such as a grounding recloser.

E. *Open Line and How the Grounding Recloser Provides Protection.*

This paper examines how the grounding recloser provides protection to distribution systems and open-line conditions. The paper provides a description of the problem and the dilemma and a solution for ride through with a grounding recloser with a PSCAD simulation with a discussion and conclusion of how the grounding recloser provides protection during islanded conditions of IBRs for distribution systems.

II. PROBLEM DESCRIPTION

The deployment of IBR reaches levels that cause reverse power flow. Reverse power flow and unintended islanding can damage connected equipment. For large plants in a three-phase system, DTT is the protection scheme of choice by most utilities [1]. However, it does not address all protection cases for backfeeding IBR [1].

An inverter-connected DER can detect primary side open-phase disturbances using negative sequence voltage and current measurements. These methods work from poor to good, depending on the transformer connection and core design; however, they do not address lateral DER protection at all generation levels.

A. Grounding Recloser Solves the Dilemma of Ride through

IBRs operating as generators or loads (battery) are required to ride under IEEE Std. 1547(2018). Ride through is a measure of the inverter's robustness to keep generating during a disturbance. As a special recloser, the grounding recloser is a breaker, bonding, and grounding device that engineers and planners can use to coordinate zone protection with ride-through requirements.

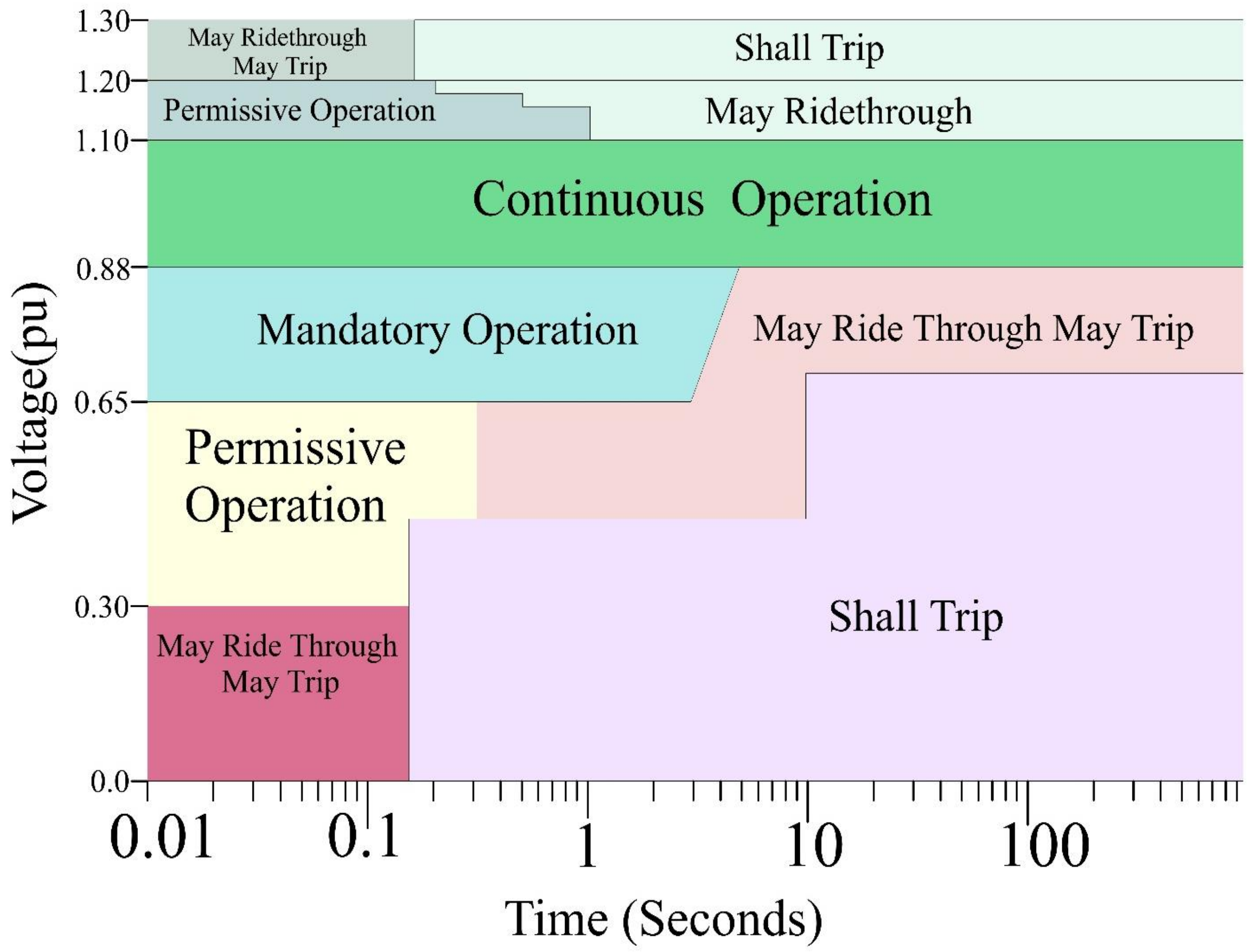


Fig. 5. IEEE 1547(2018) Ride-Through Requirements

The requirements in Fig. 5 indicate the robustness of the IBR. It does not provide a clear direction between the utility and the generator concerning protection. In addition, protection engineers may not know what the inverter is going to do even if they meet the requirements. The grounding recloser with bonding and grounding allows engineers to improve coordination between ride-through requirements and distribution protection (Fig. 6. Single-Phase Grounding Recloser and Fig. 16).

III. *DISTRIBUTION GROUNDING RECLOSER*

B. Electrical Connections and Mechanical Operation

Figure 6 and Fig. 7 show that the grounding recloser consists of two VIs, one VI connected at one end toward the mainline and the other toward the lateral. The line VI acts as the circuit-breaker portion of the device. There is a line bushing current transformer (CT) that measures the current through each phase while the unit is closed. There is a bonding and grounding bushing CT for measuring current though each bonding and grounding VI (Fig. 1 and Fig. 2). The mechanical interlock connecting the two VIs provides timing and ensures that the operation of the two VIs is timed and opposed.

C. Description Operation of the grounding recloser

The line VI acts as a circuit-breaker; when closed, it connects the mainline with the lateral, and the bonding and grounding VIs are open and vice versa. The grounding recloser comes with a line bushing CT connected on the top line VI that measures the current through each phase while the line VI is closed. When closed, the bonding and grounding VI connects or bonds the separated lateral phase conductors to each other and ground after the line **VI** opens.

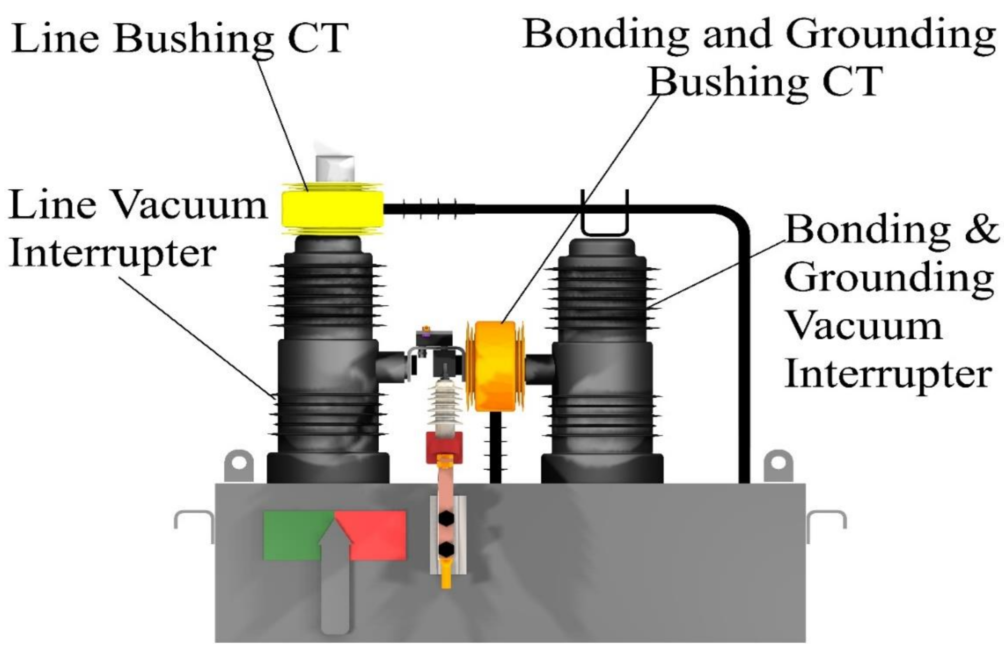


Fig. 6. Single-Phase Grounding Recloser

The grounding recloser comes with a bonding and grounding bushing CT connected to the side of the bonding and grounding VI and measures current when the bonding and grounding VI is closed (Fig. 6).

The order of operation for this device from closed to open (Trip) is that line **VI** opens first, followed by a transition when both **VIs** are open to allow for the extinguishing of the arc in line **VI,** and then the bonding and grounding **VI** closes. The process is the same for each pole (Fig. 7. A Simple Single-Line Grounding Recloser and Fig. 8. Grounding Recloser Operating Sequence).

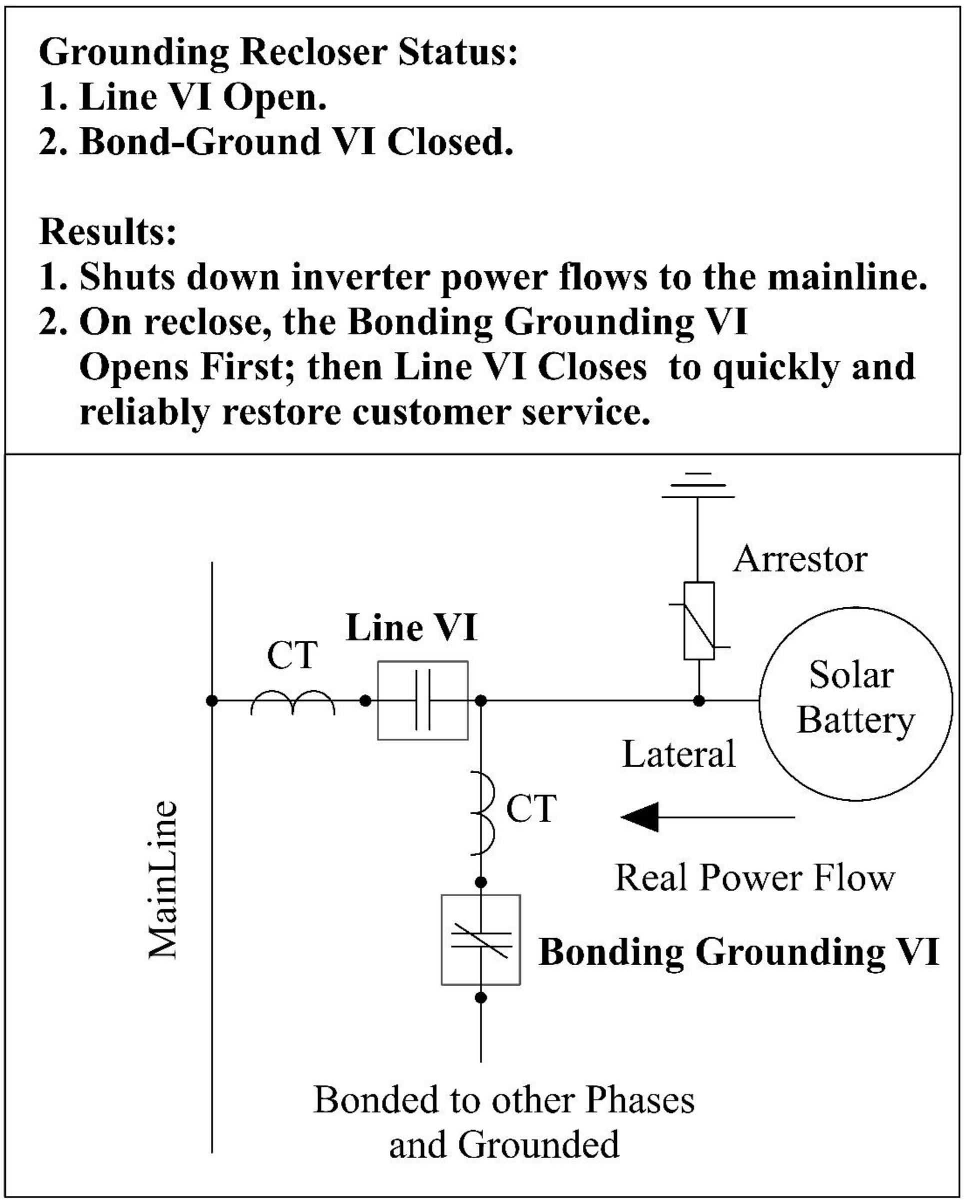


Fig. 7. A Simple Single-Line Grounding Recloser

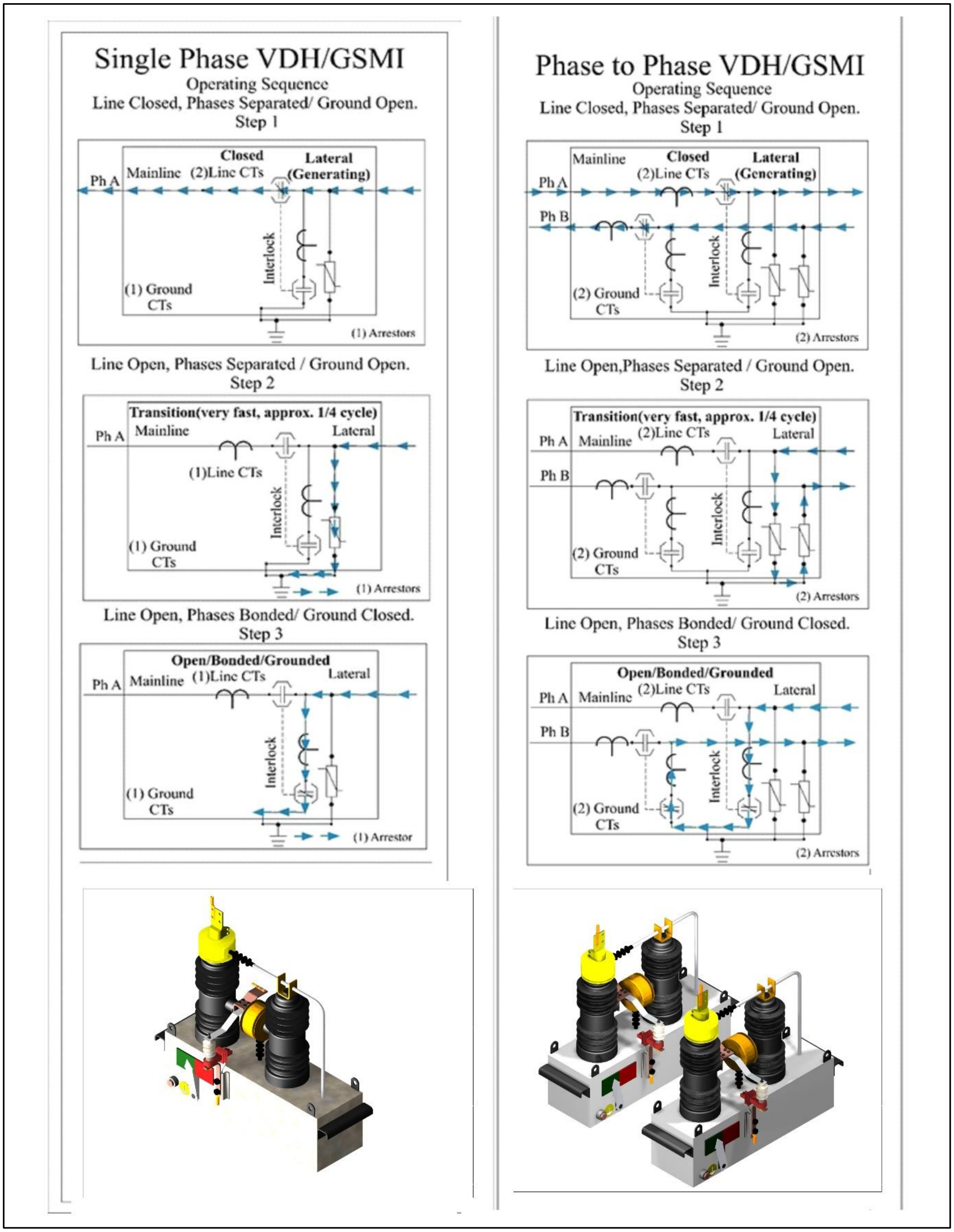


Fig. 8. Grounding Recloser Operating Sequence

D. Arrester Duty reduced by the grounding recloser by bonding and grounding phase conductors compared against other forms of protection such as DTT, Breaker, or Fuse.

There is a difference between "temporary" and "transient" when it comes to lighting arresters; notably, station and distribution class arresters are not just for handling a lighting impulse for 80 us(micro-seconds). They also manage long-duration overvoltage called temporary overvoltage (TOV). The TOV period is longer than both the subtransient (first two or three cycles) or longer duration transient state, which lasts for several cycles. Then there is the word "temporary", which is a duty specification for a lightning arrester to handle rms temporary overvoltages, which ranges from cycles to hundreds of seconds (Fig. 9). Design engineers performing insulation coordination studies need the arrester's TOV capability, which is called either the duty curve or prior duty curve. In this PSCAD simulation we use "temporary" over voltage specifications of the lightning arrester and show how the grounding recloser improves "transient" systems conditions.

Concerning this PSCAD simulation and LRO, the arrester suppresses the overvoltage during the transition of the grounding recloser, where both VIs are open for ≤16 ms. Arrester datasheets have a TOV curve, which is used to determine the minimum MCOV rating used for systems experiencing a "temporary" TOV. Notably, arresters are designed to withstand temporary AC overvoltages (see IEEE C62.22) so that system overvoltage protection may operate and insulation coordination is achieved.

The point being, the grounding recloser reduced the length of the asynchronous (IBR)-induced TOV on an islanded system because asynchronous generation produces higher TOVs, which has never been demonstrated before on synchronous power systems; conversely a synchronous generator's frequency increases during an LRO, thereby maintaining the TOV well below the conducting level of the arrester. In other words, asynchronous generation (IBR) produces higher energy and longer duration TOV than synchronous generation. The long-duration TOV destroys the arresters and then damages the addition of critical power system components (i.e., power transformers) if the grounding recloser is not applied (Fig. 9)

When applying the arrester's clamping capability of the line voltage with islanded IBR, this simulation considers the constrained IBR's control system, whereby the IBR's control system is forced to follow the volatile and changing islanded system impedance. For example, the real component of the islanded system impedance drops when the system voltage exceeds the MCOV of the arrester or other connected surge protective devices connected to the islanded system. IBRs are forced to follow each arrester's individual I/V characteristic (See Clark and Park Transforms implemented in Digital Signal Processing DSP micro-processors) connected to the islanded distribution system. The IBR generates real power and reactive power, as dictated by reactance and the I/V characteristic of one or several arresters or surge protection devices connected to the islanded distribution power system.

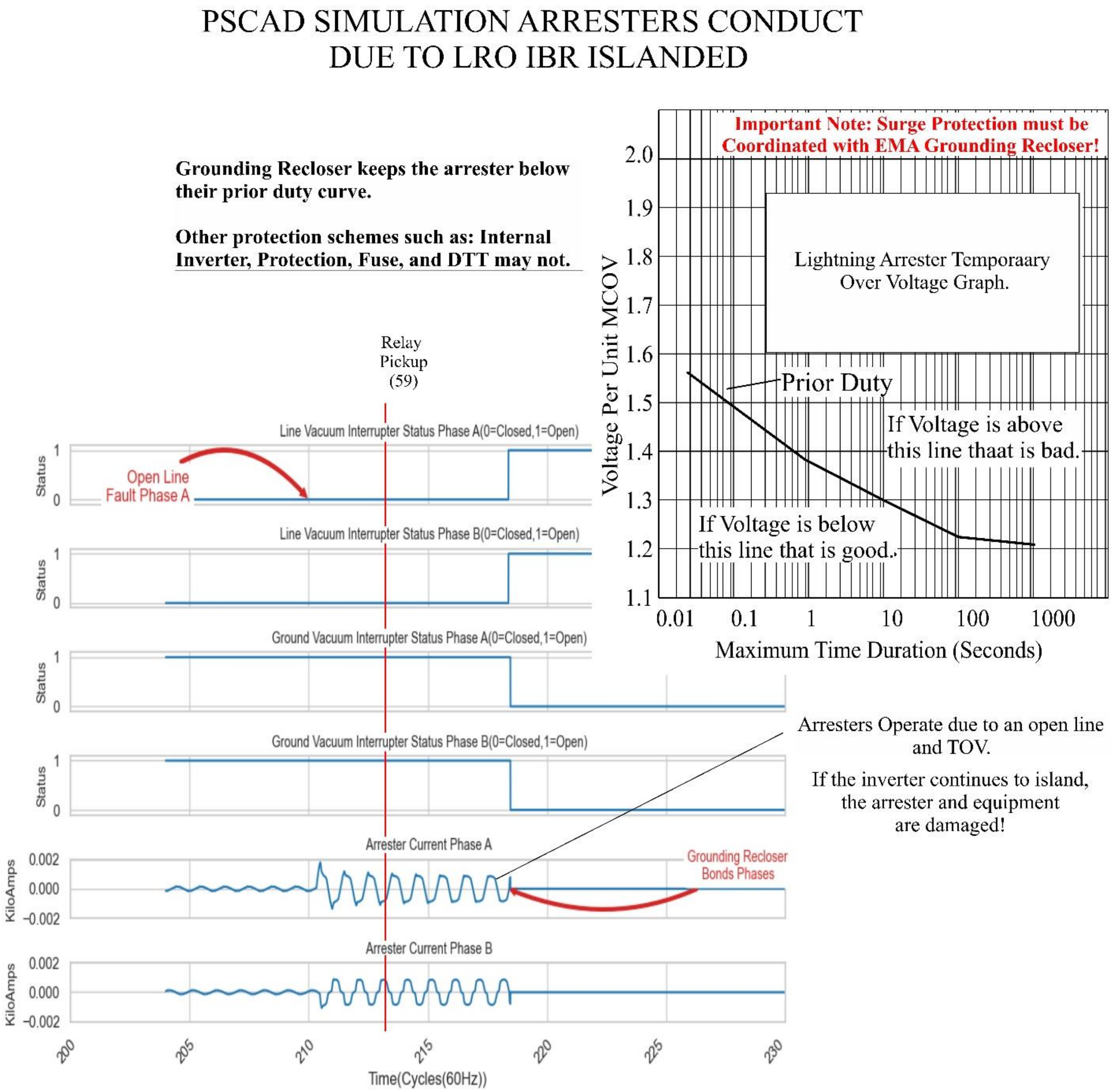


Fig. 9. Grounding Recloser Reduces TOV and Insulation Stresses

DTT Typical Breakers or Fuse Prolong TOV—Concerning the latency of DTT, typical recloser or breaker operation, and fuse misoperation, each causing a type of islanded system that prolongs the TOV caused by an islanded IBR during a reverse power flow or LRO, the TOV damages the equipment's insulation. Where this simulation indicates if a grounding recloser is added, it reduces the duration of such TOV (Fig. 9. Grounding Recloser Reduces TOV and Insulation Stresses).

Grounding Recloser and Arrester Coordination—In this simulation, the single-phase open line was between the 10 MVA transformer and the lateral (Fig. 11, Fig. 12, and Fig. 13). Depending on when the relay detects the overvoltage, the grounding recloser can take as little as 50 ms to operate and bond the lateral conductors together and to the ground (Fig. 15). Typically, when considering the IEEE 1547, there are many inverter manufacturers, and without a grounding recloser, it is unknown whether such inverters will quickly trip offline or continue to island. In addition, in this PSCAD simulation, the arrester duty (Fig. 9) may be set by the controls provided in the relay for the grounding recloser. This provides the protection engineer or planner with some of the necessary elements for performing an insulation coordination study.

Limiting Damage to Equipment—To limit or prevent damage to the arresters and connected equipment from TOV due to islanding and LRO on the affected circuit, dynamic studies should be performed to determine the amount of customer's surge protection and power system surge protection (e.g., metal oxide varistors). Use of the **grounding recloser** facilitates the determination of islanding time and TOV time (Fig. 9. Grounding Recloser Reduces TOV and Insulation Stresses).

Grounding Recloser Makes Coordination Easier—With a grounding recloser an insulation coordination study can realistically be completed because the grounding recloser allows the engineer to set the time when the phases will be bonded together and grounded during a fault and LRO; if the fault has not cleared, the grounding recloser has taken IBR equipment offline; where the relay engineer performing the study can then analyze the distribution system and set the relays without online IBR resources.

IV. GROUNDING RECLOSER DISTRIBUTION PROTECTION

Because a grounding recloser can bond each phase together, it can work on ungrounded distribution systems. If the three-phase mainline is configured delta and a lateral is connected to phases A and B of the mainline, the grounding recloser can be installed with a relay, as illustrated in Fig. 10. The grounding recloser in this configuration can be configured to reclose or remain open depending on the type of fault. The grounding recloser allows the engineer to shut down IBR on distribution systems and go back to traditional types of analysis using time current curves, as given in Protective Curves and Damage Curves with the power flow from the Substation to the Distribution Customers (not in the scope of this paper).

A. ANSI 59 (Overvoltage)

As a scenario given in this paper, during a reverse power flow and LRO, an open-line event occurs, where the grounding recloser is used to separate the lateral from the feeder, then bond the phases together to collapse the flux (Fig. 19) in the pole-mount transformer and zero the voltage on the lateral, thereby providing a clear signal to the inverter to shut down. Once the line is reconfigured and with the ground bushing CTs on the grounding recloser, indicating that no power is produced (Fig. 15) by the inverter-based generation, the unit could reclose. However, in this simulation, the fault is permanent, and the unit remains locked out.

B. PSCAD Simulation (Transformer Saturation Disabled)

In PSCAD, a three-phase ungrounded mainline rated at 4.8 kV is modeled and supplied by a 10 MVA, 69 kV, Y grounded high side: 4.8-kV delta low side ungrounded station transformer. The station transformer impedance was 6%. An ungrounded lateral is connected to the main line with a variable load and variable IBR. The pole-mount transformer connected on the lateral side is rated at 4.8 kV on the high side and 240 V on the low side with 3% impedance. Moreover, 3-kV MCOV arresters are included on both the mainline and pole line; however, no coordination study for the arresters is included in this simulation. In the simulation, the impedances for the 1-km pole line and the 10-km main line are modeled. For both the main line and lateral line, the conductor is Ortolan, with a line spacing of 1.5 ft. The grounding recloser is located at the junction of the mainline and lateral (See Fig. 10. Grounding Recloser Protection).

In this PSCAD simulation, saturation is disabled to increase simulation voltages and project worst-case stresses on insulation. Saturation plays a part in overvoltage. Distribution transformers are designed with ever higher efficiency, and it is likely that the saturation levels are changing; consequently, the peak voltage is affected. For example, CFR title 10 Chapter II Part 431 (in Appendix A of Subpart K 2016) set efficiency levels higher in 2016. By disabling the saturation in the simulation, we can presume a near worst-case voltage.

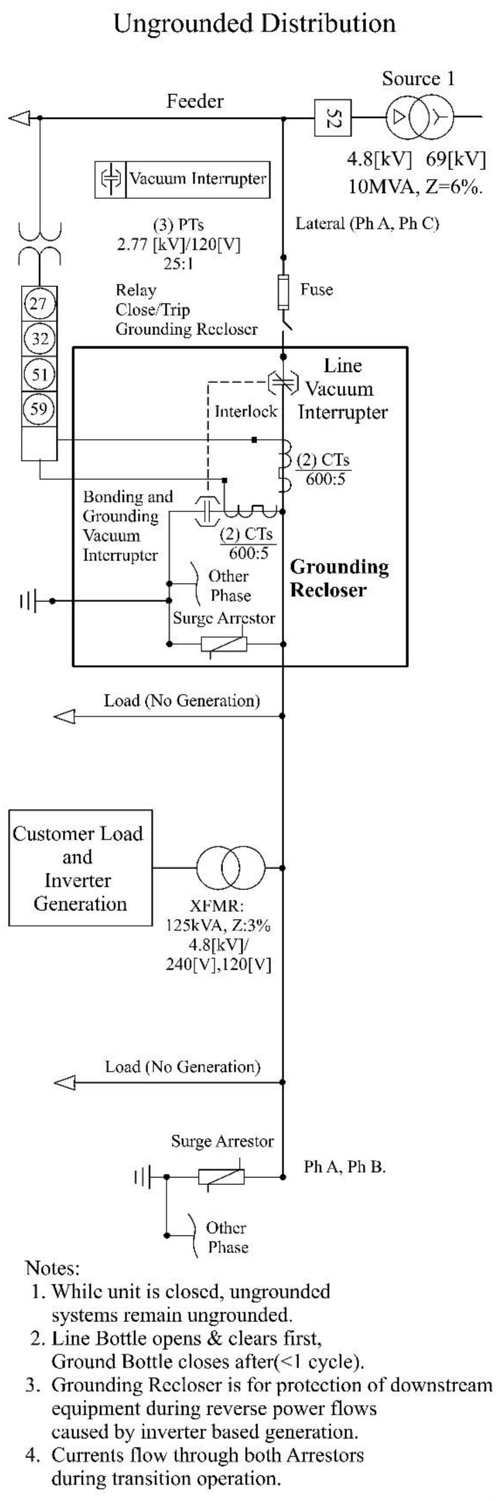


Fig. 10. Grounding Recloser Protection

1) Case 1. Open Line, No Generation

Case 1 as shown in Figure 11, begins with no generation from the IBRs and the line is energized. An open-line event in Phase A occurs at Cycle 213. The voltages drop, and service is lost to the customer. This is a typical operation without IBR.

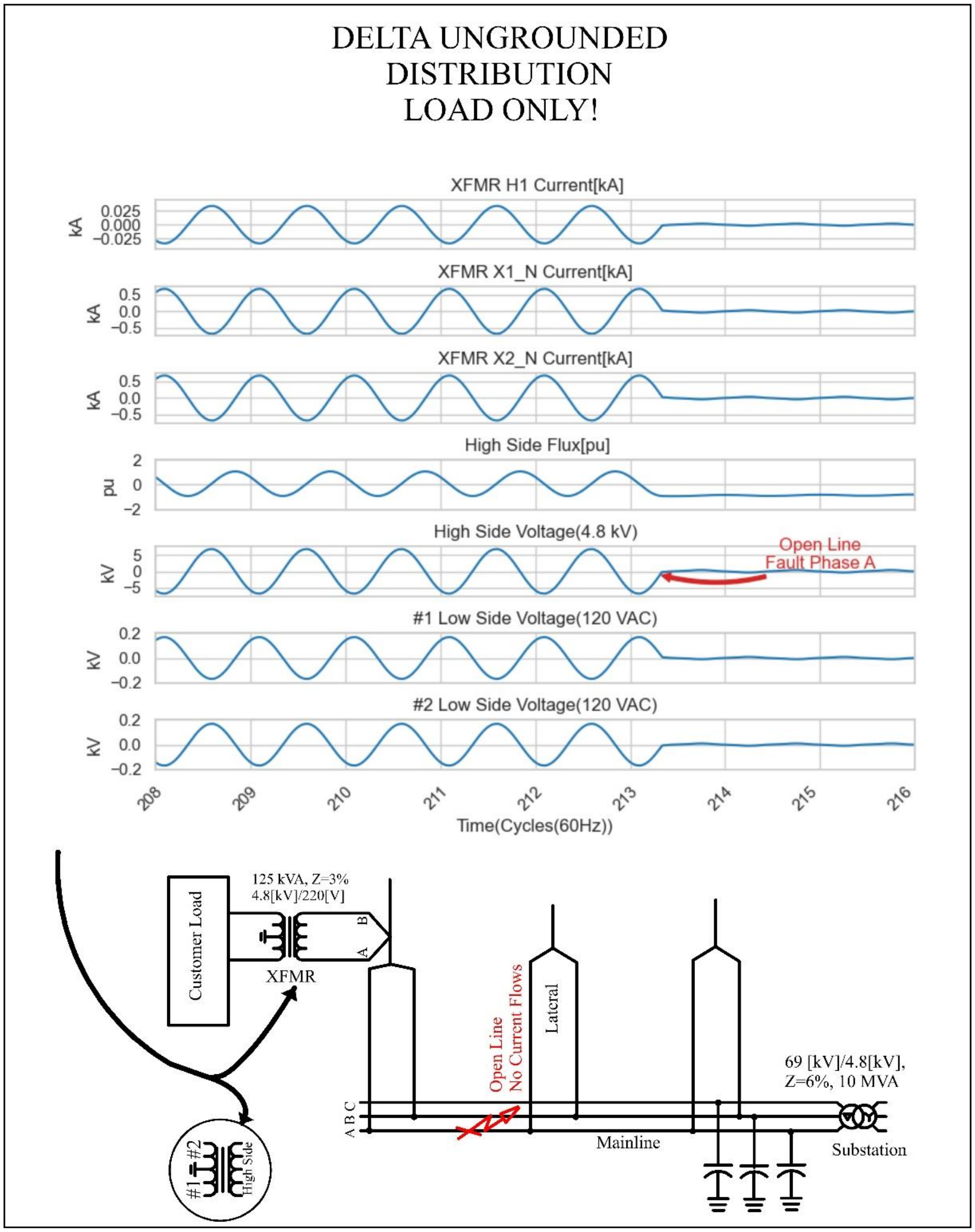


Fig. 11, Load Only, No Grounding Recloser Needed

2) Case 2. Open Line, Inverter Generation, No grounding recloser

Case 2 begins with the inverter-based generation set arbitrarily at 17 A RMS at the high-voltage side of the transformer and arbitrarily set to produce 81 kW. When the open line occurs at Cycle 210, the distorted line-to-line voltage increases to 8.92 kV peak or 1.62 per unit (4.8 kV base); note that the crest-factor ratio of peak values to the effective because the arresters are conducting and distorting the signal. In this case, the inverter current decreases when the voltage increases because the inverter controller is "attempting" to keep the power constant (Fig. 12, No Grounding Recloser, Battery/Solar Inverter Generation Greater than Load.). Figure 12 illustrates the persisting LRO.

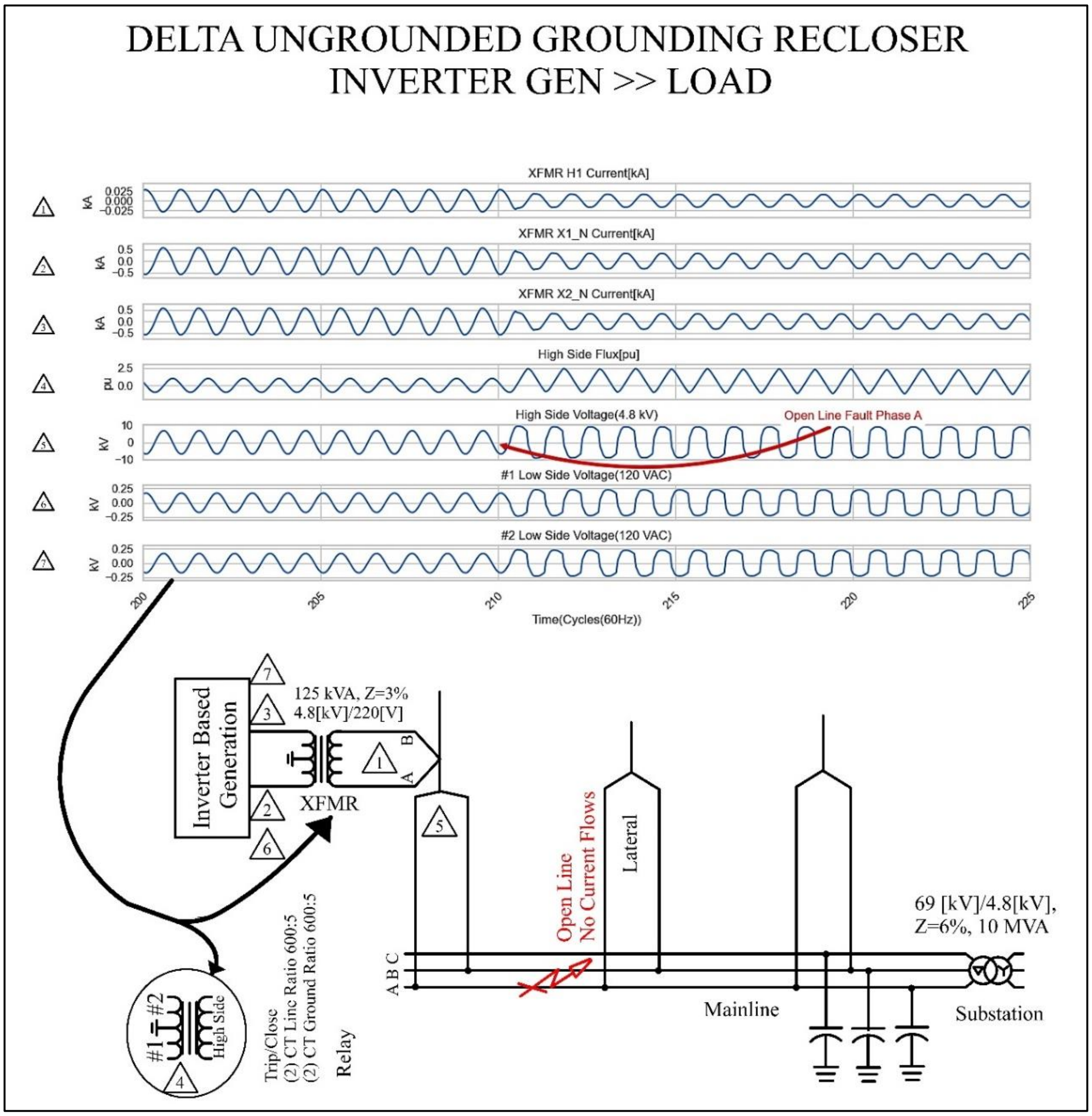


Fig. 12, No Grounding Recloser, Battery/Solar Inverter Generation Greater than Load.

Case 3. Open Line, Inverter Generation, with Grounding Recloser Protection

This case begins with inverter-based generation, where the current is arbitrarily set at 17 A RMS as measured at the high-voltage side of the transformer. All loads on the lateral were set to zero. The inverter and lateral are sourcing approximately 81 kW. The open line occurs at Cycle 210. The distorted line-to-line voltage increases to 8.92 kV peak, and the distorted voltage increases to 1.62 per unit [4.8 kV base]. The arresters are conducting, clamping, and distorting the signal. The inverter current decreases when the voltage increases because the inverter controller is “attempting” and fails to keep the power constant. The current flows through the lightning arresters but for a shorter period than Case 2 (Fig. 12), which is without the grounding recloser. Case 3 includes the grounding recloser (Fig. 13 and Fig. 14).

The difference between Cases 2 and 3 is that the grounding recloser is included in Case 3. In Case 3, the phase conductors on the lateral and the high sides of the pole mount transformer are eventually bonded together. In Case 3, the inverter current setting is “arbitrarily” set to 370 A (100%), as measured on the low side of the pole-mounted transformer. With the grounding recloser bonding and grounding, the lateral’s phase conductors. The result is that the “**grid following inverter** “model now has a low impedance path to source 500 amps (approximately 135%) of current until it shuts down (Fig 13 and Fig. 14). Both the relay and grounding recloser protect the inverters as well as the power system (Fig. 13, Bonded Inverter Current Source, Current Limiting (Typical Settings: 1.3–1.6 pu) and Fig. 14).

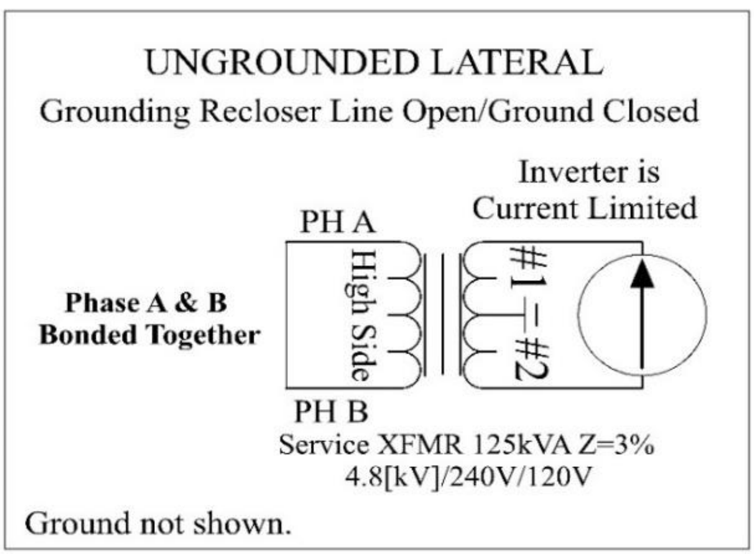


Fig. 13, Bonded Inverter Current Source, Current Limiting (Typical Settings: 1.3–1.6 pu)

Around Cycle 219, the grounding recloser causes the flux of the transformer to become zero (Fig 14) and shortly thereafter the current increases back to a 500-A peak (**low side voltage/high side current of a pole-mounted transformer**); however, the voltage on the lateral at the pole-mounted transformer is near zero (Fig. 14: Graphs 5, 6, and 7). Consequently, the voltage is forced into the ride-through area of the chart in Fig. 16 (See Page 22), where the “certified” inverter with a grounding recloser is certain to shut down.

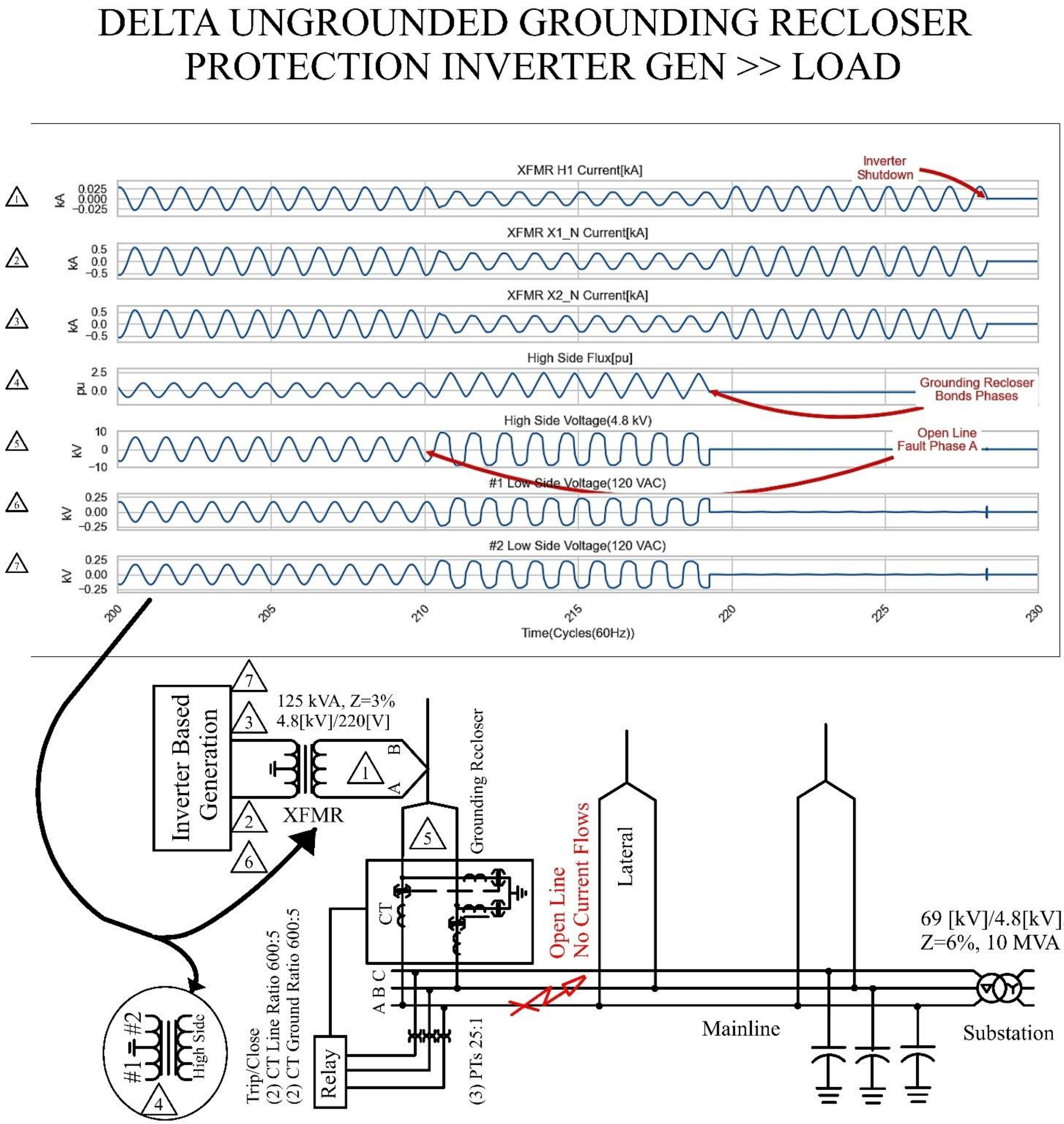


Fig. 14. *Grounding Recloser, Operation PSCAD Oscillography. IBR is shut down; reclose not shown.*

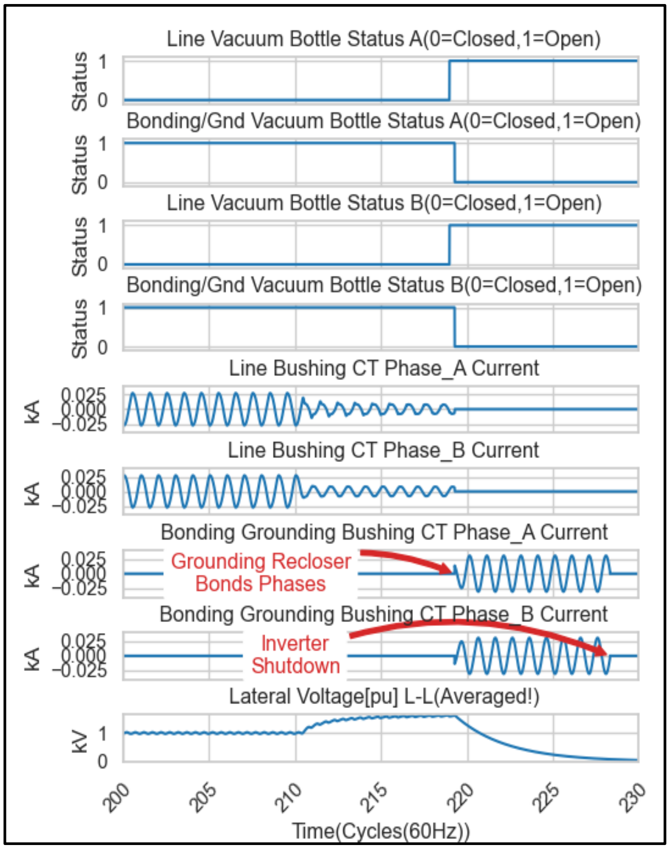
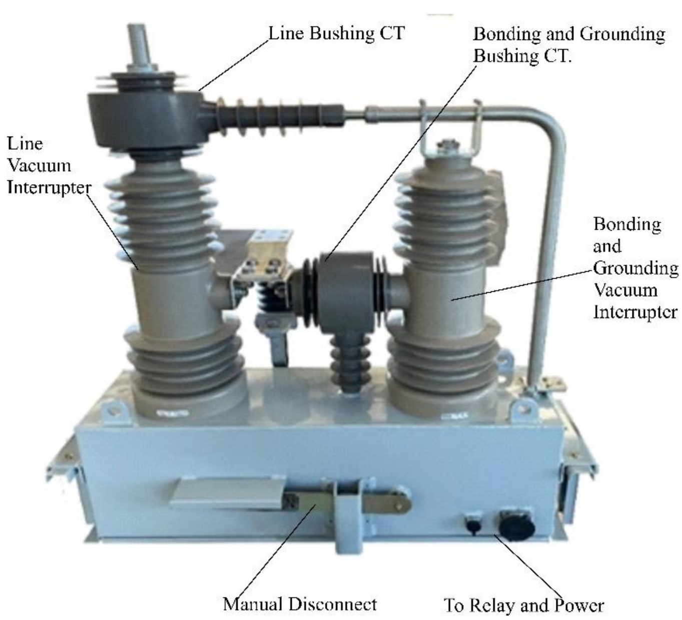


Fig. 15. PSCAD Relay Pickup and Oscillography (Case 3)



[Figure 2 on Second page].

3. *Bonding Vacuum Interrupters and Bonding and Grounding bushing CTs.*

The grounding recloser has bonding and grounding bushing CTs to measure the current supplied by the inverter(s) or EPS through the transformer for each phase. The grounding recloser provides a bonding and grounding bushing CTs which is a new and novel method for sensing, that planners and relay engineers do not have with typical reclosers. For example, Figure 15 shows that around Cycle 220, the current measured by the bonding and grounding bushing CTs increases to program a hard limit (e.g., current limiting), after the grounding reclosers have bonded and grounded the phases together; then decreases to zero after the inverter shuts down before Cycle 230(Fig 14 and Fig. 15). With the grounding reclosers protection engineers would have IBR ridethrough data via the bonding and grounding bushing CTs.

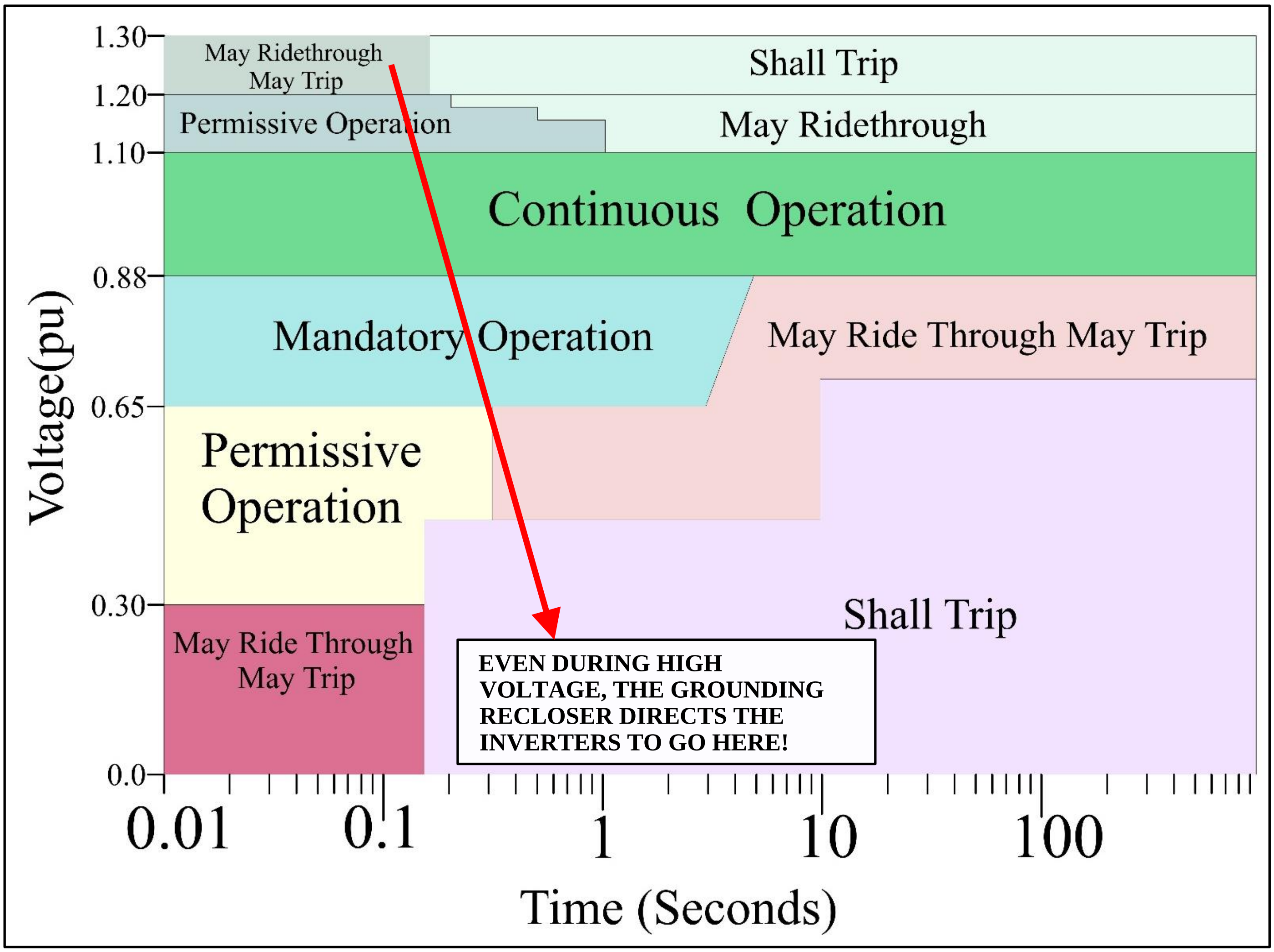


Fig. 16. IEEE 1547 Ride-through Chart

Fig. illustrates that an important feature of the grounding recloser is that the bonding and grounding bushing CT allows the engineer to determine if a single line-to-ground fault has occurred on the ungrounded lateral or that the inverter-based generation has ceased to supply current to the line. With the bonding of the phases, the voltage at the IBRs was near zero (Fig. , Fig. 16, and Fig. 17).

In transition, with both VIs open, this is nearly the same as an open line, consequently, the current is flowing through the arresters, is likely(this depends on the number, type and condition of arresters in service) they will clamp the voltage until the grounding recloser closes the bonding and grounding VI. This process takes as much as 16 ms and as short as ¼ cycle after the arc in the line VI (Fig. 17) is extinguished.

Once the bonding and grounding VI closes, the current supplied by the inverters is measured using the bonding and grounding bushing CT (Fig. 15 and Fig. 17). Conventional reclosers do not have such a function.

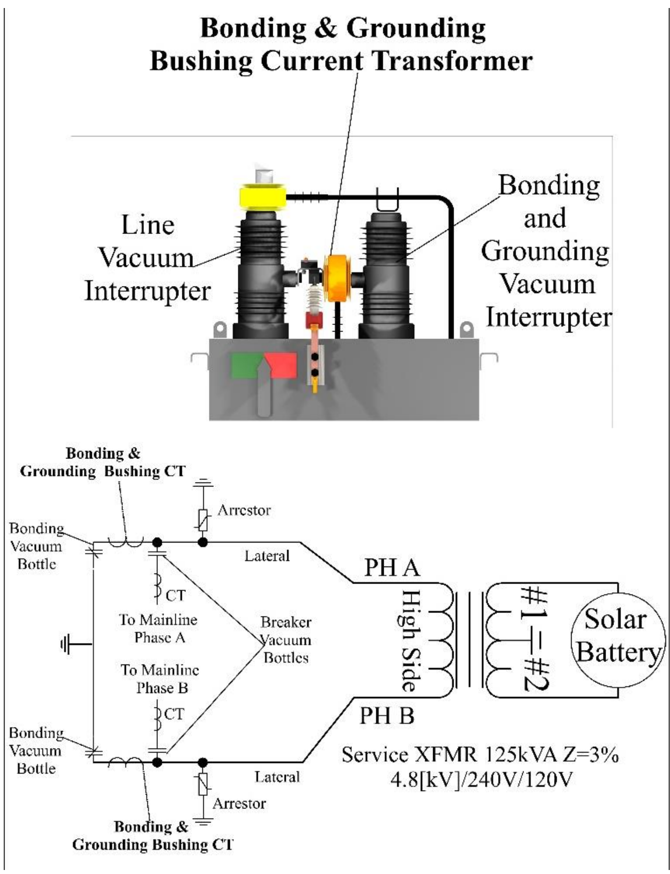


Fig. 17. ***Bonding and Grounding CT.*** *It provides inverter current measurements on each phase (Operators know if solar or battery shuts down, as specified by the manufacturer).*

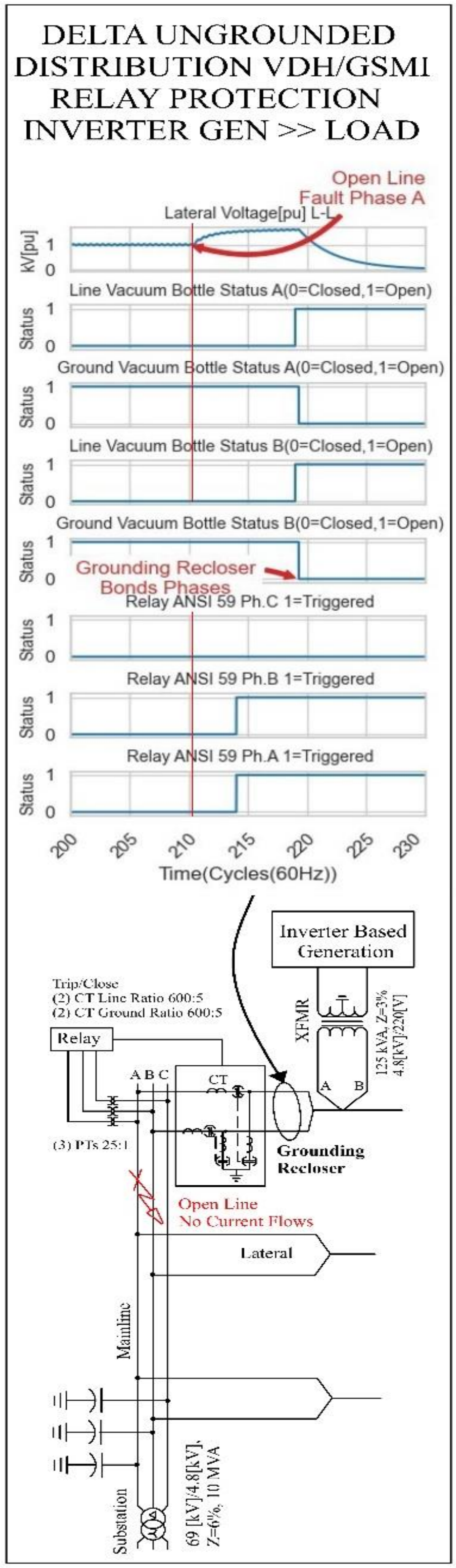


Fig. 18. PSCAD, Relaying ANSI 59-1 Overvoltage

Relaying ANSI 59-1 Overvoltage.

Fig. 18. PSCAD, Relaying ANSI 59-1 Overvoltage presents one of the mainline voltages in the simulation along with the simulated relay inputs. Figure 19 indicates the voltage measurement, and Fig. 18 shows the trigger on a per unit basis. In this case, the trigger was 1.35 pu, 2.77 kV base (line to neutral).

Fig. 18 presents the integrated mainline voltage on the top. The open line fault in Phase A starts at Cycle 210. Around Cycle 214, the ANSI 59-1 detects (Fig. 18) and sends a trip signal to the grounding recloser. The grounding recloser is delayed five cycles to trip (in certain cases, this can be reduced to three cycles). At Cycle 219, the grounding recloser trips, and the **line VIs** open first. Then, around a ¼ cycle later, the bonding and grounding VIs close (Fig. 18 and Fig.).

Figure 18 and Fig. 19 show the relay detects the LRO (caused by IBR backfeeding, then open line) overvoltage and then the response of the inverters (Fig. 19), and at last, showing when the inverters have shut down. Fig 19 shows the "islanded" inverter current is sensed flowing through the ground or the bonded phase conductors by the bonding and grounding bushing CT (Fig. 15) on the grounding recloser. This is important information typical reclosers do not provide, however the grounding recloser does.

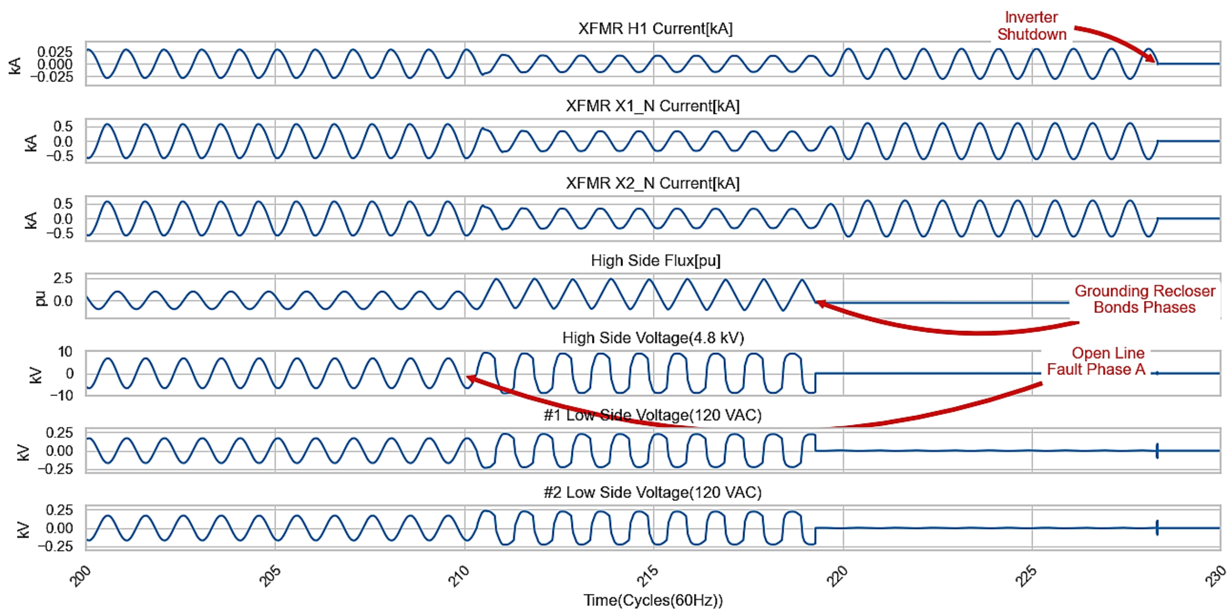


Fig. 19. PSCAD Relay Pickup and Oscillography (Taken from Case 3, Figure 14)

V. DISCUSSION

A. *Misoperation*

Misoperation can occur, and the grounding recloser relies on existing zone protection. The grounding recloser provides added protection during a reverse power flow on the distribution circuit during an LRO. Any failure of a protection system element to operate within the specified time when a fault or abnormal condition occurs within a zone of protection is called misoperation (see *National Electric Reliability Corporation Std. NERC PRC-004–3—Protection System misoperation Identification and Correction*). In addition, any operation for a fault not within a zone of protection other than operation as backup protection for a fault in an adjacent zone that is not cleared within a specified time for the protection for that zone or any unintentional protection system operation when no fault or other abnormal condition has occurred unrelated to on-site maintenance and testing activity is also called misoperation.

The grounding recloser is installed in addition to coordinated fuses and upstream relays for protection during reverse power flow on the distribution system and to provide protection when the power flow is reversed. Fuse and upstream protection may not work with reverse power flows and such “asynchronous” resources.

For example, concerning DTT, a distribution system without an installed grounding recloser during an IBR islanded LRO fits the above definition of misoperation because DTT fails as a method of protection to sense the voltage and currents necessary to distinguish when to provide zone protection during an IBR islanded LRO in accordance with IEEE 1547(2018). DTT fails to detect if the IBR has shut down, but the grounding recloser does (**see <u>bonding and grounding bushing CT,</u> Fig. 15, Fig. 17, and Fig 19**). The grounding recloser relies on existing zone protection, conversely the IBR and existing zone protection equipment relies on the grounding recloser.

A misoperation such as delayed operation by a grounding recloser would present the same effects as an open line or single line to ground fault, or line to line fault; where existing zone protection including fuses or upstream devices would detect misoperation by one or several grounding reclosers; the grounding recloser is added to protect the distribution system or EPS during reverse power flow or LRO caused by IBR.

B. PSCAD simulation

The PSCAD simulation indicates that during an open line on the mainline, overvoltage occurs if the inverters do not shut down. The IEEE [1] also provides details on such events in the field.

During reverse power flows regardless of the configuration, delta or wye, grounded or ungrounded an overvoltage occurs on a separate distribution line. When an open line occurs, the energy supplied by the inverters (which are online and produce power) increases the voltage on the separated circuit. PSCAD results revealed that the increase in voltage is high enough to damage the separated circuit (Fig. 12). In addition, the IEEE [1] reported several events occurring where the voltage increased to 1.59 pu.

The simulation indicates that an islanded IBR increases the voltage, and the grounding recloser is the fastest and most reliable way to reduce the duration of the TOV.

PSCAD simulations demonstrate that during severe islanding, when the distribution circuit is separated and the generators produce maximum power, the saturation level of the transformer and the lightning arrester and customer’s surge protectors will lower the peaks. However, lightning arresters and surge protectors age, and it is questionable that customers and utilities should rely on these devices alone. Lightning arresters are challenging to characterize. However, a grounding recloser provides a known amount of time the arrester would be burdened with TOV thereby making it easier for planners and engineers to perform a better insulation coordination study.

Generally, a distribution circuit has multiple lightning arresters connected. Usually, the manufacturers design their arrester to exceed the recommendations presented by IEEE standard 62.22 concerning TOV. However, PSCAD simulations demonstrate that during severe islanding of an affected distribution circuit or during an open line, lightning arresters are damaged.

This paper examines three cases.

Case 1. PSCAD simulations, as expected, show that without inverter generation on the distribution circuit, an open line causes the voltage to drop.

Case 2. PSCAD simulations demonstrate that if a line opens on the main line between the substation transformer and the backfeeding IBR, or while the inverters are generating and their generation is greater than the load, there will be a significant prolonged overvoltage during an LRO. IEEE reports indicate the same [1].

Case 3. PSCAD simulations demonstrate that if a grounding recloser with a relay and potential transformers is installed on an IBR fed lateral, a period of ≤9 cycles is required to drive the voltage on the lateral low enough to cause the inverter to begin detection to go offline (Fig. 15), where some inverters will instantaneously shutdown, however this inverter in this simulation was arbitrarily set to ride through and took an additional 9 cycles. In addition, the bonding and grounding bushing CT provides additional information to ensure the generation has ceased before reclosing (not shown in this simulation because the fault is persistent), after either the fault has cleared, the line is reconfigured or repaired and placed back into service. Moreover, this simulation indicates that backfeeding IBR causes the TOV or LRO, and the grounding recloser quickly resolves the LRO.

VI. CONCLUSION

A grounding recloser, if properly coordinated, can separate the affected lateral(s) from the distribution system within 3–5 cycles after the relay detects and sends a direct trip signal to the grounding recloser to operate.

A distribution grounding recloser provides a bonded path between phases and a solid ground, with the lighting arresters in mind, temporary voltages are avoided, and the grounding recloser clamps the voltage on the affected lateral to cause the inverters to safely and immediately shut down by sensing the low voltage. This avoids exacerbation of the overvoltage condition due to the IBR erroneously reacting to a transient overvoltage condition.

Existing devices, such as reclosers and DTT (remote trip), do not have the capability mentioned above.

During switching of the grounding recloser, both VIs may be open for up to 16 ms; in this case, TOV is already established and is not a factor. In other cases, however, studies need to be performed to determine which surge devices in the circuit can clamp the voltage with a worst-case real power flow from the affected IBR.

The simulation indicates the islanded IBR increases the voltage, and the grounding recloser is the fastest and most reliable way to reduce TOV duration in the affected distribution circuit.

Once a grounding recloser bonds and grounds the phase conductors together the IBR may island; however, the incident energy into the EPS is greatly reduced.

VII. Acknowledgments

The author thanks all of those working with EMA for their support in producing this paper concerning the design and operation of the grounding recloser for wind power plants and solar power plants.

VIII. REFERENCES

[1] Key, IEEE Power and Energy Vol. 18; Number 6, Nov/Dec 2020, pg. 75-85.

[2] Montich, “Circuit breaker with high speed mechanically-interlocked grounding switch,” USPTO Patent 7724489, Aug 2007.

[3] IEEE Std 1547-2018. IEEE standard for Interconnection and Interoperability of distributed energy resources with Associated Electric Power Systems Interfaces.

[4] CFR title 10 Chapter II Part 431 (in Appendix A of Subpart K 2016).

[5] NERC Bulk Electric System Definition Reference Document Version 3 | August 2018

IX. NOTES: ERRATA, CHANGES AND REVISIONS.

Changed to a single column and adjusted figures; Changed Figure 9 and provided high-resolution figures; Added discussion about asynchronous IBR; Added Figure 2 on page 23; Adjusted bullets and headings; Added section ERRATA AND CHANGES; Added subsection similarities and differences between 1547 and the Bulk Electric System; Added discussion for temporary vs transient concerning arresters; Included various clarifications and proofed read with Scribendi; fixed spelling in figure 9 and reformatted, separated figure 1 and figure 2 on two pages. Corrected spelling for arrestor, replaced with arrester; Edited figure 7, expanded on the meaning of temporary conditions. Re-rendered and improved resolution of figure 4. Reformatted figures 1 and 2 and added figure on title page. Changed Fig 1 to Fig 1a, Fig 2a. add to abstract Which can be a signal on the power line to remote trip IBR. Edited Figure 3. Fixed number problem in word file. Changed published EMA specification. The automatic grounding recloser is Rated Max Voltage:15.5 kV; Rated Lightning Impulse: 125 kV BIL; Rated Continuous Current 800 A; Rated Symmetrical Interrupting Current Main Breaker: 25 k; Rated Symmetrical Interrupting Current Ground Breaker: 12.5kA; Line Charging Current 2 A, Cable Charging Current 10 A, Dry Withstand 60 Hz 1 min 50 kV, Wet Withstand 60 Hz 10 Sec; opening Time 30msec, closing time 55msec.

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