Concerning PRC-024-2 the VDH/GSMI Supports Differentiation between Internal and External Faults

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Abstract - Because the interlocked combine breaker grounding switch (VDH/GSMI, a medium voltage vacuum circuit breaker with mechanically interlocked grounding switch) can help with differentiating between internal faults and external faults, as such, generators would know via the voltage measured at their terminals if a fault was outside the plant and keep running, to meet the US grid code PRC-024-2 under voltage ride-through requirements with zero volts at the point of interconnection. Conversely, with respect to internal disturbances, the VDH/GSMI creates a three-phase bolted ground that causes the generators to either shut down or island into very low impedance and can operate while they wait for the remote trip signal from the substation, where a regular circuit breaker opening would cause high impedances to appear on the home run cable. The generators and high impedance create possible temporary overvoltages that would damage equipment on the separate collection circuit.

PSCAD models show the VDH/GSMI allows generators to differentiate between internal faults and external faults. NERC PRC-024-2's written purpose is to ensure generator owners set their generator protective relays such that generating units remain connected during defined voltage excursions and operate down to zero percent voltage at the point of interconnect (POI) for nine cycles. PSCAD simulations show the VDH/GSMI when it opens and clears and then closes to ground causes the voltage at the mains of each generator on the affected circuit to go below 9% which is significantly below 15% concerning certain ride through requirements. As a benefit, the VDH/GSMI causes the plant to better support the transmission system by providing a differentiating voltage signal between internal and external faults.

Worldwide, utility scale wind or solar facilities have to comply to the local grid code. for instance, Submodulo 3.6 of ONS in Brazil, PT4 (Anexo I) of CAMMESA in Argentina, PRC-02402 of NERC in the USA.

PRC-024-2 requires power plants set their relays so that the plant remains connected during voltage excursions, such that the generator voltage protective relaying does not trip within the no trip zone as measured at the POI; the no trip zone in part includes nine cycles at zero volts. PSCAD simulations indicate the VDH/GSMI can help engineers provide such required PRC-024-2 functionality.

Keywords – grid, code, PRC-024-2, ONS, Submodulo 3.6, CAMMESA, PT 4, breaker, grounding, switch, remote, transfer, trip, wind, solar, electric, power, system, flash, arc, blast, temporary overvoltage, lightning, arrester, collection, circuit, cable, transformer, single, line, ground, fault, isolation, coordination.

I. INTRODUCTION

This paper was prepared to find if the interlocked-combine-breaker grounding switch (VDH/GSMI® or Grounding Breaker) coordinates well with PRC- 024-2 (HVRT-LVRT) requirements when the fault is inside and outside a wind or solar power plant. When the Grounding Breaker opens, clears, and then closes to ground the home run cable, it is expected the voltage will drop below significantly. Should the fault appear outside the plant for nine cycles with near zero volts at full power, it is expected that the voltage measured at the generators should be higher when there is zero voltage at the point of interconnection (POI) than when the Grounding Breaker opens and then grounds the collection circuit. Thus it provides a level of discrimination for protection and trip as measured at the terminals of each individual generator within the solar power plant or wind power plant.

Generators are expected to shut down quickly; or if they island, they island into a three-phase bolted ground, and they can wait for the remote trip signal without creating overvoltage and other damage.

This paper makes use of PSCAD tool to describe the design and theory of the Grounding Breaker operation, as it is applied in wind and solar power plants and how the very low impedances to ground causes very low voltage on the separated collection circuit. The operation of the Grounding Breaker with PRC-024-2 requirements coordinates well with other plant functions during a ride-through event.

The Grounding Breaker is an improvement and evolution in circuit breaker design. Circuit breakers come in a variety of forms: vacuum, air, and gas-insulated switchgear are available for medium-voltage systems, such as a 34.5 kV collection circuit of wind or solar power plant. Circuit breakers are mechanical switching devices, which connect and break the current flowing in the circuit, which can be the nominal current or the fault current. Typical circuit breakers comprise one switch that is either open or closed. Generally, wind power plants and solar power plants only use non-grounding feeder (line) circuit breakers.

When considering a collection circuit for a wind or a solar power plant, the typical circuit breaker clears the affected feeder from the main station transformer and the transmission system. However, such a design is limited and does not provide the same functionality as the Grounding Breaker does, functionality, such as anti-islanding or temporary overvoltage mitigation, needed for today's modern such plants.

The Grounding Breaker requires only one signal from a relay to separate the collection feeder circuit from the main plant transformer. Then the interlocked switch grounds the collection circuit; the full process occurs in about three cycles. With the impedance of the collection circuit cables approximately 1/15th of the impedance of an individual generation step up transformer, and with all three phases effectively bolted to ground, the voltage on the separated feeder quickly collapses.

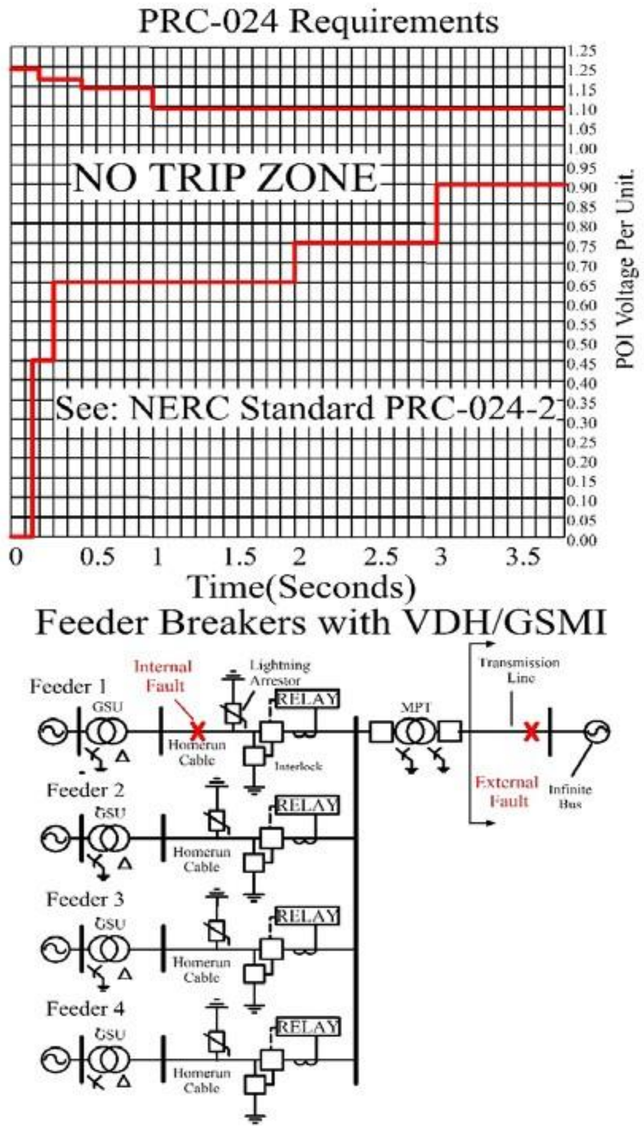

Fig. 1: Wind or Solar Power Plant Single Line.

The National Electric Reliability Corporation (NERC) that acts as an electric reliability organization (ERO) requires relay settings and wind or solar power plants to operate down to zero volts for nine cycles as shown in PRC-024-2 (Figure 1). The Grounding Breaker can help wind or solar power plant designers and engineers provide the functionality required by the local grid code, in this paper, NERC as specified in PRC-024-2.

The Grounding Breaker (Figures 1,3,4 and 11) is designed for the feeder collection circuits of wind power plants and solar power plants. The line-side circuit breaker is composed of vacuum interrupters and bushings to connect to the 34.5 kV collection circuit. For information about the operation and ratings of vacuum interrupters, see [7] and [8]. The grounding circuit when closed connects the generator's side of the feeder collection circuit to ground. The Grounding Breaker within wind or solar power plants connects between the substation bus and the wind turbines or solar inverters (Figure 1).

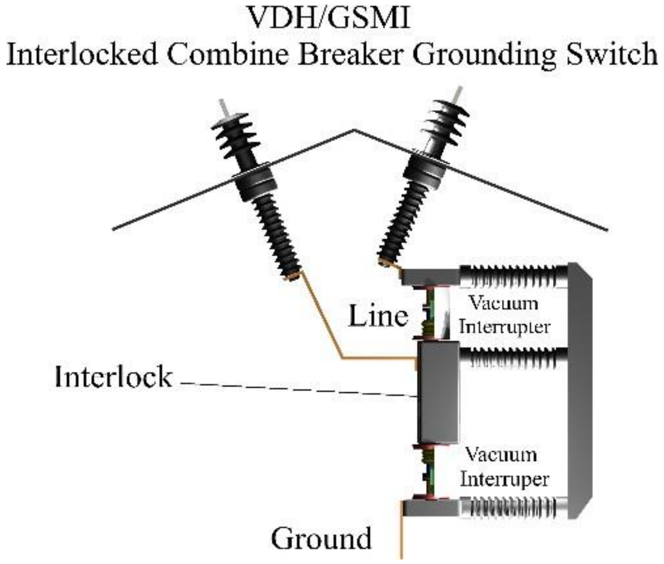

Fig. 2: Combine Breaker Grounding Switch

Figure 2 shows the Grounding Breaker. It consists in a set of three line-side phase vacuum interrupters and a set of three ground vacuum interrupters are interlocked and operate with one trip signal.

In such power plants, conventional breakers open and disconnect the affected feeder from the transmission system and then allow the delta collection circuit to operate without a ground reference (except through the cable susceptance or lightning arresters), unless a grounding transformer is connected to an individual collection circuit. If the grounding transformer provides a reference to ground, however, it is found to provide only a zero sequence path to ground but not a positive or negative sequence path, and consequently is not found to significantly lower collection circuit voltages during islanding [3], [19]. IEEE standards refer to zero sequence impedance. The positive and negative sequence current from the generators has no path, once the grounding transformer has an open secondary.

It is found [19] that the Grounding Breaker, in coordination with lighting arresters provides a better positive, negative and zero sequence ground reference than a grounding transformer and opens with an electrical switching of time of 4–12ms, i.e. less than one cycle. Thus, it grounds the collection circuit immediately and allows the unaffected feeders to generate, also allows the ride-through functionality.

Figure 1 shows the single line for a wind or solar power plant, with the Grounding Breaker; where the interlock and grounding switch are on four collection circuits or feeders, also the home run cable and the Generator Step Up Transformer (GSU) where the GSU is the equivalent of many generators. The delta side of the GSU indicates that the home run cable will float once the line breaker opens. However, the Grounding Breaker will within 38ms from receiving a trip signal, close and ground the affected collection circuit; where

16ms earlier it mechanically began to operate and 4–12ms earlier it electrically began to extinguish the arcs and ground the home run cable. All with one single trip signal.

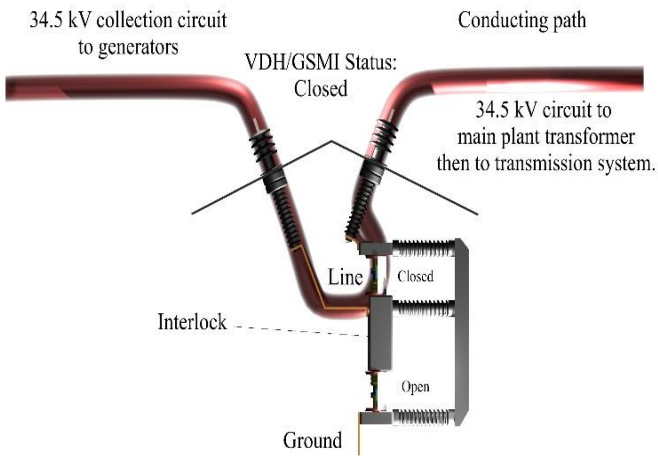

Fig. 3: Grounding Breaker Closed, Ground Switch Open.

Figures 2 and 3 show the Grounding Breaker when it is closed (the ground switch is open). The red bold line indicates the electric path from the generators on the feeder to the main plant transformer.

Figure 4 shows the Grounding Breaker opened where the feeder is grounded as shown with the green path. The home run cable's three phases are bolted to ground. By bolting to ground the home run cable of a feeder, the generators see very low impedance while islanding. Generally, wind and solar power plants should remain on-line during voltage disturbances for specified time periods per PRC-024-2 as shown in Figure 1, where such periods include a transition period and a post-transition period with normal clearing times of four to nine cycles [15].

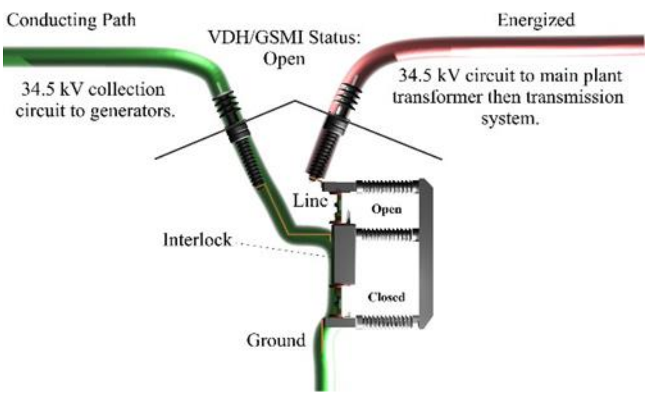

Fig. 4: VDH/GSMI Open, Grounding Switch Closed.

II. FERC ORDER 661 AND NERC PRC_024-02

Concerning FERC order 661, wind and solar generated power plants are required to continue to generate power (e.g., in service) during three-phase faults with normal clearing. Generally, the clearing time and the voltage ride through for a wind power plant for a three-phase fault is nine cycles at a voltage as low as 0.15% of nominal, as measured at the high side of the wind-generated plant step-up transformer at the point of interconnection. Many generator manufacturers can operate with this specification for individual generators. However, NERC issued standard PRC-024-2; this standard requires more than nine cycles at zero voltage as measured at the point of interconnection (Figures 5 and 6).

For years, NERC, an electric reliability organization, has been presenting and reaffirming that a fault that occurs on a transmission line near a wind power plant could cause the voltage at that point to drop to zero. NERC states that; allowing a wind or solar power plant to disconnect when the voltage drops below 15% from the nominal at the point of interconnection; the loss of a transmission line and the loss of the real power (and any reactive power) produced by such plant, results in a double contingency event (loss of the transmission line and the plant itself) [16].

To provide a remedy for this problem, NERC requested that wind or solar power plants (Figure 1) should be altered so that for 150 ms if the voltage at the point of interconnection is reduced to zero the plant would ride through. If after 0.300 s the fault persists, the wind or solar power plant stays connected as long as the voltage is at or above 0.45 pu of nominal voltage. It is presumed that NERC presents such conditions to reduce the risk to the reliability of the electric power system to an acceptable level.

In this section, the Grounding Breaker (Figure 8) provides support for a generation plant concerning PRC-024-2 and ride-through capabilities concerning the many types of faults. For internal and external faults, the Grounding Breaker is shown to provide clear different high (external) and low (internal collection circuit fault) signals to the generators. After the Grounding Breaker opens and clears and then closes and grounds, the resulting line to ground impedance on the home run cable is significantly reduced. With that in mind, the Grounding Breaker provides "easy" islanding capability where the voltage remains very low. As PRC-024-2 requires nine cycles of ride-through capability, with zero voltages at the point of interconnection, the Grounding Breaker supports the generators by providing a voltage level that indicates whether the fault is inside or outside the plant to an individual generator.

III. GROUNDING BREAKER AND PRC-024-2

This section concerns how the Grounding Breaker provides support for a generation plant regarding PRC-024-2 and ride-through capabilities for the many types of faults. After the Grounding Breaker opens and then closes, the line to ground impedance on the home run cable is significantly reduced. It provides an "easy" islanding capability where the voltage remains very low. As PRC-024-2 requires nine cycles of ride-through capability, with zero voltages at the point of interconnect, the Grounding Breaker provides engineers and designers with an option not found in a typical feeder breaker.

If the fault is within the plant, such a fault can be isolated from the plant and the transmission system with the Grounding Breaker, separating the affected collection circuit. The unaffected feeders are able to ride through and remain on-line. The Grounding Breaker and the ride-through capabilities of the generators work together to meet the regulatory requirements specified in the U.S. Federal Energy Regulatory Commission (FERC) Order 661 and NERC PRC-024-2, and similar grid code applicable in other countries.

Many types of faults can occur. However, this paper considers internal single line faults to ground and external three phase bolted faults. The faults can be within a wind or a solar power plant or outside of such plant. The fault can be on a collection circuit, at a generator, or in a substation. The fault impedance can be high or low; it can be steady or pulsing. Given all the faults, types and locations, the transmission provider requires that the wind or solar power plant ride through and discriminate when it should and should not ride through concerning internal and external faults (Figure 7). The Grounding Breaker is an essential part of fulfilling such requirements.

When the Grounding Breaker provides such low impedance when it grounds the home run cable, the generators either know to shut down when the Grounding Breaker operates or allows the generators to remain on-line and generate into a bolted three-phase to ground. It also allows the protection system to send a remote signal to shut down the generators (Figure 7). By providing symmetry to a faulted collection circuit, it reduces mechanical stress during islanding. Figure 7 shows oscillations disappearing after the Grounding Breaker closes.

If the fault is external, i.e. on the transmission system, and the voltage is zero volts, the Grounding Breaker provides discrimination that other types of circuit breakers do not. When Grounding Breaker operates, it provides a clear signal to the generators that the main plant transformer is or is not part of the circuit. If the fault is on the transmission system, the Grounding Breaker is not expected to operate, similar to other regular breakers. What makes the Grounding Breaker different is that it can ground the collection circuit and provide a clear reference to ground by changing the impedance of the collection circuit.

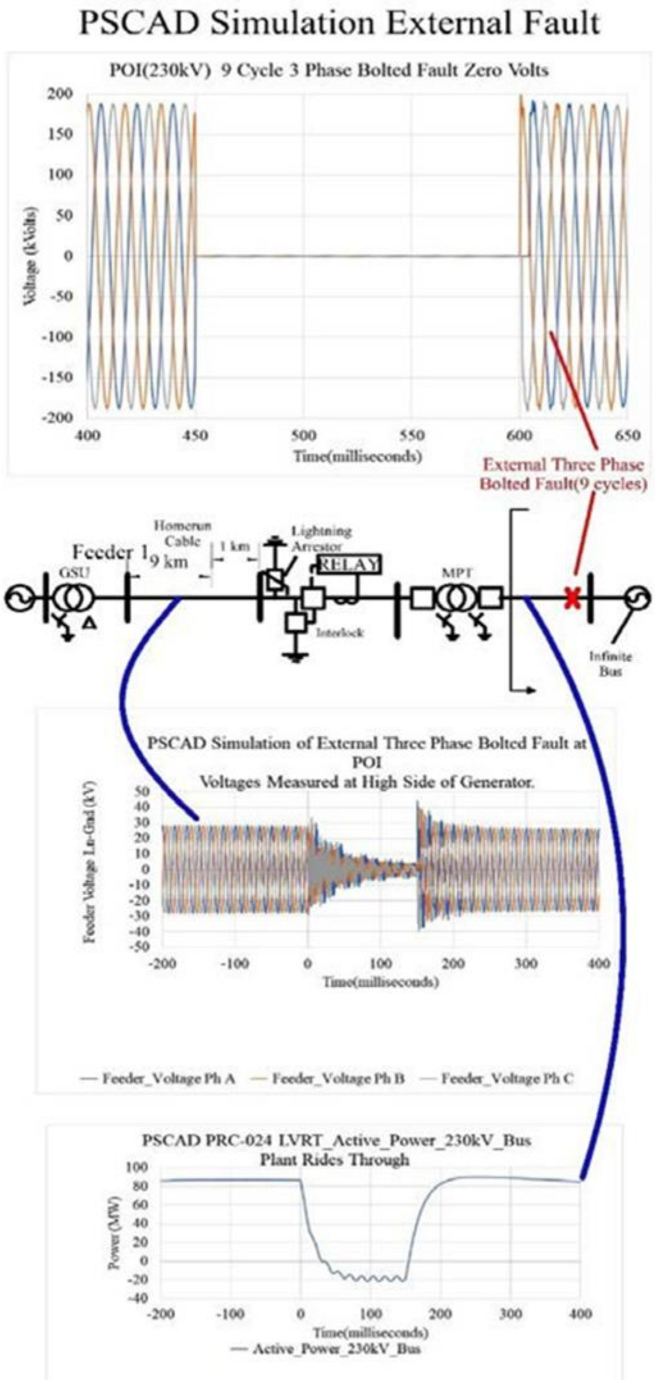

Fig. 5: PSCAD Simulation External Fault.

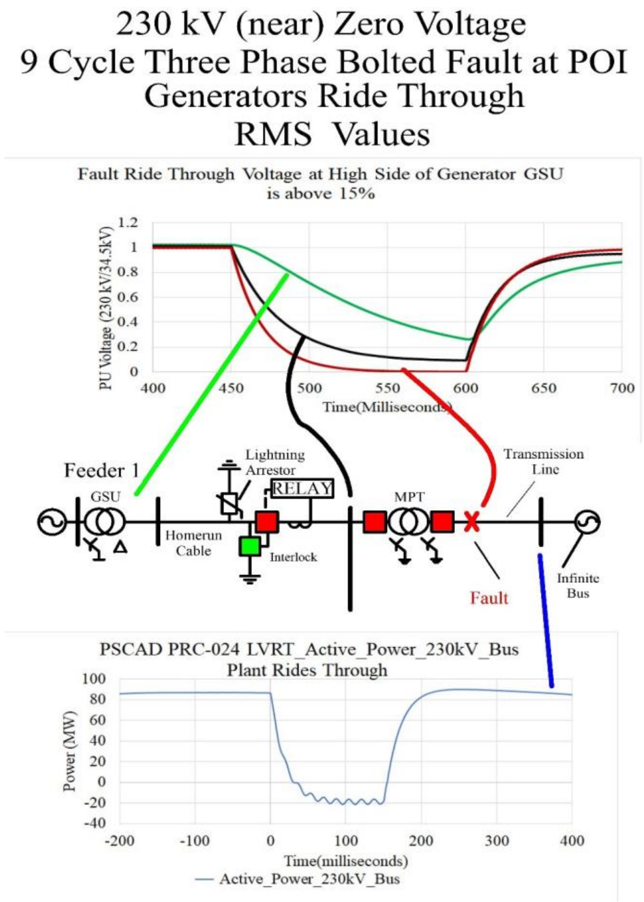

Fig. 6: PSCAD Simulation Voltage Curves during nine Cycles of (Near) Zero Voltage at the POI.

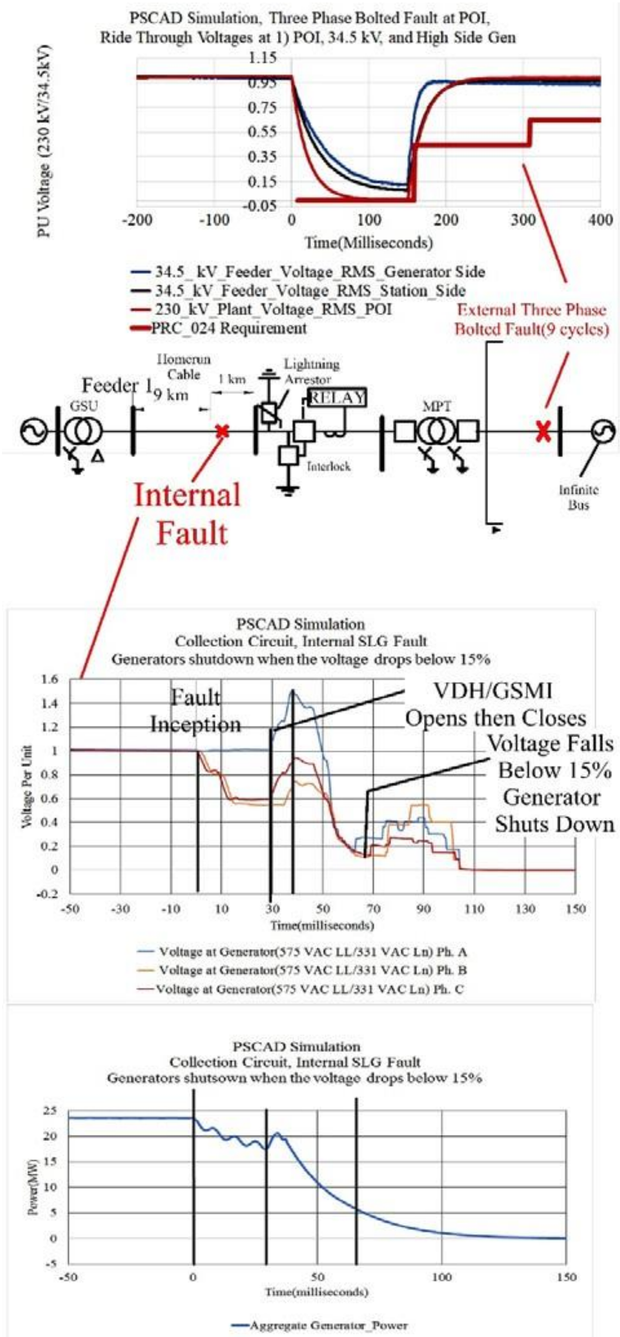

Fig. 7: Grounding Breaker and Ride-Through Voltages.

The impedance of a home run cable can be between 1 Ohms and 2 Ohms, and the current sourced on a 34.5 kV collection circuit can be 500 amps. The generators can limit the current during a fault. Once the Grounding Breaker separates the affected collection circuit from the plant, the fault current is reduced from more than 15 kA to 0.5 kA. When the Grounding Breaker grounds the home run cable, the impedance of the affected collection circuit is now down to 1-2 Ohms at the home run cable. With 0.5 k Amps and 1-2 Ohms, the voltage rise is around 3% to 5% at full power. The current from the 2 MW generator at 34.5 kV is approximately 40 Amps with a series impedance through its generator step-up transformer of 5.5% (3 MVA); therefore, the voltage increases across the GSU would be a maximum of approximately 4% to 5%. To sum up, the rise from the home run cable to the mains of the generator on the low side is projected to be less than 10%, where some PSCAD simulations demonstrated 12% or less due to asymmetry at the low side of the generator and on the collection circuit and added reactive power flow during a single line to the ground fault (Table 1 and Figure 7).

PSCAD Plant Impedances			
	Main Power Trf.	1000 MCM Cable (10 Kms)	Gen.Step-up Trf. (Equivalent)
% Z	8	N/A	5.5
MVA	90	N/A	3 / (x10) 30MVA
Ohms	*j* 1.05	*j* 2.00	*j* 21.80 / *j* 2.18
External Fault	Included	Included	Included
Internal Fault	**Excluded. Gen. side after Grd. Breaker operates.**	Included	Included

Table 1: Impedances included in PSCAD simulations.

PRC-024-2 requires the facility to operate down to zero percent of the rated voltage. With PRC-024-2 in mind, the Grounding Breaker provides three functions for a wind or solar power plant:

- low impedance for a separated collection circuit to generate;
- low voltage for the wind turbines to recognize that they can shut down;
- low impedance to mitigate severe islanding; if there are plant conditions that require the generators to operate below 0.15 per unit, the low impedance on the collection circuit provided by the VDH/GSMI allows a remote trip signal to get to the generators to shut them down without causing overvoltages or damage to the collection circuit.

While a regular breaker separates a faulted collection circuit from the plant and the transmission system just like the Grounding Breaker, a regular breaker does not ground the collection circuit. A regular breaker opens and causes high impedance to appear on the collection circuit resulting in temporary over voltage (TOV) and damaging voltage on the collection system. A regular breaker does not provide very low voltage as a discrimination function for generators to detect; therefore, generators are left to island for long periods. In contrast, the Grounding Breaker provides differentiation between internal and external faults in wind and solar power plants (Figure 8) allowing the generator to quickly shut down.

The Grounding Breaker does not require delays for clearing a fault on a collection circuit. However, a regular breaker may require a delay in clearing the fault from the plant, and therefore, the other unfaulted collection circuits are exposed to longer internal plant fault times where the plant as whole is impacted. Such an impact may degrade the plant's dynamic reactive power performance; if a Grounding Breaker had been installed, the faulted circuit could be cleared as fast as possible. Faster clearing allows the plant to transition back to prefault voltages and improved dynamic support of the transmission system.

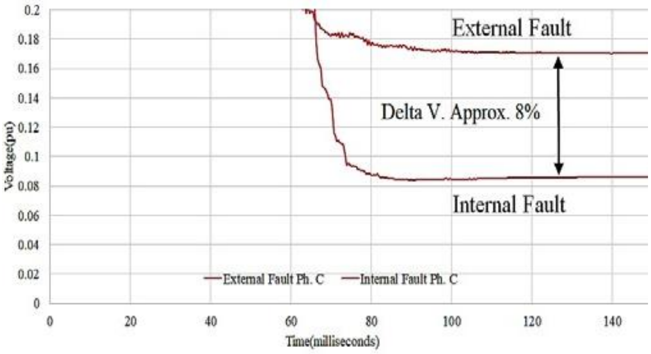

Fig. 8: Differentiation between an External (POI) and Internal (Collection Circuit) Faults.

IV. GROUNDING BREAKER OPERATIONAL

To describe and understand the design and operation of the Grounding Breaker VDH/GSMI, the focus has to be on a feeder circuit within a wind or solar power plant and the change in impedance that occurs when a fault appears on the collection feeder home run cable (Figure 10). The PSCAD simulation of the operation of a Grounding Breaker demonstrates that it grounds the collection circuit.
The states of the VDH/GSMI (Figure 9) are, (i) CLOSED, i.e. the line breaker is closed, and the ground switch is open; (ii) TRANSITION, both switches are open; and (iii) OPEN, the line switch is open, and the ground switch is closed. It actually has two distinct states of operation: OPEN and CLOSED. However, for studies propose the TRANSITION state is included between the two states, with a total mechanical operating time of 16 ms and an electric clearing time of 12 ms (Table 2).

Closed status means the line vacuum interrupters are closed, and the ground vacuum interrupters are open. The transition state includes the coincident operation of the two interlocked vacuum interrupters with at least one trip command from a relay (Figure 10). First, the line vacuum interrupter (breaker) starts opening to separate the feeder from the transmission system. At nearly the same time, the ground vacuum interrupter starts closing to ground the feeder circuit.

State	Electrical Time [ms]	Mechanical Operating Time [ms]
CLOSED (Initial)	0	0
Clearing Fault (opening)	24–34	N/A
TRANSITION (open and grounding)	4–12	16
OPEN and grounded		38

Table 2: Electrical and mechanical operating time of the VDH/GSMI

GROUNDING BREAKER VDH/GSMI - STATES			
State		Line Breaker	Ground Breaker
1	Closed	Closed	Open
2	Transition	Open	Open
3	Opened	Open	Closed

Table 3: States of the VDH/GSMI

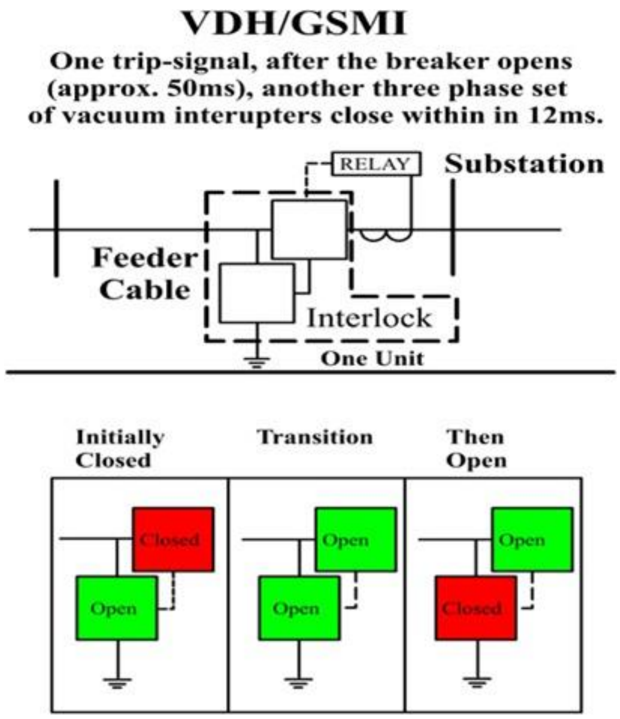

Fig. 9: VDH/GSMI States.

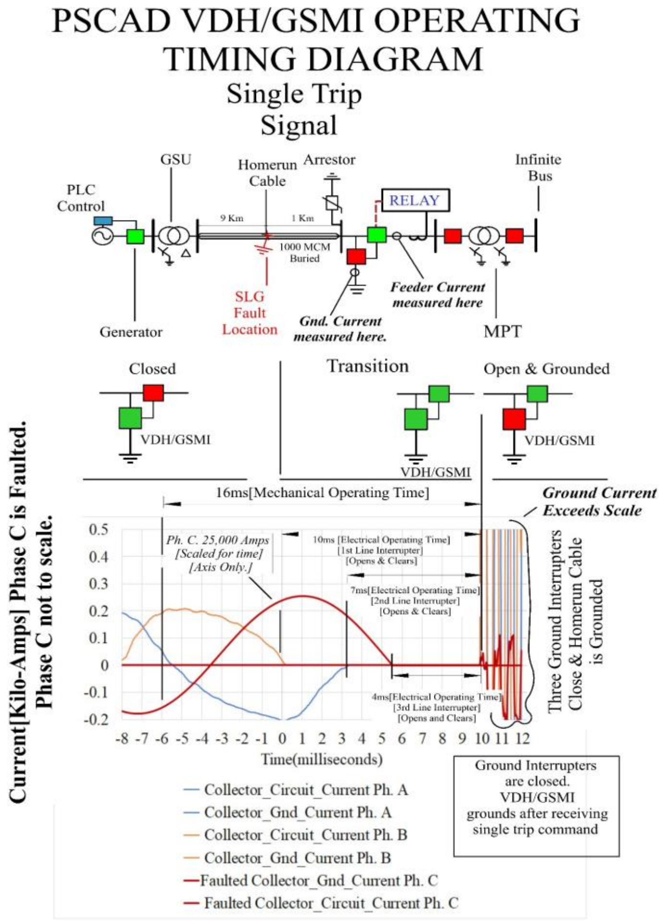

Fig. 10: PSCAD Simulation VDH/GSMI Timing Diagram.

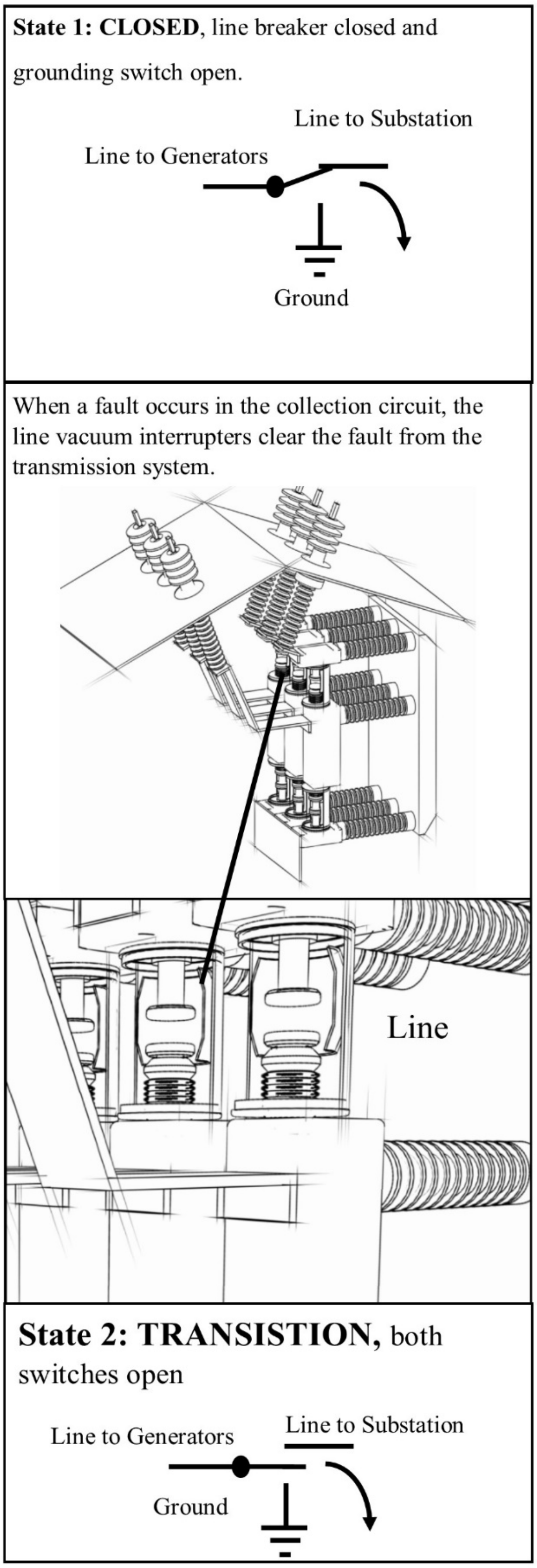

Fig. 11: VDH/GSMI Operating Sequence. The three-phase vacuum interrupters open first.

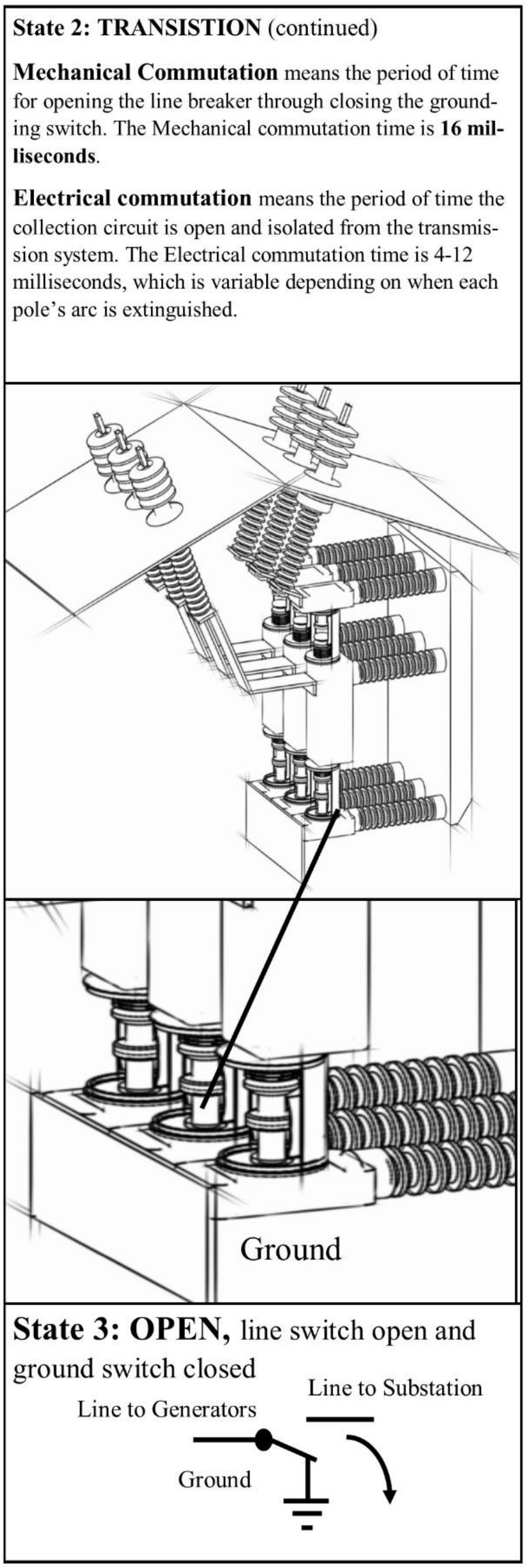

Fig. 12: VDH/GSMI Second Operating Sequence. The three-phase ground vacuum interrupter that closes the collection circuit is grounded.

Open status means the transition is complete, the line-side vacuum interrupters are open, and the grounding vacuum interrupters are closed. As a result, the feeder is electrically separated from the plant, and the phase conductors of the home run cable and the feeder circuit are now grounded at the station (Table 3). The mechanical interlock opens the line vacuum interrupter first. Then approximately 4-12 ms later, the interlock has caused the grounding vacuum interrupter to close. Concerning the opening of the line vacuum interrupters, the TP135-0 IEEE tutorial [17] on vacuum switch gear states: “Opening of a switch typically occurs at random with respect to the power frequency current, i.e. the contacts can separate at any instant. However, the current interruption takes place at the current zero. In typical medium voltage and high voltage switchgear the current waveform during the arcing phase of the switch, after the physical contact parting and before the current zero, is not significantly modified by the arcing voltage. The exception to this rule are the current limiting devices.” (Figure 10)

Figure 10 shows that when the line-side breaker opens, the currents stops flowing between 4 ms and 12 ms before the ground interrupters close. When the ground interrupters close, the currents flow into three-phase bolted ground.

V. CONCERNING PSCAD AND VDH/GSMI

A typical simulation starts as shown in Figure 13, where the PSCAD simulation initial power level is 24 MW and 70 MW for the unaffected feeder, and the currents and voltages are symmetric and undisturbed. Figure 14 focuses on the incident energy, where the VDH/GSMI has limited the fault current sourced from the transmission system to three cycles. In addition, Figure 16 shows that after the collection circuit is grounded, the voltage is low enough to cause the generators to go offline. However, the higher the impedance of the collection circuit, the less likely this will happen.

Figures 14 and 15 show the simulation with the relay picking up the fault within a quarter of a cycle or 4ms. Then the same relay sends the trip command 3ms later to the VDH/GSMI, which has opened and grounded the collection circuit 38ms later. The total clearing and grounding time is 45ms. During the transition, the lightning arrestors clamp the voltage for a very short period of time, and the burden appears below the TOV duty curve.

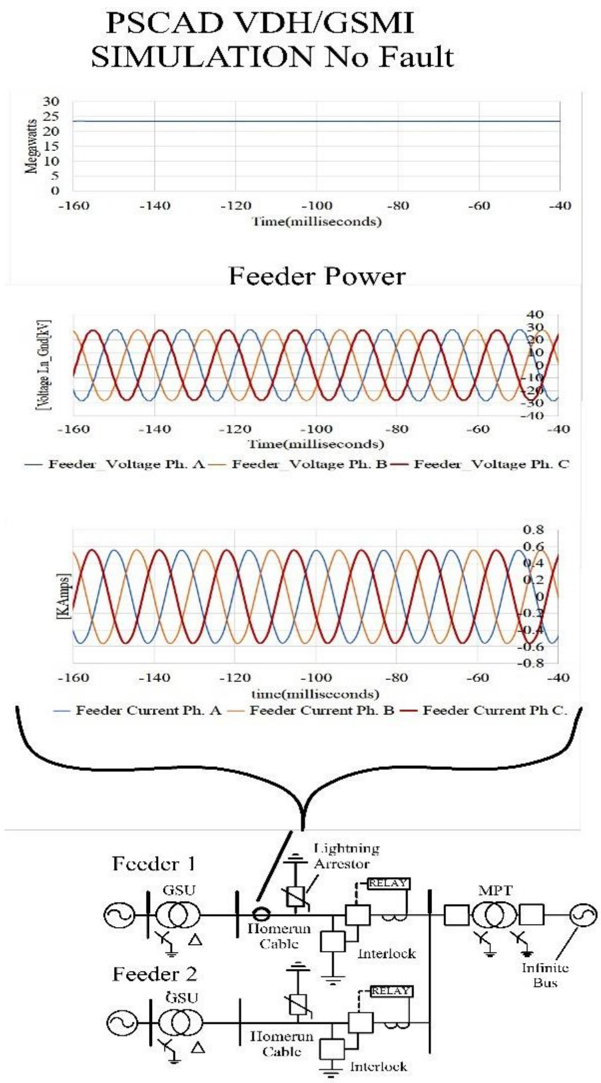

Fig. 13: PSCAD Simulation. It starts with no fault and a symmetrical feeder current. Active power is around 24 MW.

Concerning the states of the VDH/GSMI breaker, it is very important to consider the impedance of the home run section of the feeder cable during the three states of operation. In its quick transitions to ground, the collection circuit forms three-phase bolted ground on the home run cable. Therefore, this reduces the impedance looking into an end of 10 Kms home run cable to near 1 *j* Ohm to ground. This can be compared to a generator step-up transformer with a positive sequence impedance of 25 Ohms or a grounding transformer with similar or higher impedance.

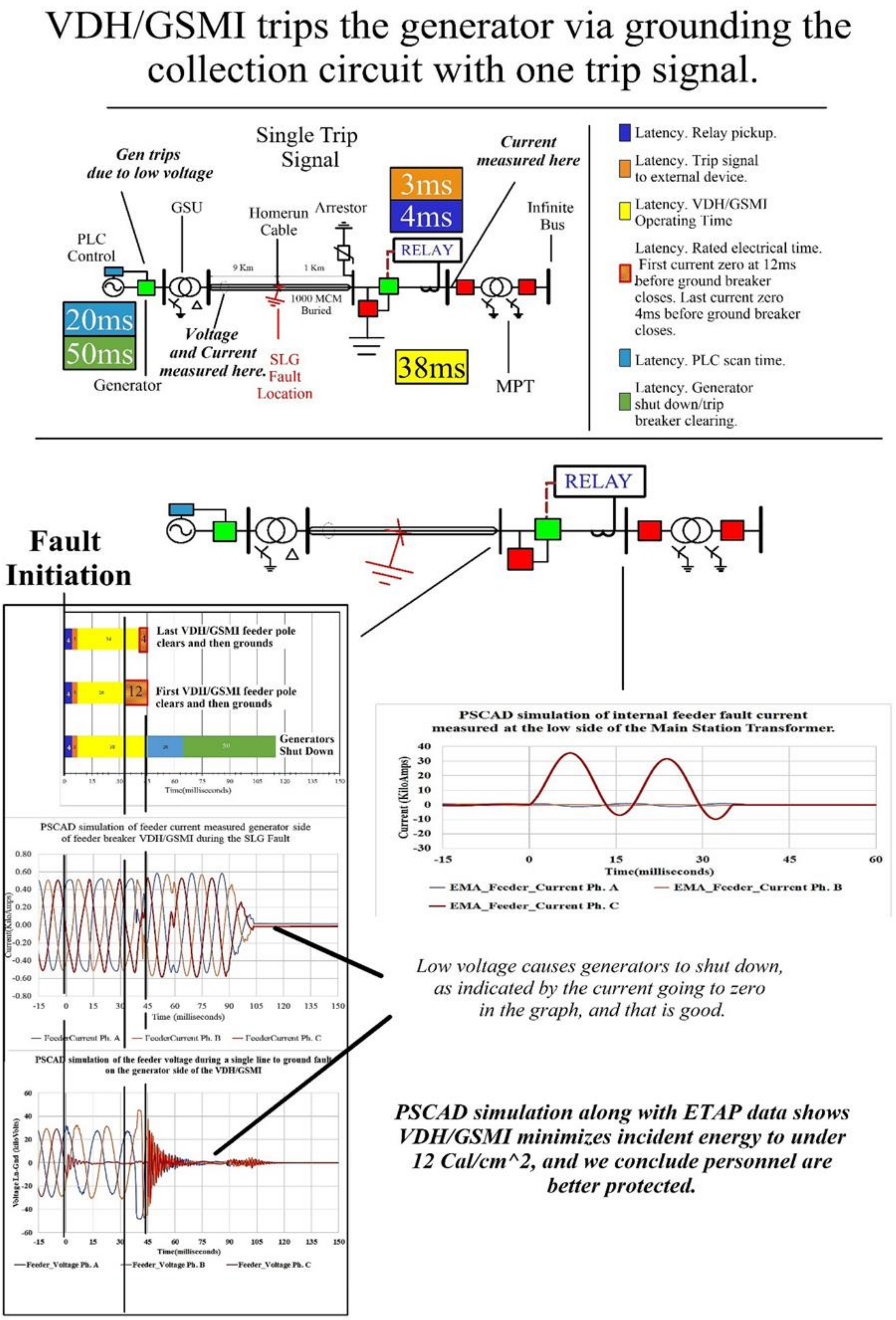

Fig. 14: PSCAD VDH/GSMI Timing Diagram.

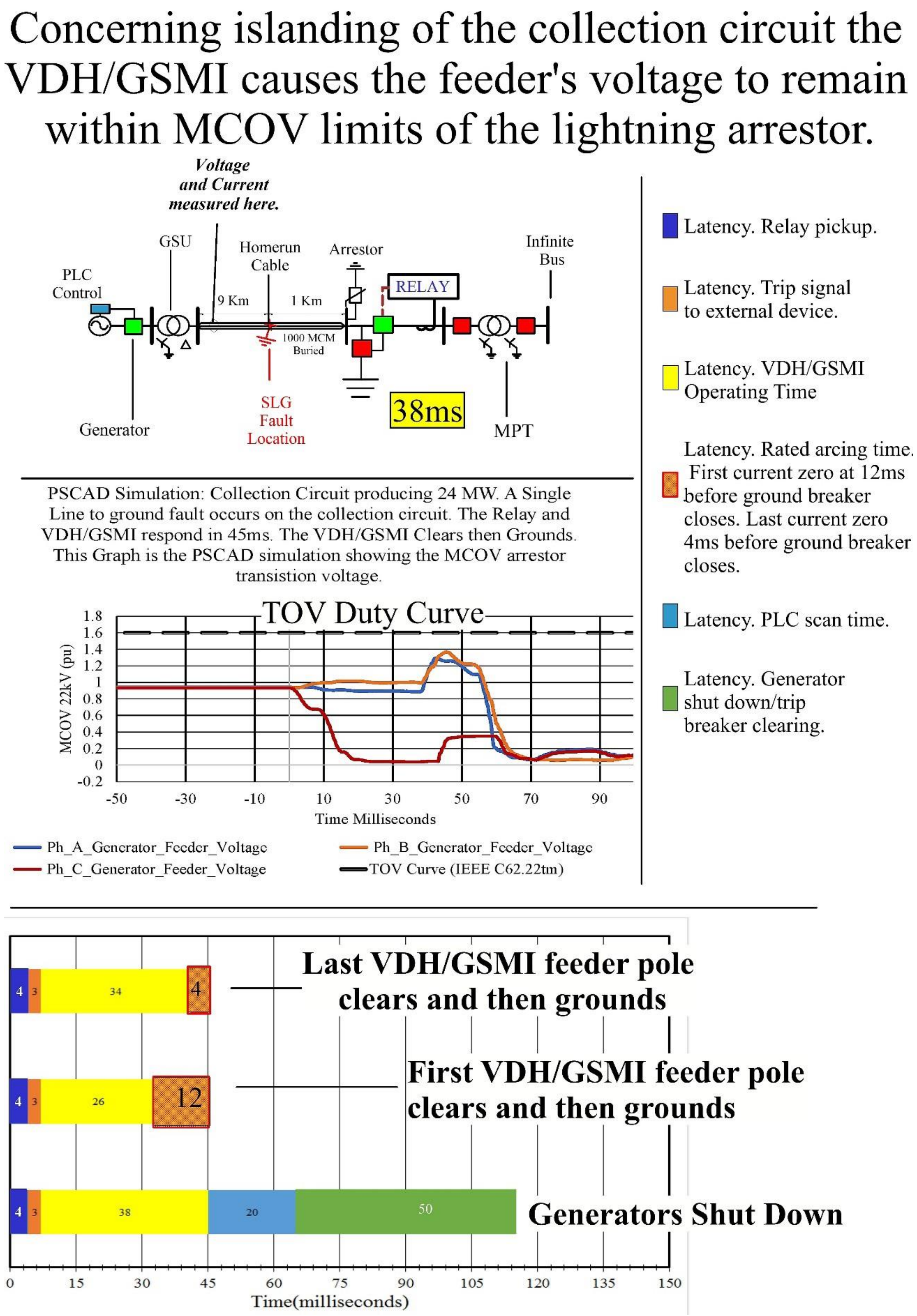

Fig. 15: PSCAD Simulation: TOV, Prior Duty Curve.

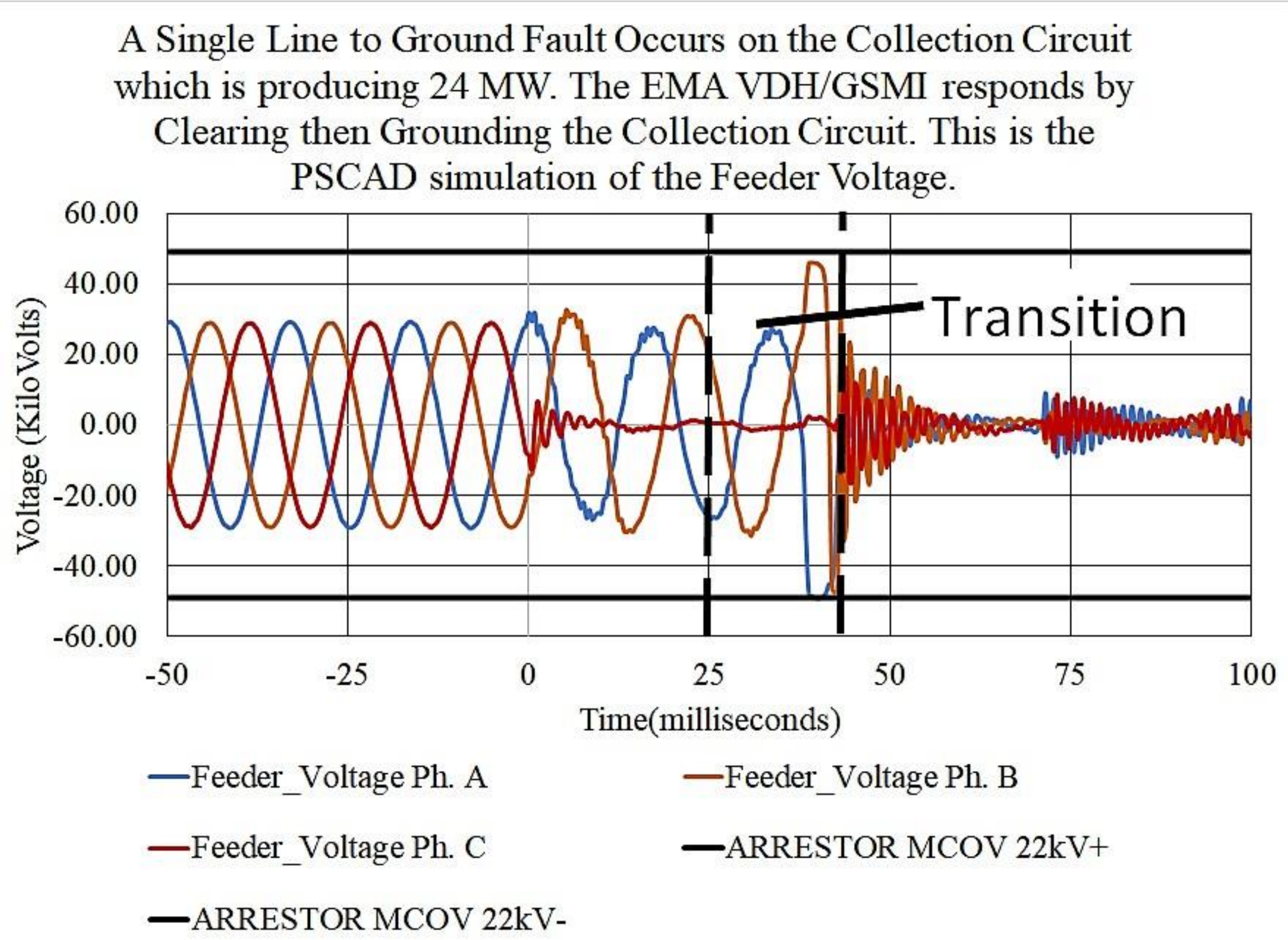

Fig. 16: PSCAD Simulation.

Figures 15 and 16 show the maximum continuous operating voltage (MCOV) rating of the lightning arrestor of 22 kV. The line to ground voltage rating of the collection circuit is 19.920 kV.

In this case, as shown in Figure 16 when the VDH/GSMI switches feeder Phase C races up, however, the ground interrupter closes fast enough to prevent the voltage from exceeding the duty curve.

In Figure 16, after the ground interrupters close, the feeder voltage drops significantly and provides support for the generators so that they could potentially be set to differentiate between an internal plant fault and an external transmission system fault. Figure 16 indicates a type of ringing with the change in impedance. However, within 20ms the voltage is clearly approaching zero and is low enough for the generators to shut down.

The PSCAD simulation shows that the VDH/GSMI clearly can protect and make it easier for engineers to perform ride-through coordination concerning events within the plant and events outside on the transmission system. The PSCAD simulation also shows that a coordination study for a collection circuit should be performed with a VDH/GSMI, as every plant design is different, and the transients are not the same.

VI. PSCAD MODELING

For emulating type 3 and type 4 wind turbines or inverters, Figure 17 shows the PSCAD single line model with two aggregate generators. The model emulates a wind power plant or a solar power plant with a type 4 wind generator or inverter-based generation.

The generators use a Clarke/Park [18] transform that follows voltage at the transformer mains. The plant is rated at approximately 100 MW. The main plant transformer is rated over 100 MVA. Without fans, it is rated at 90 MVA oil natural air natural (ONAN), with ½ fans it is rated 120 MVA oil natural air forced (ONAF), with all fans it is rated at 150 MVA (ONAF). There are two feeders. One feeder is an equivalent feeder (75 MW), and the other is the faulted feeder (25 MW). On the faulted feeder is the home run cable. The production values concerning active power(P) reactive power

(Q) and voltage (V) are allowed to fluctuate within a narrow band.

The home run cable is represented by an infinite pi model of varying distances. In PSCAD, this model is called a Bergeron model as shown in Figure 20. The VDH/GSMI is shown in Figures 17 and 19. The line breaker, remote trip, and grounding breaker relay model are also provided in Figure 19. The simulation is very simple and consists of time delays for the relays to open the appropriate breaker, while the generators produce power, and a single line to ground fault occurs on the home run cable or a three-phase bolted fault occurs at the point of interconnection. Although the line and grounding breakers are interlocked, the control is reflected by using appropriate delays. Next, concerning remote transfer trip a delay is used to emulate the breaker delay at the generators.

Figure 18 is a model of the timing of the relays used to open and close the appropriate breaker. For example, in a simulation, the Vac_Interrupter_Line signal causes the line breaker in the VDH/GSMI to open. Then the Vac_Interrupter_Gnd signal causes the VDH/GSMI ground breaker to close. Concerning Remote_Trip, the delay provides enough time to shut down the generators within the wind power plant or solar power plant before the line breaker opens. Depending on the simulation, the Remote_Trip signal or Vac_Interrupter_Gnd signal may or may not be used in the simulation. An example of this is simulating the worst-case TOV and not allowing the feeder VDH/GSMI ground breaker to close or allow the wind turbine's breaker to open.

The model begins with a very strong source rated greater than 1000 MVA. The main plant transformer (Figures 19 and Figure 25) is rated at 90 MVA at 8% impedance with a 30 to 1 X/R ratio, with a nominal voltage at 230 kV line to line on the high side and 34.5 kilovolts line to line on the low side. In this simulation, the high-side and low-side breakers connected to the main plant transformer are set to remain closed. The equivalent feeder is set to produce at 75 MW, and the faulted feeder is set to produce 25 MW. Reactive power is set to flow near zero, and depending on the simulation, that value is adjusted. The voltage at the point of interconnection is set at 1 pu. In addition, a three-phase bolted fault is added to create the nine cycles of zero voltage at the point of interconnection to characterize the VDH/GSMI's contribution to the generation plants' reliability and stability.

Figure 21 is the three-phase PSCAD cable model. Figures 22 and 23 provide R, X, and B for the cable. The impedance of a leg can be calculated by looking into the 1000 MCM home run cable from the junction box to the main plant transformer and using the manufacturer's specified data for a 1000 MCM direct buried cable. However, the PSCAD model applied uses cable constant's positive sequence impedance XL, positive sequence resistance R, and susceptance B.

VII. CALCULATIONS

The following equations are taken from [9] and are used to go back and forth between pu unit and actual values:

$$I_{base} = S_{base} / 3\sqrt{3}V_{base} \qquad (1)$$

$$Z_{base} = \frac{\left(\frac{V_{base}}{\sqrt{3}}\right)^2}{\frac{S_{base}}{3}} \qquad (2)$$

$$P_{base} = S_{base} \qquad (3)$$

$$Z_{MPT} = Z_{base} * \left(Z_{[pu]MPT}\right) \qquad (4)$$

For example (models provided in Figures 23, 24, and 25), considering the 230 kV/34.5 kV main plant transformer with 8% (X/R ratio of 30:1) impedance on the 34.5 kV bus, rated at 90 MVA, and connected to an infinite bus, the calculated impedance is:

$$Z_{mpt} = \frac{\left(\frac{34{,}500\ Volts}{\sqrt{3}}\right)^2}{\frac{90{,}000{,}000}{3}} = 13.225\ Ohms$$

$$X_l = 0.08 * 13.225 = +1.05\ jOhms$$

$$R = \frac{1}{30} * 1.05 = 0.035\ Ohms$$

Therefore, the impedance into the main power transformer is approximately 1 Ohm.

The same equation can be used to calculate the impedance of the step-up transformer at each, type 3 or type 4, wind generator turbine, solar inverter or even a grounding transformer.

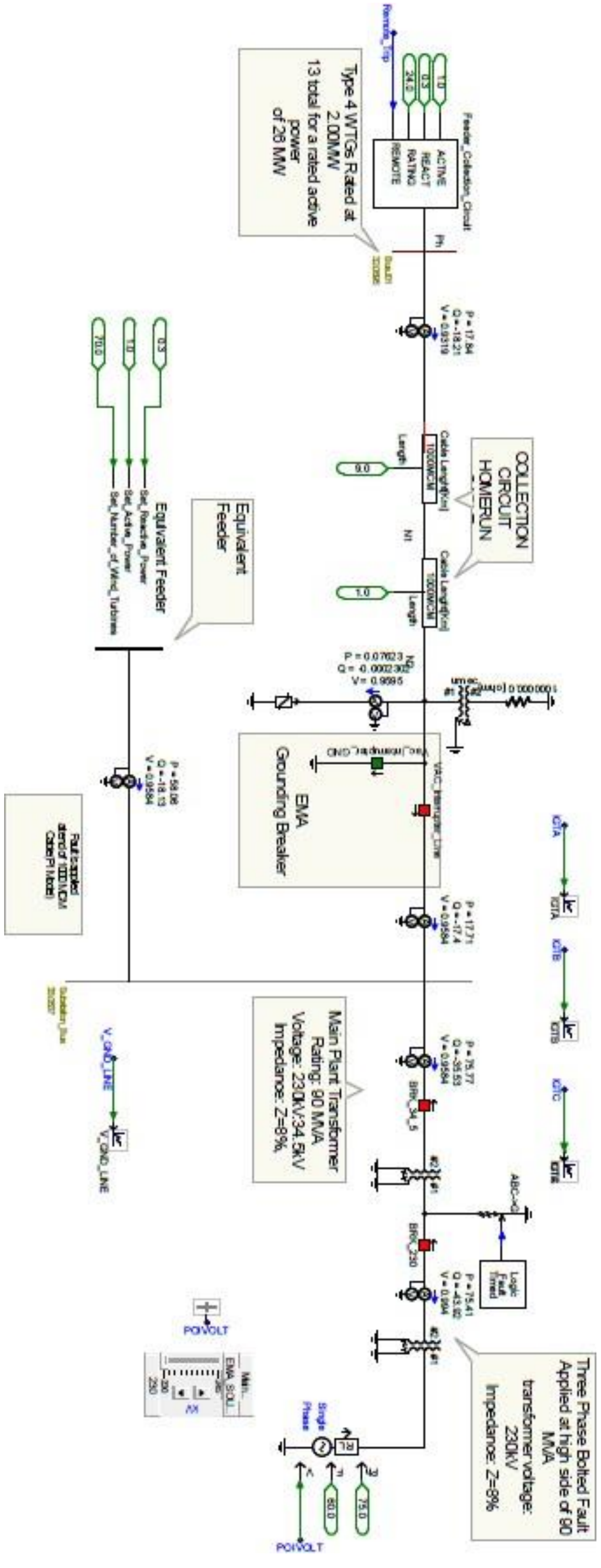

Fig. 17: PSCAD Model: Single Line.

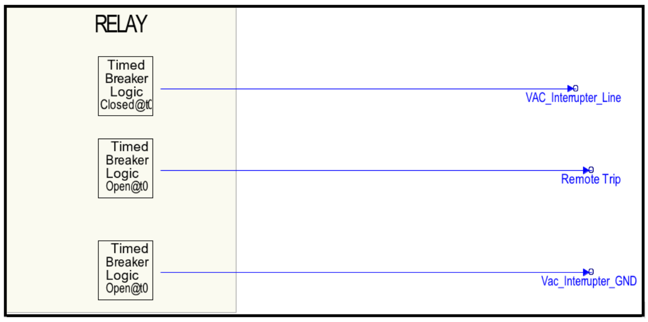

Fig. 18: Breaker Timing.

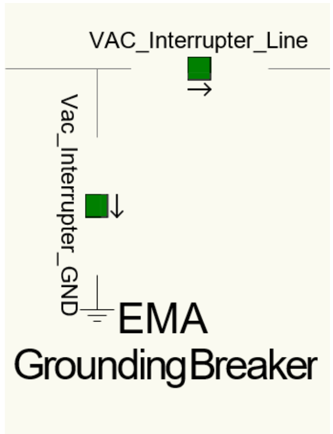

Fig. 19: EMA Line and Grounding Breaker Model.

Figures 20 to 23 show PSCAD model of feeder, which main characteristics are: leght of 10 Kms (1 Km and 9 Kms sections), copper, R=0.014 (pu), XL=0.15 pu (Ohms), B=0.228 (pu). Aluminum cable values are nearly the same.

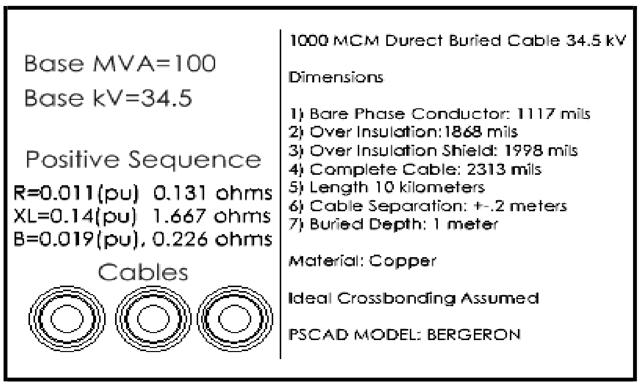

Fig. 20: PSCAD Line Constants Model.

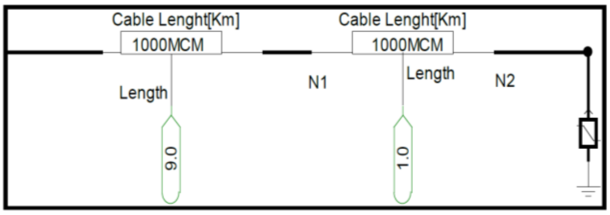

Fig. 21: PSCAD Cable Model (the 10 Kms model separated into 1 Km and 9 Kms sections).

```
Per-Unit Quantities Based On:
Base Voltage:   34.50 kV, L-L,RMS
Base MVA:  100.00 MVA
LONG-LINE CORRECTED SEQUENCE RESISTANCE
RLLsq [p.u.]:
         + Seq. Self: 0.114015367E-02
         0 Seq. Self: 0.208521907E-01
LONG-LINE CORRECTED SEQUENCE REACTANCE
XLLsq [p.u.]:
         + Seq. Self: 0.148258142E-01
         0 Seq. Self: 0.675852755E-02
LONG-LINE CORRECTED SEQUENCE SUSCEPTANCE
BLLsq [p.u]:
         + Seq. Self: 0.197606297E-02
         0 Seq. Self: 0.197606034E-02
```

Fig. 22: PSCAD 1 Km 1000 MCM Cable Parameters.

```
Per-Unit Quantities Based On:
Base Voltage: 34.50 kV,L-L,RMS
Base MVA:  100.00 MVA
LONG-LINE CORRECTED SEQUENCE RESISTANCE
RLLsq [p.u.]:
         + Seq. Self: 0.102533611E-01
         0 Seq. Self: 0.187602863
LONG-LINE CORRECTED SEQUENCE REACTANCE
XLLsq [p.u.]:
         + Seq. Self: 0.133378508
         0 Seq. Self: 0.609190208E-01
LONG-LINE CORRECTED SEQUENCE SUSCEPTANCE
BLLsq [p.u]:
         + Seq. Self: 0.177880411E-01
         0 Seq. Self: 0.177861250E-01
```

Fig. 23: PSCAD 9 Mile 1000 MCM Cable Parameters.

3 Phase Transformer MVA	30.25
Base operation frequency	60
Winding #1 Type	0
Winding #2 Type	1
Delta Lags or Leads Y	1
Positive sequence leakage reactance	0.02
Ideal Transformer Model	1
No load losses	0.00135
Copper losses	0.00765
Tap changer on winding	0
Graphics Display	2
Display Details?	0
Winding 1 Line to Line voltage (RMS)	0.575
Winding 2 Line to Line voltage (RMS)	34.5
Saturation Enabled	1
Saturation Placed on Winding	2
Air core reactance	0.2
In rush decay time constant	1
Knee voltage	1.25
Time to release flux clipping	0.1
Magnetizing current	1

Fig. 24: WTG Aggregate Transformer Parameters.

Transformer Name	T1
3 Phase Transformer MVA	90.0 [MVA]
Base operation frequency	60.0 [Hz]
Winding #1 Type	1
Winding #2 Type	0
Delta Lags or Leads Y	1
Positive sequence leakage reactance	0.08 [pu]
Ideal Transformer Model	0
No load losses	0.001 [pu]
Copper losses	0.0001 [pu]
Tap changer on winding	0
Graphics Display	2
Display Details?	0
Winding 1 Line to Line voltage (RMS)	230 [kV]
Winding 2 Line to Line voltage (RMS)	34.5 [kV]
Saturation Enabled	1
Saturation Placed on Winding	1
Air core reactance	0.2 [pu]
In rush decay time constant	0.0 [s]
Knee voltage	1.17 [pu]
Time to release flux clipping	0.0 [s]
Magnetizing current	1 [%]

Fig. 25: MPT Transformer Parameters.

Concerning PRC-024-2, the voltage increases across padmount transformers is due to the current and the angle across the transformer impedance, which dominates in value over the branch impedance when the home run cable is bolted to ground. Typically, the impedance of a generator transformer is 5.5% with an X/R ratio of 30 to 1 and a rated MVA of between 2.5 and 3 MVA which is calculated for 2.5 MVA at 0.866 + *j* 26.2 Ohms or 3 MVA at 0.726 + *j* 21.8 Ohms. Considering an equivalent 30 MVA transformer representing 10 generators is *j* 2.18 Ohms (Table 1). The branch of feeder impedance is assumed to be much lower than the transformer impedance and is estimated at 1.4 + *j* 1.3 Ohms. The impedance of a 10 Kms home run cable from PSCAD is 0.131 + *j* 1.67 Ohms. The positive/negative sequence impedance of a grounding transformer is assumed to be the same as the padmount transformer except that it is open on the secondary, resulting in a very high positive/negative sequence impedance at the grounding transformer and the path to ground is then through the lighting arrestors when the conduct.

The calculations show the VDH/GSMI provides relatively low impedance when it opens and shorts the home run cable to ground. Within a range of fault locations on the cable, the impedance of the cable remains low compared to the impedance at each transformer at each wind turbine. With this in mind, the wind turbines or inverters are hard-pressed to remain on-line when the grounding breaker closes. When the ground breaker operates and is in state 3, the impedance is so low that a type 3 or type 4 wind turbine [10] that is limiting its current will be hard-pressed to keep its voltage up and will trip offline because the voltage is so low.

VIII. PSCAD TRANSIENTS AND MODELING METHODOLOGY

The focus of this paper is the Grounding Breaker operating under PRC-24-2 requirements. In addition, how it can protect the MV collection circuit within a wind or solar power plant. PSCAD is used to model switching transients and other electro-dynamic and control system events. The simulation focuses on the impact of various faults on a specific collection system feeder circuit when the wind power plant or solar power plant uses line breakers, grounding breakers, and remote trip protection arrangements.

IX. DISCUSSION

Generally, Figures 26 and 27 concern PSCAD simulations of inverter-based generation and how at the point of interconnection the voltage recovers and an affected collection circuit that the VDH/GSMI pulls the collection circuit voltage very low where it would be easy for a generator to differentiate whether the fault were external or internal to the plant. For external faults, the impedance to the generators is from the main plant transformer, the collection cables, and the generator step-up transformer. For internal faults, the main plant transformer is excluded.

Figures 26 to 30 show how the PSCAD simulations of the VDH/GSMI may protect and provide support to the faulted collection circuit and the transmission system. The VDH/GSMI forms three-phase bolted ground and provides a zero reference closer to the generators than the zero reference that forms with three-phase bolted ground at the point of interconnection; the difference in impedance between internal faults and external faults is the impedance of the main plant transformer where the main plant transformer has an impedance of 8%. Figures 28 to 30 show at near full power for the wind or solar power plant that the delta in voltage between the two fault locations is 8%. As a result, each generator could detect and discriminate between each fault location. Therefore, the VDH/GSMI provides signaling between an islanding event or ride-through event.

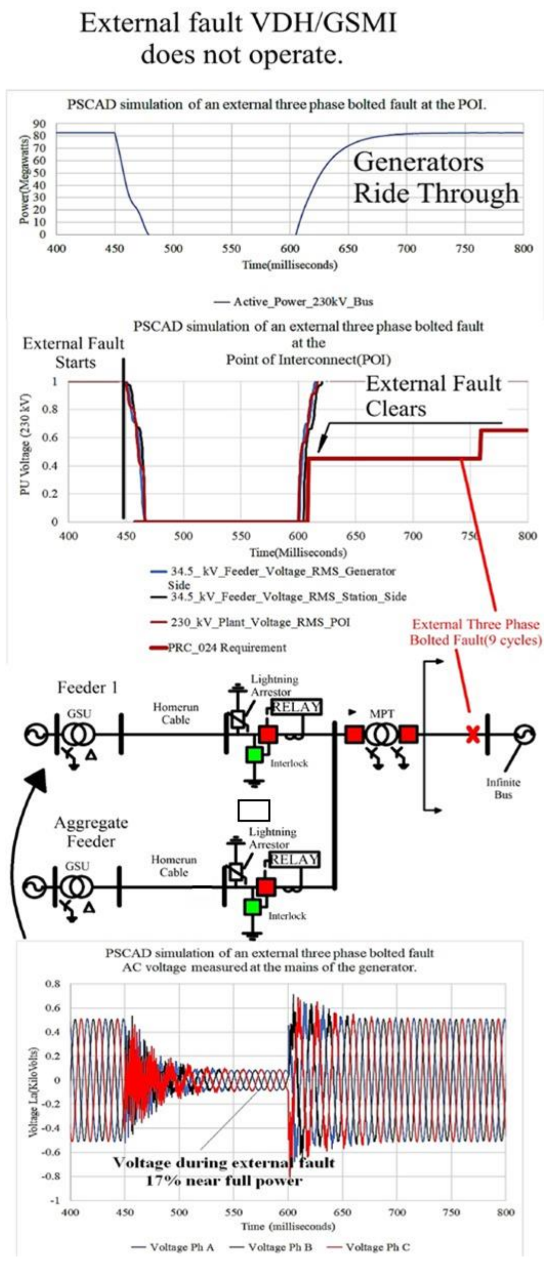

Fig. 26: External Fault..

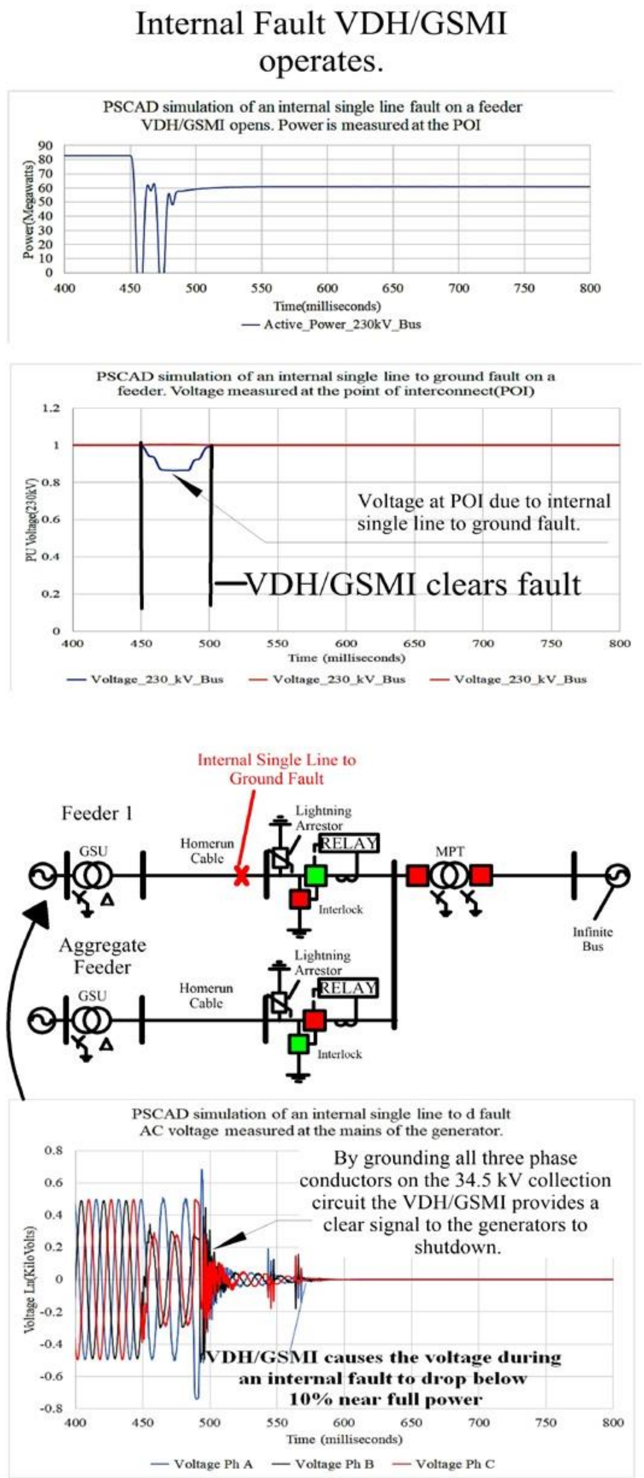

Fig. 27: Internal Fault.

X. CONCLUSION

A VDH/GSMI once grounded creates three-phase bolted ground on the home run cable. This, in turn, creates an impedance on the home run cable of less than 2 Ohms as seen from the junction box to the VDH/GSMI for a 1000 MCM cable that is 10 Kms long.

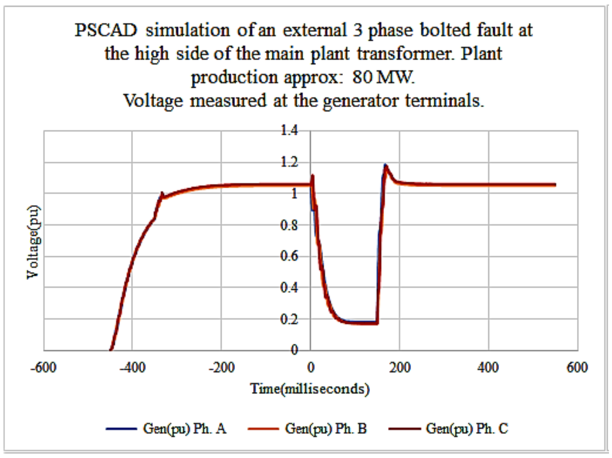

Fig. 28: Voltage During External Fault (Gen. Protection Disabled).

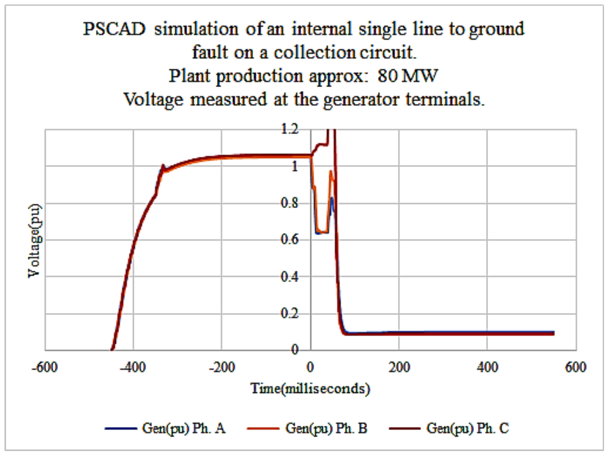

Fig. 29: Voltage During Internal Fault (Gen. Protection Disabled).

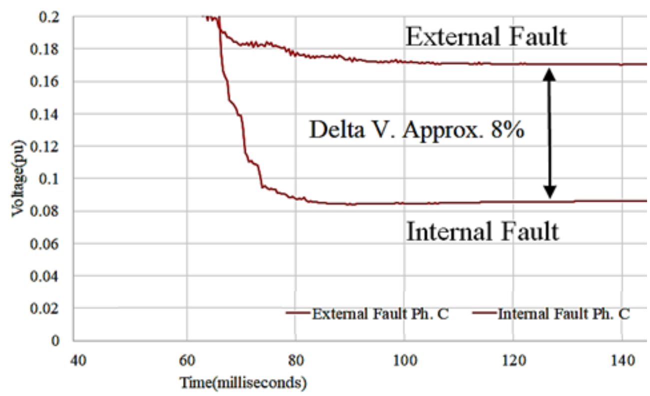

Fig. 30: Delta Voltage During External and Internal Faults.

Compared to the home run cable impedance, the generator step-up transformer impedance, which is *j* 28 Ohms at 34.5 kV, the ratio is approximately 15 to 1.

When the home run cable is grounded by the VDH/GSMI, each generator limits the current to a maximum magnitude during the fault of approximately 42 amps at 34.5 kV, and the voltage rise across the generator step-up transformer is less than 1.1 kV.

At that point, each generator should trip off-line, and islanding should not occur. In addition, and with the above in mind, each generator should coordinate well with the PRC-024-2 requirements. However, if islanding does occur, the impedance is so low that temporary overvoltages should not be present while the generators wait to receive a remote trip signal from the substation.

Concerning PRC-024-2, the VDH/GSMI signals the wind turbines that the fault is inside the plant and shuts them down for events that the turbines should not ride through, therefore providing a valuable discriminatory function that standard circuit breakers do not. With PSCAD simulations show that the Grounding Breaker causes a lower voltage to appear at the terminals of the generators for internal faults than for external faults (Figures 28, 29, 30). Therefore, the generators are shut down faster than remote trip. In case the remote trip is used, the very low impedance caused by the Grounding Breaker measured on the collection circuit will protect the generators.

Using Grounding Breaker as feeder breaker and complying with PRC-024-2 requirements within a wind or solar power plant, PSCAD simulations show that an impedance to ground is sufficient for signaling the generators to shut down or provides a benign islanding impedance.

Presented in this paper is a sequence of events and an operational overview concerning the Grounding Breaker VDH/GSMI applicable to wind and solar power plants.

1. The VDH/GSMI operates two vacuum interrupters with an interlock; therefore, it operates with only one signal.
2. The transition state of the within the VDH/GSMI where both vacuum interrupters are open is from 4 to 12ms.
3. The operation of a VDH/GSMI demonstrates a clear change in impedance as the VDH/GSMI operates; then the generators can detect such a change and act on it.
4. The VDH/GSMI when closed to ground results in a very low impedance of the home run cable to less than 2 Ohms measured from a junction box (1000 MCM less than 10 Kms).
5. Given the typical design variations in wind and solar power plants and generators with current limiting capability, the VDH/GSMI should provide very low impedance on the feeder circuit and cause the AC mains voltage at each generator to go below the minimum operating voltage and force them off-line to prevent islanding.

The PSCAD simulations show the VDH/GSMI provides designers and engineers the ability to distinguish between external and internal faults as shown in Figures 26 to 30, where generators may be set to trip if the fault is in the plant, or ride through if the fault is outside the plant. The VDH/GSMI completely operates in less than 50ms to separate the affected collection circuit and grounds it, so it collapses the voltage allowing islanding if needed. As a result, it is possible to conclude that the use of the Grounding Breaker in the design and construction of generating projects, such as wind and solar power plants, constitutes a best practice.

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