Interlocked Combined Breaker Grounding Switch (VDH/GSMI) provides better protection for insulation coordination than a grounding transformer. We present the reasons why.

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Abstract: Grounding transformers connected to wind power plants (WPPs) and solar power plants (SPPs) do not a provide positive or negative sequence path to ground. Islanding occurs when all or a portion of the power generated by a WPP or SPP becomes electrically isolated from the remainder of the electric power system. For example, when a collection circuit producing power at 24 MW separates severe islanding occurs. This paper includes PSCAD simulations and references that indicate when a standard circuit breaker opens and then separates the collection circuit from the transmissions-system with a grounding transformer, severe islanding occurs and an insufficient path to ground to shunt the islanding power is created. This results in temporary over voltage (TOV) and loss of insulation coordination, which in turn results in damage to the lightning arrestors. When the lightning arrestor's I-V characteristic changes, they fail as a short. But before they do, while a feeder is islanding, an arrestor's current carrying capability may be reduced to where the islanding-power through the arrestor causes voltages that exceed the temporary overvoltage rating of the arrestor, if the arrestor I-V characteristic changes there is a loss of insulation coordination.

PSCAD models show that the VDH/GSMI (medium voltage vacuum circuit breaker with mechanically interlocked grounding switch) provides a lower ground reference orders of magnitude less than a grounding transformer. As a result, it coordinates well with lightning arrestors and maintains the collection circuit's insulation coordination by keeping switching transients and temporary over voltages within the operating specifications of the lightning arrestors.

Keywords—interlocked, combine, breaker, grounding, switch, remote, transfer, trip, WPP, SPP, wind, solar, electric, power, system, flash, arc, blast, temporary over voltage, lightning arrestor, collection circuit, cable, transformer, single line-to-ground fault, wind, solar, arrestor coordination, grounding transformer.

1. INTRODUCTION

While both the interlocked combine breaker grounding switch (VDH/GSMI, *a medium voltage vacuum circuit breaker with mechanically interlocked grounding switch*) and the grounding transformer provide protection for insulation coordination, the VDH/GSMI provides less than 1 ohm to ground, whereas the grounding transformer provides a path to ground that the PSCAD model indicates does not pass active power to ground. However, a VDH/GSMI does, as a result, a VDH/GSMI provides better protection for solar power plants (SPPs) and wind power plants (WPPs) by reducing incident energy and eliminating temporary over voltage (TOV). Elimination of TOV is an important feature of the VDH/GSMI. When TOV is eliminated during opening of the circuit breaker, the lightning arrestors are operated below their duty curve, insulation coordination of the feeder circuit is maintained, and equipment is more reliable. This paper compares the grounding transformer and the VDH/GSMI regarding Islanding, TOV and arrestor coordination .

The paper will first discuss the design and theory of operation of the grounding transformer as applied in both WPP and SPP, and how the impedance to ground included with a grounding transformer causes a loss of insulation coordination and diminishes the safety and reliability of the collection circuit over time. Second, the paper will discuss in detail the operation of the VDH-GSMI. This paper uses PSCAD to support claims made concerning the operation of the grounding transformer and to show where the VDH/GSMI overcomes the grounding transformer's limitations and provides a superior very low impedance path to ground.

Circuit breakers are mechanical switching devices that connect and break the current flowing in the circuit, which can be either the nominal current or the fault current. Typical circuit breakers comprise one switch that is either open or closed. They come in a variety of forms: vacuum, air and gas-insulated-switchgear circuit breakers are available for medium voltage systems such as a 34.5 kV collection circuit used in WPP or SPPs. Generally, some WPPs and SPPs only use "non-grounding" feeder (line) circuit breakers, as shown in Figure 1.

In a collection circuit for a wind or solar power plant, a typical circuit breaker clears the affected feeder from the main station transformer and transmission system. Such a design is limited does not provide the functionality—such as anti-islanding or TOV mitigation—needed for today's modern plants.

The VDH/GSMI is a special type of circuit breaker that provides greater functionality and protection (see [1] and [2]). The VDH/GSMI requires just one signal from a relay to separate the collection feeder circuit from the main plant transformer. The interlocked switch then grounds the collection circuit, with the full process occurring in about three cycles from the initiation of a fault. With the impedance

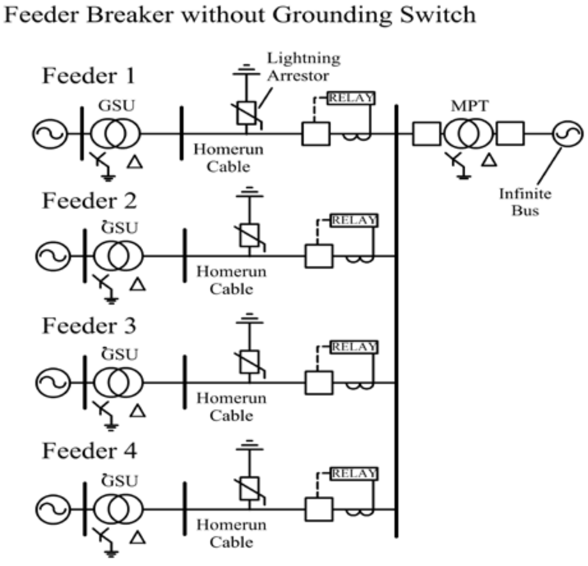


Fig. 1. Wind power plant (WPP) or solar power plant

(SPP) single line.

of the collection circuit, approximately 1/15th of the impedance of an individual wind turbine transformer, and all three phases effectively bolted to ground, the voltage on the separated feeder quickly collapses.

As seen in Figure 2, the VDH/GSMI is designed for the feeder collection circuits of WPPs and SPPs. The line side circuit breaker comprises vacuum interrupters and bushings to connect to the 34.5 kV collection circuit. For information concerning operation and ratings of vacuum interrupters, see [7] and [8].

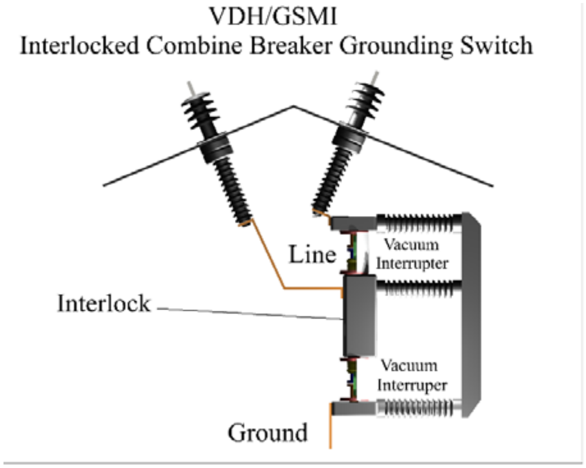


Fig. 2. VDH/GSMI with a set of three line-side vacuum interrupters and a set of three interlocked collection side ground vacuum interrupters. The switch operates with a single trip signal.

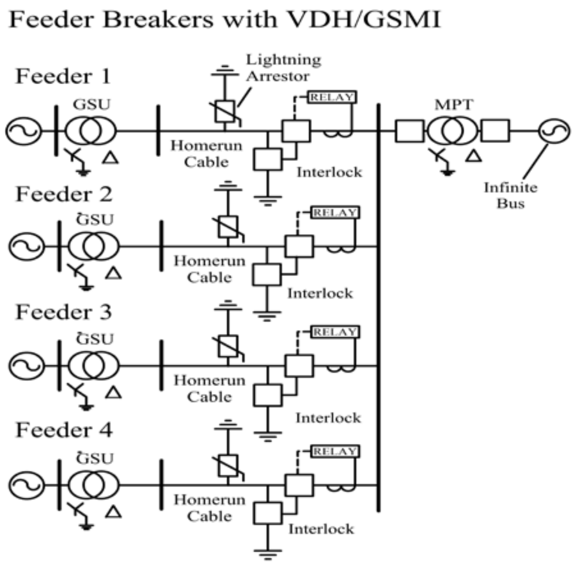


Fig. 3. WPP or SPP with VDH/GSMI protecting at each feeder circuit.

When closed, the grounding circuit connects the generator's side of the feeder collection circuit to ground. When used in WPPs and SPPs, the VDH/GSMI connects between the substation bus and the wind turbines or solar inverters, as shown in the single line in Figure 3.

As shown in Figure 4, the VDH/GSMI (line) breaker is closed and the grounding switch is open, as indicated by the red outline illustrating a path for the flow of current. When the relay commands the breaker to open, both sets of interlocked (emphasis added) vacuum interrupters operate, the line side opens first, and then the ground side closes, as shown in Figure 5. The interlocked grounding switch automatically switches the collection circuits to ground immediately after clearing the fault and feeder from the plant. As a result, the VDH/GSMI provides improved anti-island functionality, superior TOV protection, and less incident energy into an arc flash or arc blast.

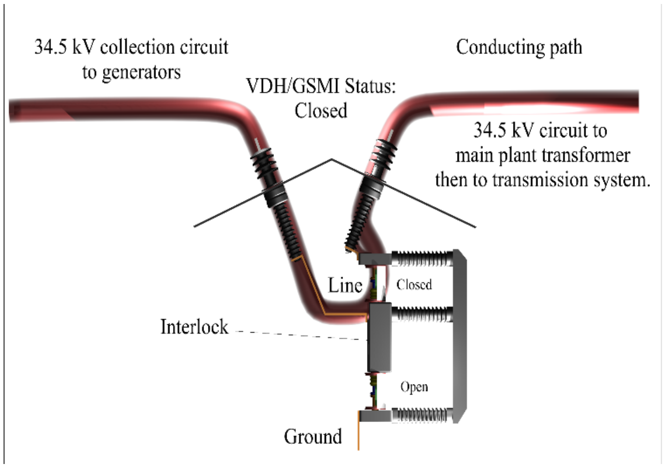


Fig. 4: VDH/GSMI Closed, Ground Switch Open.

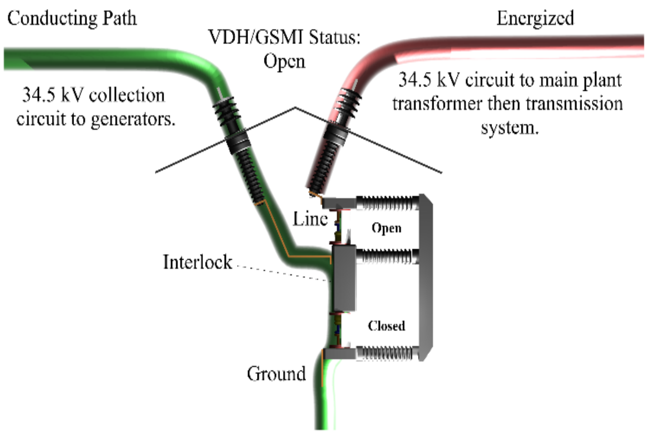


Fig. 5. VDH/GSMI open, grounding switch closed.

When used in WPPs and SPPs, conventional breakers open and disconnect the affected feeder from the transmission system. Unless a grounding transformer is connected, these breakers allow the delta connected collection circuit to operate with capacitive high impedance ground reference through the insulation of the cable. If a grounding transformer is installed the positive and negative sequence impedance of the grounding transformer for an open circuit is very high and the zero sequence can exceed 30 Ohms as calculated at 34.5 kV.

Compared to a conventional circuit breaker, the VDH/GSMI provides a superior ground reference (collection circuit is effectively bolted to ground) and clears and opens then closes and grounds with an electrical switching time of 4–12 milliseconds, or less than one cycle, thus coordinating well with TOV requirements for lightning arrestors.

Using PSCAD simulations, the following section of the paper discusses grounding transformers as designed for and installed on WPPs or SPPs and how they result in more damage to equipment. Together with PSCAD, the paper presents claims that the VDH/GSMI overcomes such TOV problems and thus provides superior protection over grounding transformers.

The paper ends with a discussion and comparison of the two techniques and concludes that the VDH/GSMI constitutes a best practice concerning protection of personnel and equipment working with collection feeder circuits in WPPs and SPPs.

2. LIGHTNING ARRESTORS

This section concerns lightning arrestors and how their TOV curve is exceeded and consequently the lightning arrestors are stressed on a separated and islanding collection circuit within a WPP or SPP. The purpose of the lightning arrestor is to limit the voltage rise during transient over voltage that occurs during a switching event or a lightning strike. Lightning arrestors also provide protection for TOVs with longer durations than transient over voltages (see Figures 6 and 7).

The institute for electrical and electronic engineers (IEEE) standard C62.11 defines a temporary overvoltage(TOV) as

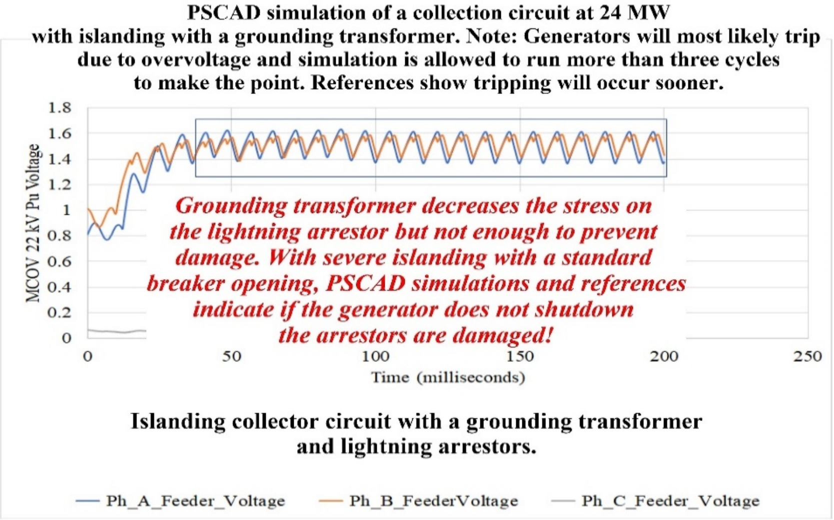
“an oscillatory phase to ground or phase to phase overvoltage that is at a given location of relatively long duration in seconds or minutes and that is undamped or weakly damped.”.

Lightning arrestors limit the peak voltage on collection circuits within the SPP or WPP and on the interconnected transmission system. They come with a given TOV curve called a duty curve that can be found on a graph supplied by the manufacture. The graph shows the (50hz–60hz) withstand voltage vs. time for arrestors. The time is usually given from 0.01 seconds to 10,000 seconds in RMS values in a per unit rating based on the maximum continuous operating voltage (MCOV). IEEE Standard C62.11-1993 includes tests performed to demonstrate the TOV capability of the lightning arrestor’s duty conditions. The test includes several voltage levels applied across a sample of the representative arrestor for a time duration sufficient to exceed the voltages claimed by the manufacturer and presented with the duty curve. The manufacturer’s claim usually states that within 100 milliseconds after the TOV, the sample is thermally stable, with that same sample dissipating less than the maximum allowed watts loss. There are five TOV tests performed for time periods of 0.01–0.1, 1–10, 10–100, 100–1000, and 1001–10,000 seconds. Each sample passes when it exceeds the manufacturer’s specified duty curve and demonstrates thermal stability (see Figure 7 on page 7).

When a feeder is separated from the plant with the generators still running and attempting to produce approximately 20MW, the PSCAD simulations show that the TOV duty curve is typically exceeded regardless of the I-V characteristic used, and the path to ground for that attempt of power production would be through the lightning arrestors. At this point, the arrestor can fail short or open, depending on failure mode.

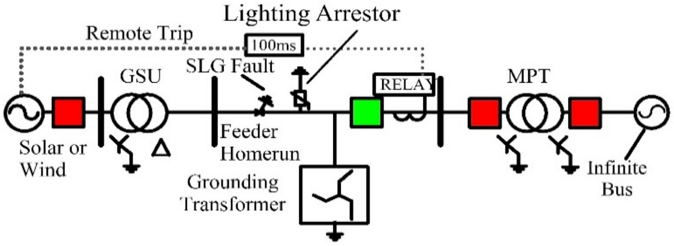
Thermal stability of the lightning arrestor is critical. If the voltage applied across the arrestor from line to ground causes it to burn up, the results could be disastrous. The lightning arrestor is subjected to over voltage during testing, and it gets hot. If the temperature runs away within 100 milliseconds with the applied voltage, the arrestor is found to be thermally unstable, and damage is likely. The United States Nuclear Regulatory Commission [14] reports that a station class arrestor will not fail when it exceeds the given TOV specifications. However, the arrestor will be damaged, and its I-V characteristic will change. Thus, we must consider that the insulation coordination for the affected feeder would be lost when the lightning arrestor is damaged (see Figure 6).

With Grounding Transformer

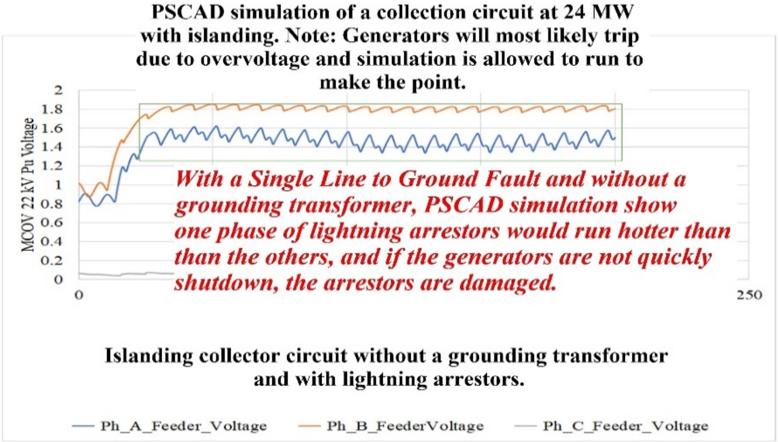

PSCAD simulation of a collection circuit at 24 MW with islanding with a grounding transformer. Note: Generators will most likely trip due to overvoltage and simulation is allowed to run more than three cycles to make the point. References show tripping will occur sooner.

Grounding transformer decreases the stress on the lightning arrestor but not enough to prevent damage. With severe islanding with a standard breaker opening, PSCAD simulations and references indicate if the generator does not shutdown the arrestors are damaged!

Islanding collector circuit with a grounding transformer and lightning arrestors.



Without Grounding Transformer


PSCAD simulation of a collection circuit at 24 MW with islanding. Note: Generators will most likely trip due to overvoltage and simulation is allowed to run to make the point.

With a Single Line to Ground Fault and without a grounding transformer, PSCAD simulation show one phase of lightning arrestors would run hotter than than the others, and if the generators are not quickly shutdown, the arrestors are damaged.

Islanding collector circuit without a grounding transformer and with lightning arrestors.

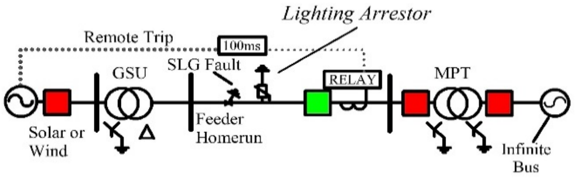


Fig. 6. PSCAD simulation grounding transformer, lightning arrestors, remote trip, and TOV.

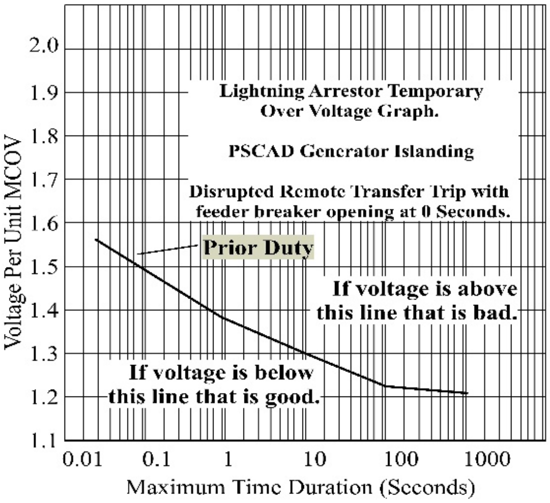


Fig. 7. Prior duty curve.

Lighting arrestors are manufactured with metal-oxide surge arrestors and are typically gapless. They are constructed by stacking disks that resemble hockey pucks and are designed not to conduct during normal operation. Metal-oxide arrestors begin to conduct current sharply when voltage exceeds a designed value, and they stop conducting current sharply when the voltage drops below a designed value. In WPPs and SPPs, heavy-duty station class arrestors are located near the substation with usually with a 22 kV MCOV rating. According to [14],

> *"Surge arrestors and surge suppressors will eventually degrade or fail. If they fail as a short circuit, the circuit that they protect will be taken out of service by fuses or circuit breakers: If they fail as an open circuit or functionally, the components in the circuit are likely to be exposed to stress which may result in failure…In general, normal wear for a surge protective device may be reduced to the combination of (1) the number of overvoltage pulses (which may not follow a simple linear repetitive pattern), including their magnitude and duration (which are both variables) it shunts to ground, and, (2) the environmental conditions under which it operates. It is apparent that the determination of age for SPDs is not a simple matter of collecting data [14]"*

Lightning arrestors limit the peak voltage on collection circuits within an SPP or WPP. The lightning arrestor and duty curve are critical for protecting WPPs or SPPs. If the lightning arrestor fails, a voltage rise on the collection circuit will damage any equipment that is connected electrically. The energy conducted by a lightning arrestor causes it to overheat and change its I-V characteristic; as a result, it may fail to open, close, or reduce its current conducting characteristics, thus leaving the collection circuit without adequate protection. With the above in mind and to state it again, the insulation coordination for the affected feeder would be lost if the lightning arrestor is damaged.

3. REMOTE TRIP AND ISLANDING

This section discusses islanding and why generators keep producing into a collection circuit that has separated from the transmission system. Reasons may include a remote trip, where another relay has detected a fault and belatedly signals the generators to shut down. Relay strategies may include limiting incident energy or TOV, where both protection goals are competing and where, if the signal does not reach the generators, the resulting islanding could prove disastrous (Figures 6 and 9).

Generators island because they do not detect the fault or the separation from the transmission system. In addition, the latency of the trip signal sent from the substation relay can take more than 200ms from the inception of a fault, and thus notice of such a separation is belated. Consequently, the generators keep attempting to generate into a circuit that has separated from the transmission system. The causes of latency are many and include fault pick-up time, switch latency, fiber-cable (or radio) latency, and control system and equipment latency (see Table 1). There are standards that identify the typical latencies one should expect when sending a signal for equipment to operate. IEC 61850, a contemporary standard concerning the configuration of devices for electrical substation automation systems, provides methods that allow different components to communicate with each other. Such protocols can run over TCP/IP networks or substation LANs using high-speed switched Ethernet to obtain response times around 4 milliseconds or longer for protective relaying.

Remote trip and transfer trip are similar, some readers are very familiar with transfer trip and we include the definition from [3]. According to the California Public Utilities Commission, transfer trip means "the opening of a circuit breaker or recloser from a remote location by means of a signal over a communication channel such as microwave, power line carrier, radio, or, most likely for devices at the distribution level, a leased telephone line [3]." Remote trip and transfer trip are similar, with respect to how a trip signal is sent from a substation to the generators within a SPP or WPP, which are miles away.

	Remote Trip Causes of Substation Communication Failure
Item#	Causes
1	Processor Power Supply Failure
2	Cyber Intrusion
3	Firmware Upgrades
4	Data Path Reconfiguration.
5	Fiber Optic Cable/Damage Radio Failure
6	Bandwidth Saturation

Table 1. Causes of remote/trip communication failure

	Grounding Transformers do not Provide a Path for Active Power During Islanding	
Item#	**Impedance**	**Value**
1	Main plant transformer	1-2 ohms
2	Grounding transformer @ 34.5kV collection circuit	During islanding is not found to effectively shunt active power to or from generators.

Table 2. Ground path

The opening of a wind turbine or solar inverter circuit breaker from a remote location by means of a signal over a communication channel such as fiber takes time to complete; such a delay is called latency. There are numerous objectives with protecting a collection circuit; here we are focused on two: (1) clearing the fault from the plant as quickly as possible to reduce the incident energy and (2) clearing the fault from the individual generators as quickly as possible to reduce TOV. Both objectives are in competition with each other.

The first objective is clearing the fault from the plant and transmission system to reduce both the incident energy and the time that personnel and equipment are exposed to the huge fault currents sourced from the transmission system. When the feeder breaker operates first and clears the plant from the fault, current from the transmission system that exceeds 15,000 amps is limited in time, and that is positive. However, TOV can present a problem, since the generators may be islanding.

The second objective is to get the generators to shut down without islanding; this objective competes with the first objective of quickly opening the feeder breaker. It could take 200 milliseconds for the signal to reach the generators and order them to shut down. With this protection objective in mind, some designers place a grounding transformer on the collection circuit when trying to avoid TOV. In certain cases, however, the grounding transformer will not be effective when it comes to reducing TOVs and subsequent damage to the lightning arrestors.

Table 1 lists the failure modes (in addition to latency) that prevent the message from reaching the equipment. If such failure modes are not present and the message gets to the right device, the typical latency times with respect to remote trips introduce delays; these are shown in Table 2 [4]. In addition, [5] presents that feeder clearing times could exceed 122 milliseconds when using a remote trip. Figures 6, 8, and 9 and Table 3 show that both techniques—a delay in feeder breaker clearing or no delay in feeder breaker clearing—have consequences. The consequences are incident energy or severe over voltages that destroy collection circuit equipment and kills personnel.

Other PSCAD reports of modeling and simulation of WPPs and SPPs confirm that islanding can and will destroy lightning arrestors and can exceed the BIL. They appear to confirm that during islanding, even with a grounding transformer, the voltage can exceed 1.6 pu of the MCOV. Some reports imply that they simulate islanding at low power and that a grounding transformer can keep the voltage below the MCOV (The PSCAD model used for this report confirms the same.) However, this report goes further, to where the islanding is set to occur at full power and where the collector voltages quickly rise as the lightning arrestor conducts.

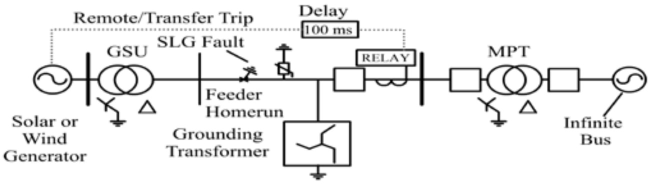


Fig 8. Remote trip that a grounding transformer does not solve.

4. GROUNDING TRANSFORMERS

Generally, the grounding transformer (see Figure 8) provides a grounded system when one doesn't exist. Grounding transformers create a zero sequence path to ground. Concerning WPPs and SPPs with delta-configured collection circuits, grounding transformers provide a relatively low zero sequence impedance compared to the susceptance of the collection circuit. However, the impedance is not low enough to prevent a severe voltage rise during a fault followed by a severe islanding event for WPPs or SPPs. Grounding transformers are placed on collection circuits where such circuits have generator-step-up-transformers that are delta connected for when the feeder breaker opens (See Figure 10). These become the reference to ground and provide a zero-sequence path for the current to flow, and they allow current to be shared across the phases; where the zero-sequence current is shared between the phases. Grounding transformers help the lightning arrestors share the load during a fault and separation from the transmission system. In addition, if the grounding transformer is a zig zag-connected transformer with sectionalized windings on one side, it can suppress third (triplen) harmonics in the line to neutral as well as the line-to-line voltage [15].

The positive, negative, and zero-sequence impedance of a grounding transformer is calculated at 60 Hz. However, the positive and negative sequence is infinite; only the zero-sequence path exists. However, such consideration assumes that the power quality of a separated circuit remains. While the power quality of each inverter at the low side of the generator-step-up transformer remains reasonably intact, the high side on the collection circuit is another story. The 60 Hz impedance may become irrelevant due to the very lightly loaded and very underdamped circuit. The grounding transformer provides a highly inductive line-to-ground path. In addition, the lightning arrestors provide a switched and clamping path to ground. The calculation of impedance, whether it be zero-sequence or positive or negative sequence, on such a turbulent floating circuit may become irrelevant. Interestingly, most WPPs or SPPs do not have installed current transformers or potential transformers to measure voltage and current on the high-side collection circuit.

Each plant responds differently to a fault. However, some characteristics are common to most plants. Generally, the transmission system sources the current to the fault on the affected feeder until the feeder circuit breaker clears the fault from the transmission system and plant. The breaker opens, separating the affected feeder from the plant and transmission system and thereby clearing the fault from the plant. Since the collection circuit is delta connected at each generator-step-up transformer, the collection circuit floats. Consequently, after the feeder circuit opens, the susceptance provided by the capacitance of the cables provides a relatively higher impedance path to ground. A grounding transformer is installed on the separated collection circuit and, with degraded power quality in mind, provides a shunt path of inductance. The cable provides a shunt path of capacitance, and the resistance is a switch resistor called a lightning arrestor.

A grounding transformer is introduced to provide a ground path for currents to flow in a delta-configured collection circuit, during primarily single line-to-ground faults after the feeder breaker has opened and separated the collection circuit from the transmission system. With degraded power quality in mind, and with the impedance to ground relatively high, high voltages should be observed on the collection circuit. Grounding transformers are included on the feeder to limit voltage spikes concerning transient over voltage. However, when it comes to islanding, they do not limit TOV. In addition, the voltage spikes they produce may exceed the BIL of equipment connected electrically to the separated collection circuit (see Figure 9 and Table 3).

Only if there is load and if a grounding transformer is a five-leg core or a shell form design, the zero-sequence impedance is equal to the positive-sequence impedance of the transformer, however there is no load [16] and the positive and negative sequence impedances are effectively infinite. However, if the grounding transformer is a three-limb core, the magnetic return path is through air and the tank walls of the transformer. Therefore, the magnetic impedance, which is inversely proportional to the magnetic reluctance, is very low. In addition, if the core is saturating, then the nonlinear characteristics of each core type must also be considered. However, with the nonlinearities of the lightning arrestors and both saturating generator-step-up transformers and grounding transformers, such impedances may be irrelevant for a lightly loaded-floating collection circuit where the voltage may still rise past prior considerations concerning insulation coordination and “60hz” becomes cursory and requires engineers to consider higher frequencies.

Grounding transformers provide a zero-sequence path for currents to flow. During islanding, they provide a ground reference with zero-sequence impedance saturating. In the PSCAD model, small amounts of saturation begin around 1.3 pu voltage and increase as the voltage goes up. During islanding on the affected feeder collection circuit, the grounding transformer provides two functions: (1) a zero-sequence path for the current on the faulted circuit and (2) saturation impedance that reduces impedance as the voltage increases on the islanding feeder circuit. PSCAD simulations, however, show that the grounding transformer provides inadequate relief to the lightning arrestors.

	PSCAD Simulation results with severe Collection Circuit Islanding	
Item	***With Ground Transformer***	***Without Ground Transformer***
1	*Arrestor TOV 1.6 pu and is aging; is accelerated depending on inverter trip time.*	*Arrestor TOV 1.8 pu most likely will fail sooner rather than later.*
2	*150 kV occurs and you fail equipment on collection*	*200 kV excessive*

Table 3.

5. INVERTER CROWBAR AND TEMPORARY OVERVOLTAGES

According to [18], and as shown in figures 10 and 6, over voltages occur in solar inverters when the breaker opens even with a crowbar. A crowbar is a device that discharges energy at the generator located in the inverter. [18] proceeds to show that the over voltages of 1.34 pu are seen with a crowbar, and voltages of 3.5 pu are observed without a crowbar. The crowbar was introduced as a means of fast protection. However, [18] shows that with fast protection, a voltage of 1.8 pu can be expected at the mains of the inverter, which is what the VDH/GDMI can better protect against. However, using both together is believed to be the optimum solution.

The crowbar is used to “shunt” the energy away to protect both WPPs and SPPs. [18] describes the deployment of a crowbar during an overvoltage event where the main feeder breaker had opened and parallel converters were islanding. The crowbar takes the excess energy and dissipates it. However, manufacturers do not guarantee when the crowbar deploys relative to the opening of a breaker, and the variable timing guarantees a miscoordination between the crowbar and the feeder breaker.

With the above in mind, the PSCAD simulation will not use overvoltage protection and will allow the simulation to run to show that the lightning arrestors take the brunt of the energy from a latent shutdown of a solar or wind power inverter.

Miscoordination of protection for the inverter and the feeder breaker and the stress imposed on the insulation are presented in the PSCAD simulation. The simulation would be unrealistic if the inverter were not tripped and were simply allowed to go on. However, according to [18], the inverter or other equipment would have blown up!

PSCAD simulation shows without lighting arrestors and if the feeder breaker opens while generators are producing at full power the voltage exceeds 200 kV without a grounding transformer and 150 kV with a grounding transformer.

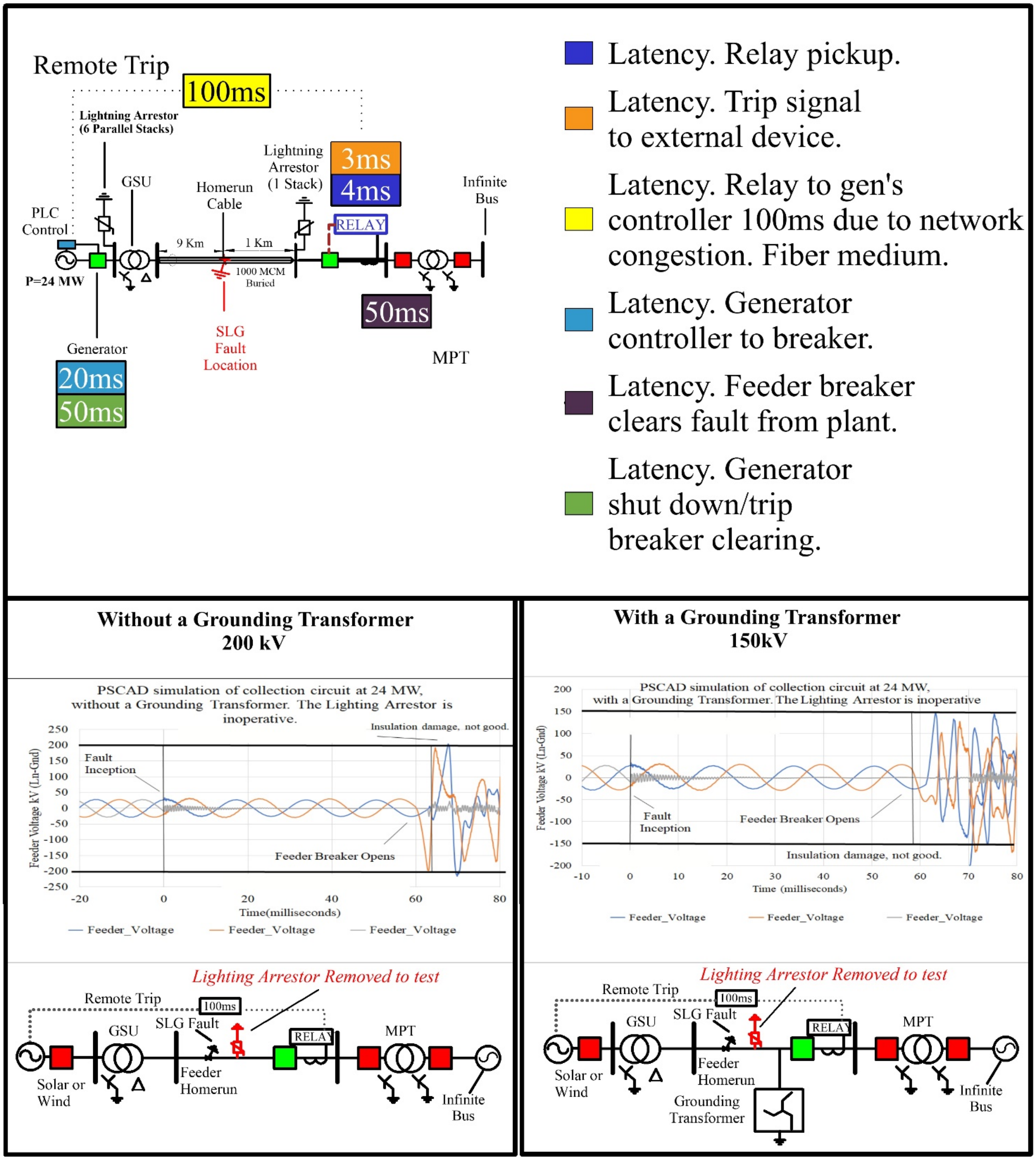
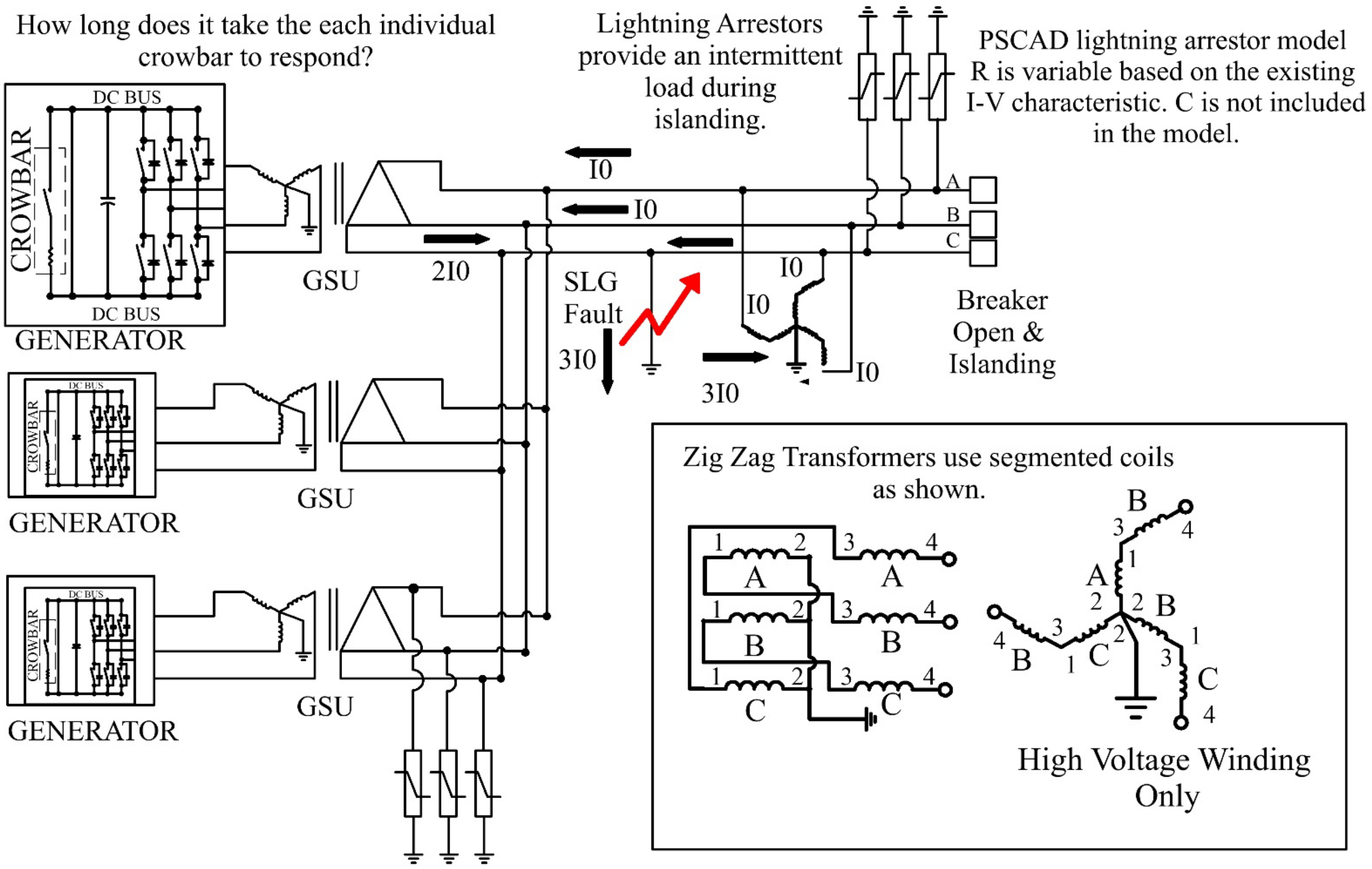


Fig. 9. PSCAD simulation, switching transient.

CROWBAR AND GROUNDING TRANSFORMER


How long does it take the each individual crowbar to respond?

Lightning Arrestors provide an intermittent load during islanding.

PSCAD lightning arrestor model R is variable based on the existing I-V characteristic. C is not included in the model.

Zig Zag Transformers use segmented coils as shown.

High Voltage Winding Only

A. Concerning a Grounding Transformer

1) A grounding transformer provides a path for zero sequence currents to flow during a single line to ground fault.
2) A grounding transformer does not provide a three-phase bolted short to ground.

B. Concerning Protection & Crowbar

1) Those performing protective relaying tasks may not know how the inverter or generator is programmed.
Even though a crowbar can dissipate the energy in the circuit, protection engineers may not know or predict when it will be enabled during a fault.

Fig. 10. Crowbar and grounding transformer.

6. GROUNDING BREAKER OPERATIONAL OVERVIEW

This is an operational overview concerning the VDH/GSMI for WPPs and SPPs. To describe the design and operation of the VDH/GSMI, the overview focuses on a feeder circuit within a WPP or SPP and the change in impedance that occurs when a fault appears on the collection-feeder homerun cable (Figure 12). The PSCAD simulation concerning the operation of a grounding breaker demonstrates that it grounds the collection circuit.

Figure 11 and Table 5 show the states of the VDH/GSMI: 1) Closed, line breaker closed, and ground switch open; 2) Transition, both switches open; 3) Open, line switch open, and ground switch closed. The grounding breaker operation has two distinct states of operation: open and closed. However, a transition state is included between the two. Thus, there are three states total with a mechanical operating time of 16 milliseconds and an arc clearing time of 12 milliseconds. They are presented in Table 4.

State	electrical time (ms)	Mech. Operating Time(ms)
Initial State	0	0
Clear Fault or Open	26-34	N/A
Transition	4-12	16
Open & grounded	38	38

Table 4. Electrical and mechanical operating time of the VDH/GSMI

Closed status means that the line interrupters are closed (see Figure 13) and the ground interrupters are open. Transition includes the coincident operation of the two interlocked vacuum interrupters with at least one trip command from a relay (Figure 12). First, the line (breaker) vacuum interrupters begin 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 (see Figure 14).

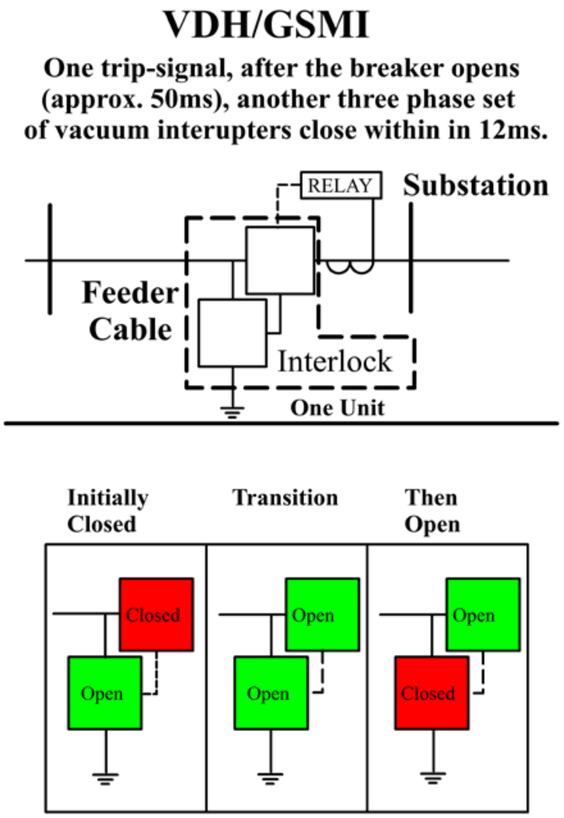


Fig. 11. VDH/GSMI states.

	States of the VDH/GSMI		
State	VDH/GSMI Breaker	Line Breaker	Ground Breaker
1	Closed	Closed	Open
2	Transition(4-12ms)	Open	Open
3	Open	Open	Closed

Table 5. States of the VDH/GSMI

Open status means that 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 homerun cable and feeder circuit are grounded at the station (Table 5).

The mechanical interlock opens the line vacuum interrupter first. Then, approximately 4–12 milliseconds later, the interlock causes the grounding vacuum interrupter to close. The TP135-0 IEEE tutorial on the vacuum switch gear reads:

"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." (See Figure 12.)

Figure 13 shows that the when the line side breaker opens, the current stops flowing 4 milliseconds to 12 milliseconds before the ground interrupters close. When the ground interrupters close, the currents flow into a three-phase bolted ground.

7. CONCERNING PSCAD VDH/GSMI SIMULATIONS

Figures 15, 16, 17, and 18 illustrate how the VDH/GSMI provides protection and shows how it specifically protects the affected circuit by reducing incident energy and TOV. The simulation begins with Figure 15, where the PSCAD simulation initial power level is approximately 24 MW and the currents and voltages are symmetric and undisturbed. Figure 16 focuses on the incident energy, where the VDH/GSMI has limited the fault current sourced from the transmission system to three cycles. Figure 16 and 17 shows that the voltage is low enough to cause the generators to go offline after the collection circuit is grounded. (The higher the impedance of the collection circuit, the less likely this will happen.)

Figure 16 and Figure 17 show the simulation with the relay picking up the fault within ¼ cycle or 4 milliseconds. The same relay then sends the trip command 3 milliseconds later to the VDH/GSMI, and the VDH/GSMI opens and clears then closes and grounds the collection circuit 38 milliseconds later. The total clearing and grounding time is 45 milliseconds. 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.

PSCAD VDH/GSMI OPERATING TIMING DIAGRAM

Single Trip Signal

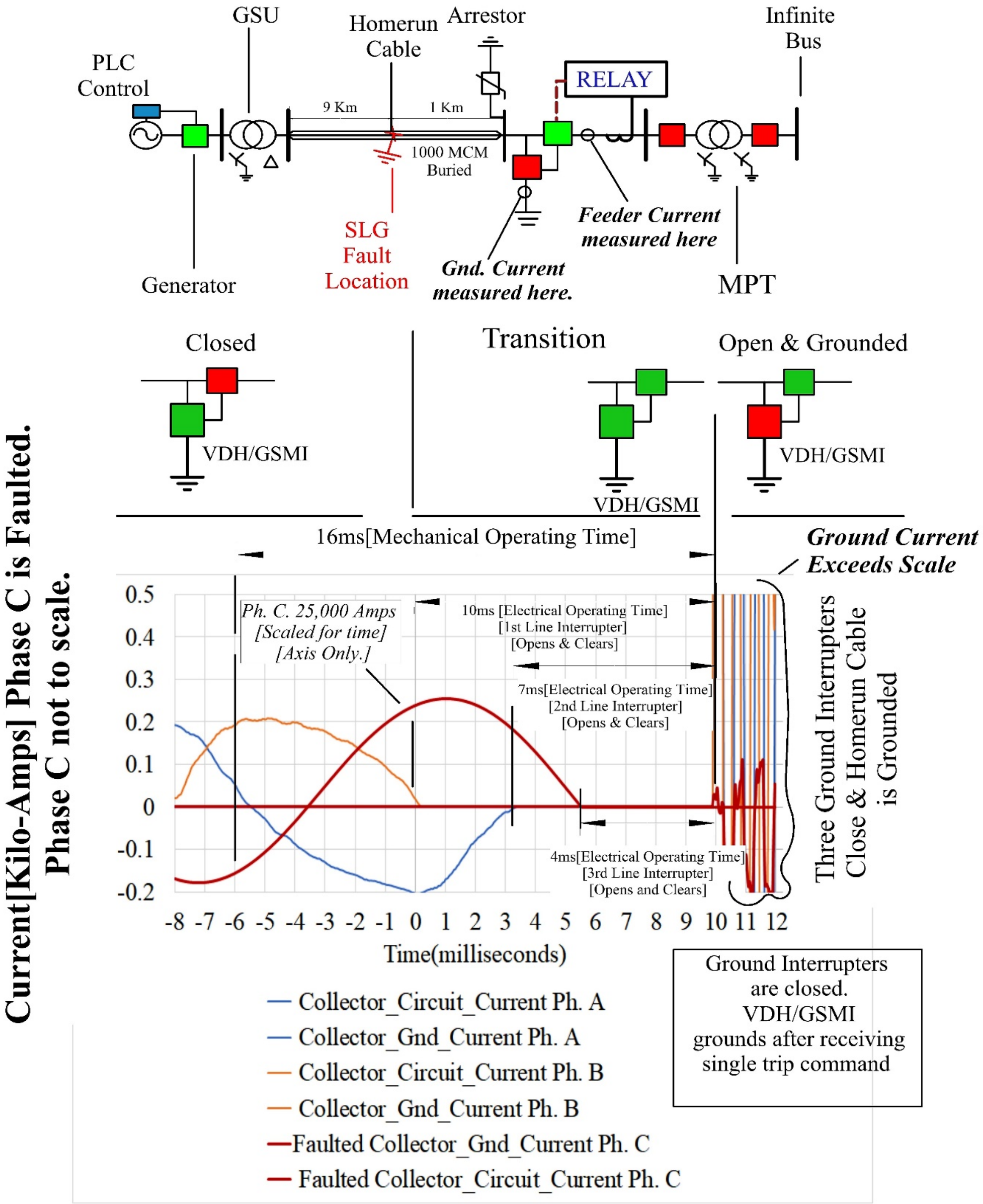
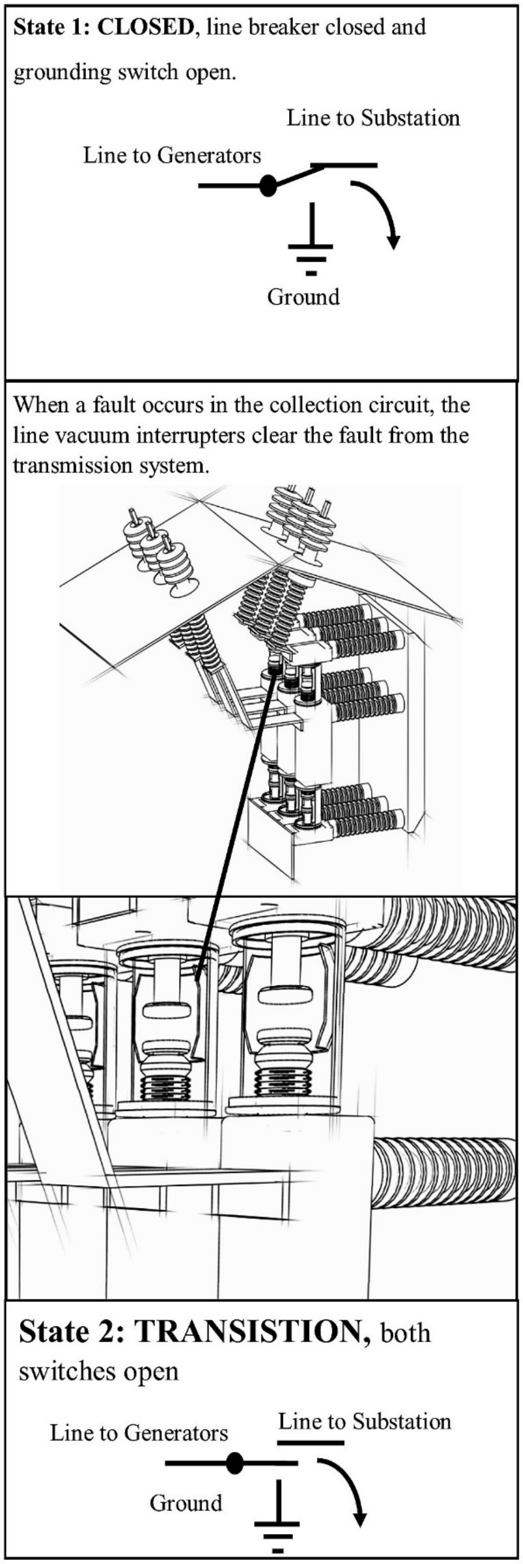


Fig. 12. PSCAD simulation VDH/GSMI timing diagram.

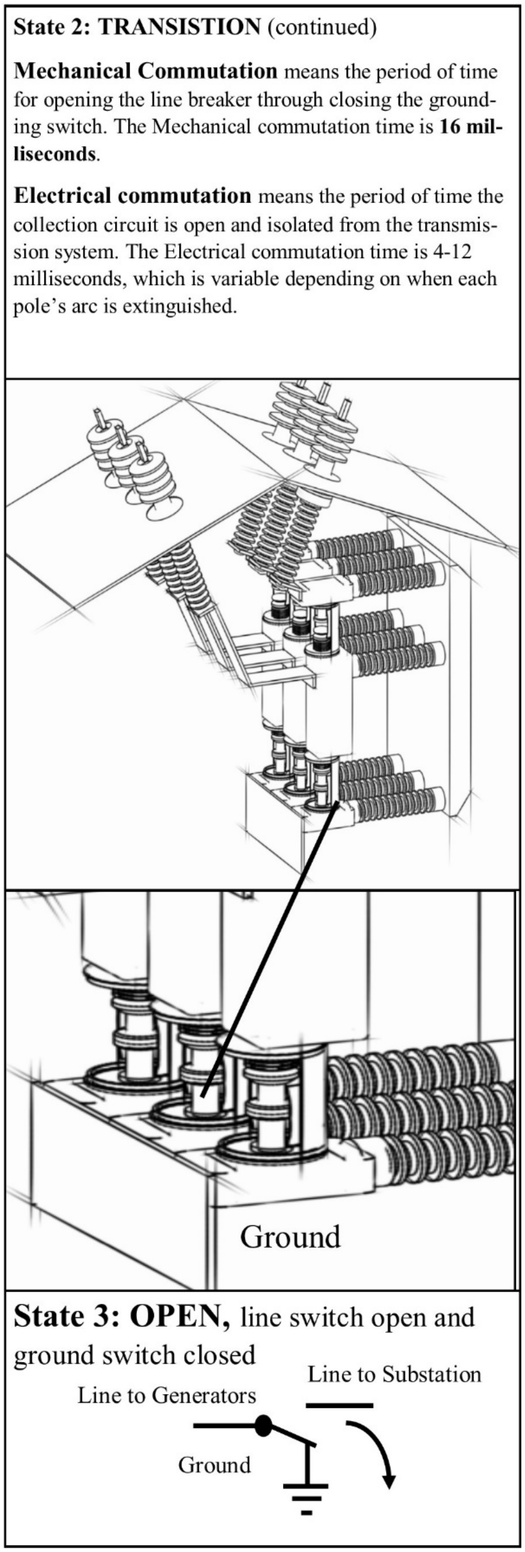


State 1: CLOSED, line breaker closed and grounding switch open.

When a fault occurs in the collection circuit, the line vacuum interrupters clear the fault from the transmission system.

State 2: TRANSISTION, both switches open

Fig. 13. VDH/GSMI operating sequence; three-phase vacuum interrupters open first.



State 2: TRANSISTION (continued)

Mechanical Commutation means the period of time for opening the line breaker through closing the grounding switch. The Mechanical commutation time is **16 milliseconds**.

Electrical commutation means the period of time the collection circuit is open and isolated from the transmission system. The Electrical commutation time is 4-12 milliseconds, which is variable depending on when each pole's arc is extinguished.

State 3: OPEN, line switch open and ground switch closed

Fig. 14. VDH/GSMI second operating sequence; three-phase ground vacuum interrupter closes, collection circuit is grounded.

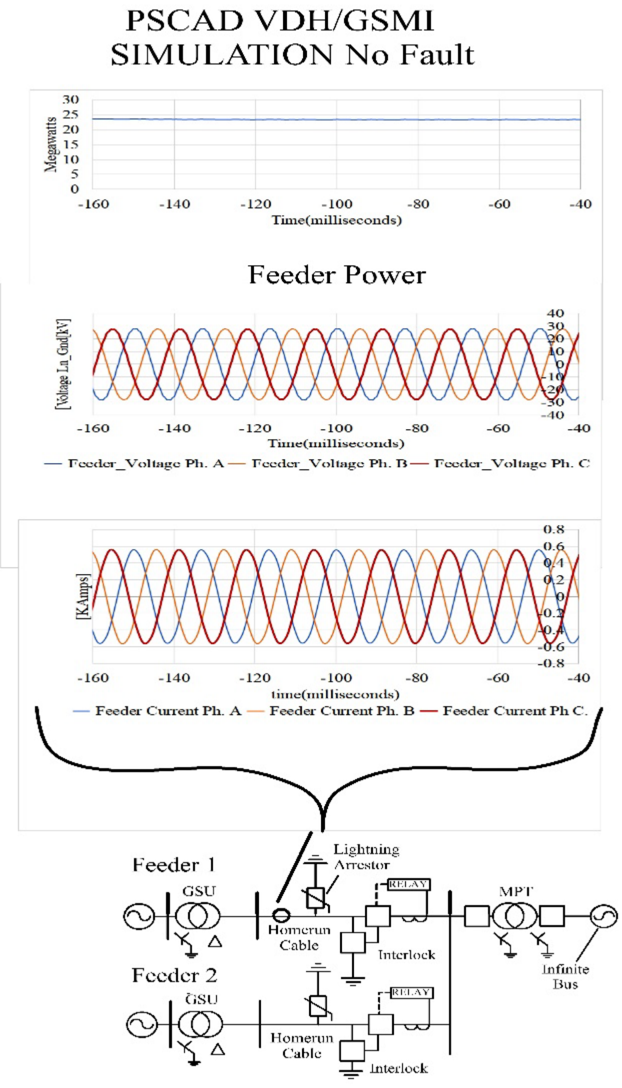


Fig. 15. PSCAD simulation start with no fault and symmetrical feeder current. Active power is around 24 MW.

Concerning the states of the VDH/GSMI breaker, it is critical to consider the impedance of the homerun section of the feeder cable during the three states of operation. Why? Because the operation of the breaker quickly transitions to ground, the collection circuit forms a three-phase bolted ground on the homerun cable. This reduces the impedance at the end of a 10-km homerun cable to near 1 to 2 j ohms to ground. Compare this to a generator-step-up transformer with a positive-sequence impedance of 25 ohms.

Concerning the PSCAD simulation, Figures 16 and 17 include a lightning arrestor with an MCOV rating of 22 kV. The line-to-ground voltage rating of the collection circuit is 19.920kV. Since the scale of the graphs is in hundreds of milliseconds, the slope of the TOV in figure 18 curve is not evident.

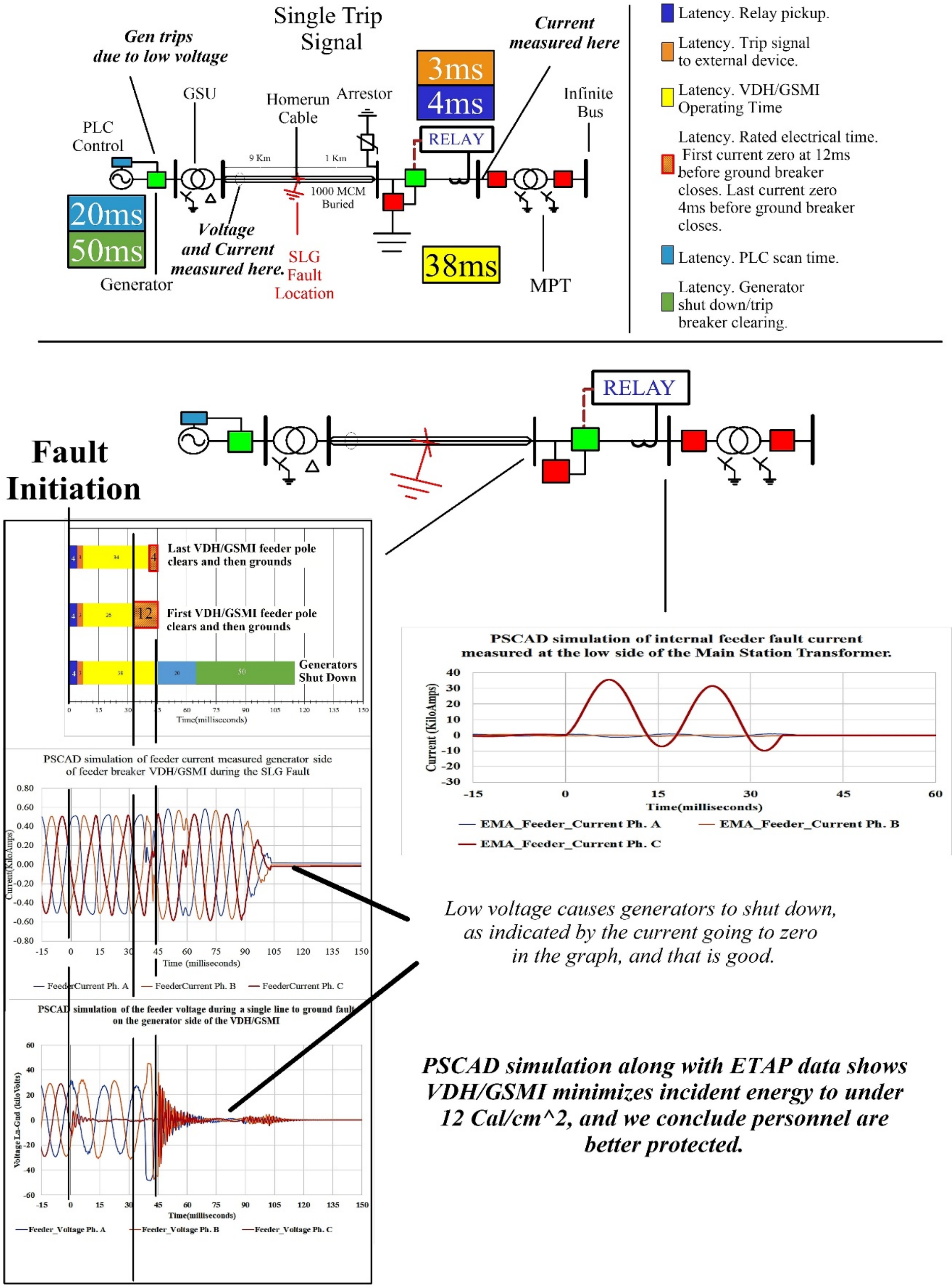
The TOV specification is given in terms of the power frequency of the electric power system, which is 60hz. Typical duty curves start around 1.55pu, and prior duty curves start out at 1.46 pu of the MCOV rating of the lightning arrestor.

The duty curve for a lightning arrestor concerns conditions where the arrestor has not operated. The prior duty curve concerns conditions where the arrestor can operate again and again if the voltage stays below the line.

As shown in Figures 17 and 18, when the VDH/GSMI switches, the unfaulted phase voltages increase rapidly causing the undamaged arrestors to operate and clip the voltage, thus protecting collection circuit. The ground interrupter closes fast enough to prevent the voltage from exceeding the duty curve, however. We also see in Figure 18 that the feeder voltage drops significantly toward zero after the ground interrupters close. There is a ringing with the change in impedance, however, and within a brief time the voltage is clearly approaching zero as the generator is shutting down.

This PSCAD simulation shows that the VDH/GSMI clearly can preserve insulation coordination as well as make it easier for engineers to perform an insulation coordination study and feel comfortable about their assumptions. It also makes clear that a coordination study for a collection circuit should be performed with a VDH/GSMI, because they are very simple to perform. As every plant design is different and all transients are not the same it is painfully obvious from the simulations that any insulation coordination study without a VDH/GSMI is questionable.

VDH/GSMI trips the generator via grounding the collection circuit with one trip signal.

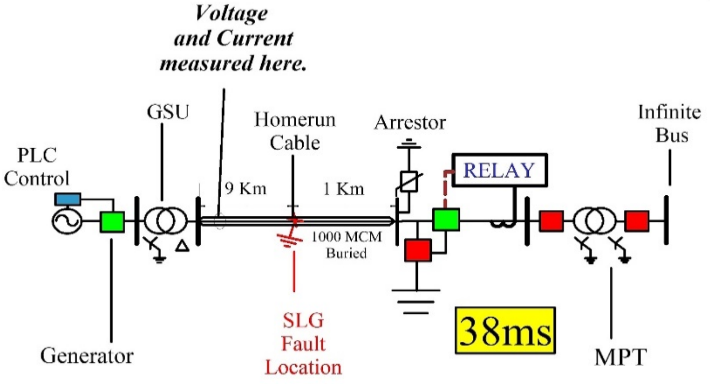


Low voltage causes generators to shut down, as indicated by the current going to zero in the graph, and that is good.

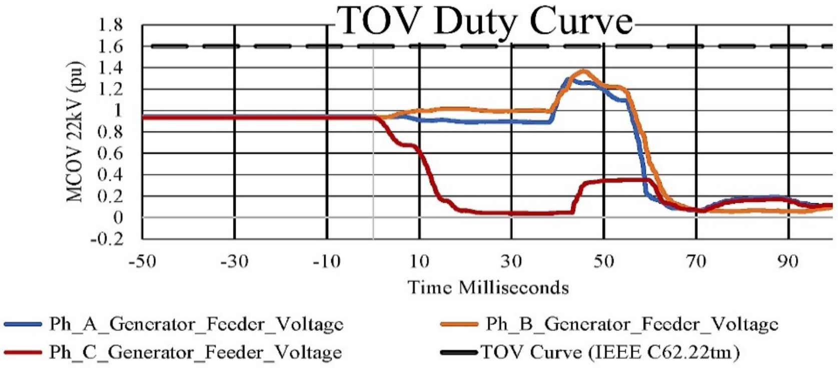
PSCAD simulation along with ETAP data shows VDH/GSMI minimizes incident energy to under 12 Cal/cm^2, and we conclude personnel are better protected.

Fig. 16. PSCAD VDH/GSMI timing diagram.

Concerning islanding of the collection circuit the VDH/GSMI causes the feeder's voltage to remain within MCOV limits of the lightning arrestor.



PSCAD Simulation: Collection Circuit producing 24 MW. A Single Line to ground fault occurs on the collection circuit. The Relay and VDH/GSMI respond in 45ms. The VDH/GSMI Clears then Grounds. This Graph is the PSCAD simulation showing the MCOV arrestor transistion voltage.



🟦 Latency. Relay pickup.

🟧 Latency. Trip signal to external device.

🟨 Latency. VDH/GSMI Operating Time

🟧 Latency. Rated arcing time. First current zero at 12ms before ground breaker closes. Last current zero 4ms before ground breaker closes.

🟦 Latency. PLC scan time.

🟩 Latency. Generator shut down/trip breaker clearing.

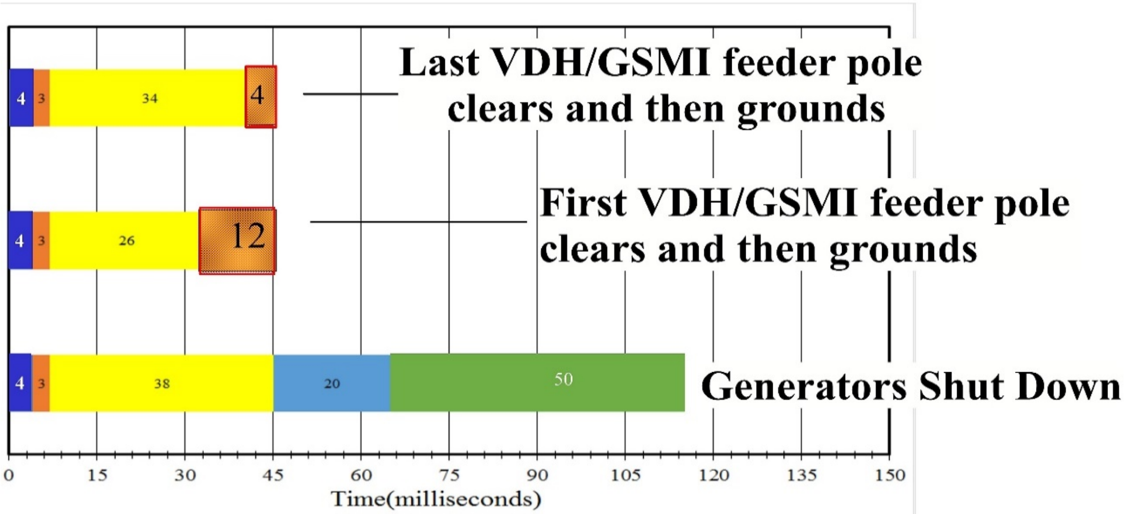


Fig. 17. PSCAD simulation: TOV, prior duty curve.

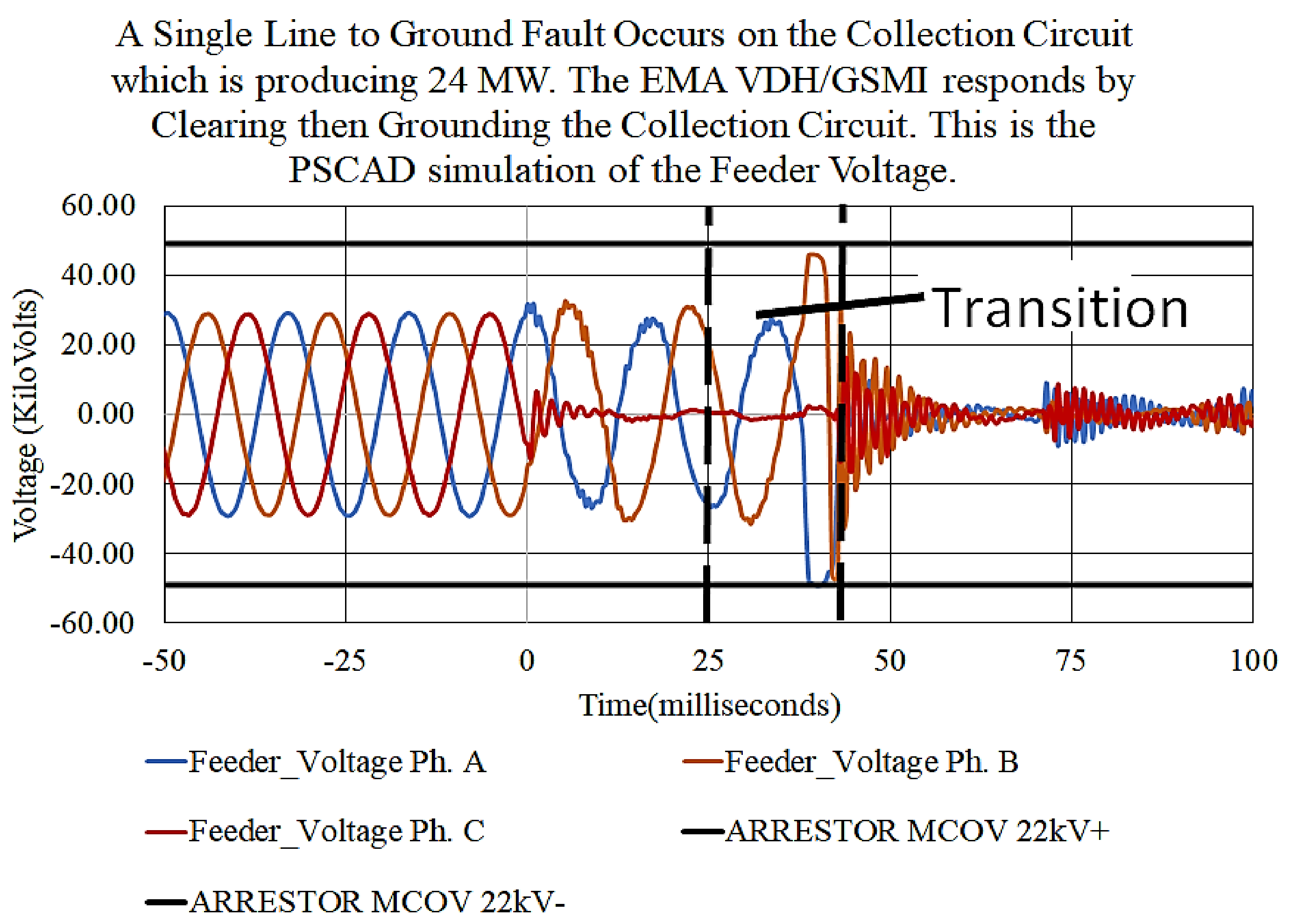


Fig. 18. PSCAD simulation.

8. PSCAD MODELING

Figure 19 shows the PSCAD single line model with two aggregate generators. The model emulates a WPP or SPP with a type 4 wind generator or an inverter-based generator similar to that presented in [19]. The generators use a current source inverter and Clark/Park transforms that are similar to those presented in [19] and that follow voltage at the mains of the transformer and power to compute the current (Id, Iq) and the instantaneous currents ia, ib, and ic from commanded power and reactive power. The plant is rated at approximately 100 MW. There are two feeders. One is an equivalent feeder (75 MW), and the other is the faulted feeder (25MW). The homerun cable is on the faulted feeder.

The homerun cable is represented by an infinite pi model of varying distances. In PSCAD, it is called a Bergeron model, as shown in Figure 22. The VDH/GSMI is shown in both Figure 19 and Figure 21. The line breaker, remote trip, and grounding breaker relay models are also provided in Figure 20. The simulation is very simple and consists of time delays for the relays to open the appropriate breaker while the generators produce power and while a single line-to-ground fault occurs on the homerun cable. Even though 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 20 models 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. The "Vac_Interrupter_Gnd" signal then causes the VDH/GSMI (see Figure 21) ground breaker to close. Concerning "Remote_Trip," the delay provides enough time to shut down the generators within the WPP or SPP (see Table 3) before the line breaker opens to avoid severe overvoltages. The "Remote_Trip" signal or "Vac_Interrupter_Gnd" signal may or may not be used, depending on the simulation. An example of this would be simulating a worst-case TOV and not allowing the feeder VDH/GSMI ground breaker to close or the wind turbine's breaker to open.

The model described herein begins with a powerful source rated greater than 1000 MVA. The main plant transformer and GSU (see Figure 21, Figure 26, and Figure 27) are 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 kV line to line on the low side. The GSU is an aggregate model to create a generator step-up. (*Note: The GSU impedance was not equivalenced, as this simulation is to demonstrate the VDH/GSMI, where all plants are different and should be modeled on a case-by-case basis*.) 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 75 MW, and the faulted feeder is set to produce approximately 24 MW. Reactive power is set to flow and depending on the simulation, that value is adjusted. The voltage at the point of interconnection is set at 1 pu.

Figure 22 and Figure 23 show the three-phase PSCAD cable model. Figure 24 and Figure 25 provide R, X, and B for the cable. One could calculate a leg's impedance looking into the 1000 MCM homerun cable from the junction box to the main plant transformer and using manufacturer-specified data for the 1000 MCM direct buried cable. PSCAD can do this, however, and thus we use the PSCAD cable constant positive-sequence impedance XL, positive sequence resistance R, and susceptance B.

9. CALCULATIONS

The following equations are taken from [9] and are used to alternate between pu unit and actual values.

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

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

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

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

Considering the 230kV/34.5kV 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

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

$$X_l = 0.08 * 13.225 = +1.05\ j\ ohms$$

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

Thus, we find that the impedance looking into the main plant transformer is approximately 1 ohm. We can use the same equation to calculate the impedance of the step-up transformer at each type 3 or type 4 wind-turbine or solar inverter or even at a grounding transformer.

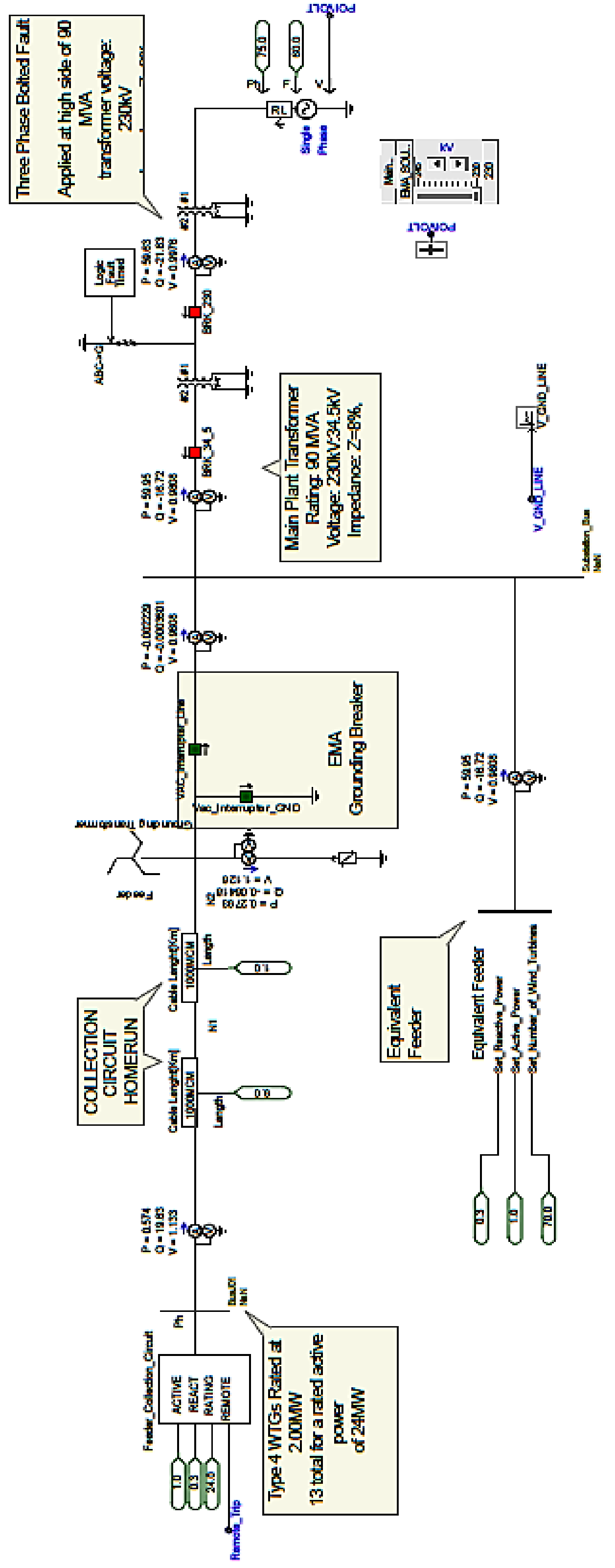


Fig. 19. PSCAD model: single line.

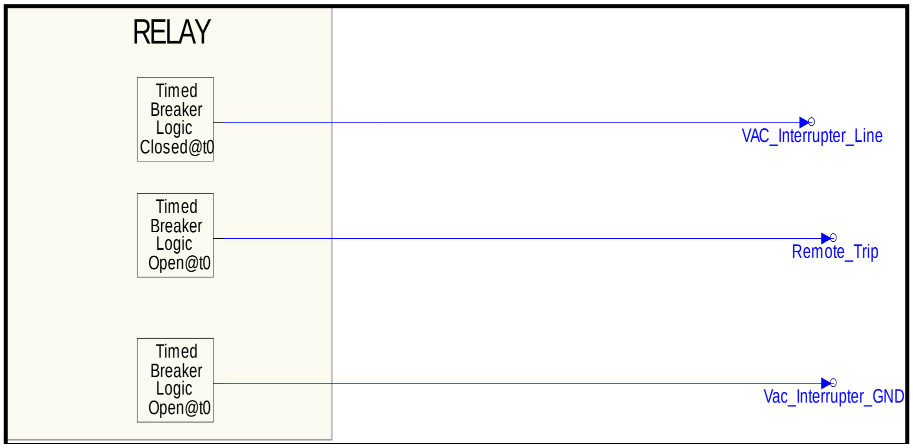


Fig. 20. Breaker(s) timing.

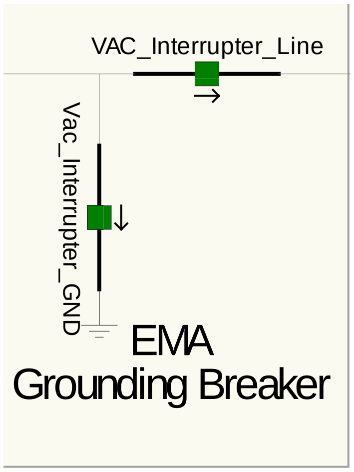
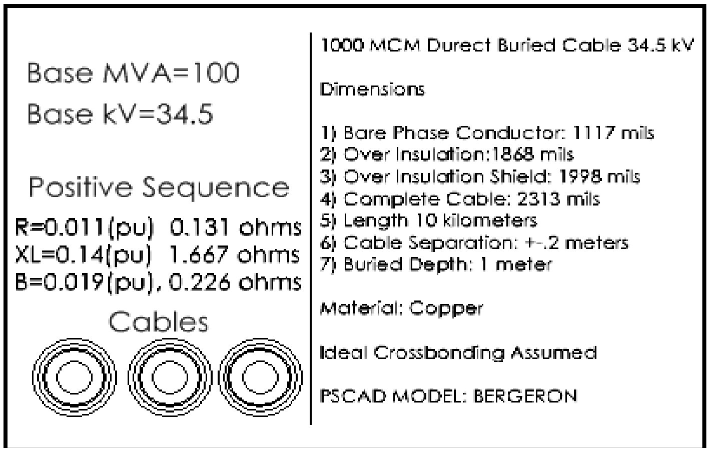


Fig. 21. EMA line and grounding breaker model.

-



Base MVA=100
Base kV=34.5

Positive Sequence
R=0.011(pu) 0.131 ohms
XL=0.14(pu) 1.667 ohms
B=0.019(pu), 0.226 ohms

1000 MCM Durect Buried Cable 34.5 kV

Dimensions

1) Bare Phase Conductor: 1117 mils
2) Over Insulation:1868 mils
3) Over Insulation Shield: 1998 mils
4) Complete Cable: 2313 mils
5) Length 10 kilometers
6) Cable Separation: +-.2 meters
7) Buried Depth: 1 meter

Material: Copper

Ideal Crossbonding Assumed

PSCAD MODEL: BERGERON

Fig. 22. PSCAD line constants model 10 km (note for aluminum the values are R=0.014(pu), XL=0.15 pu(ohms), B=0.228 (pu)). In this paper, we will use copper where either value is nearly the same (see Figure 22). The following figures separate the cable into 1 km and 9km lengths.

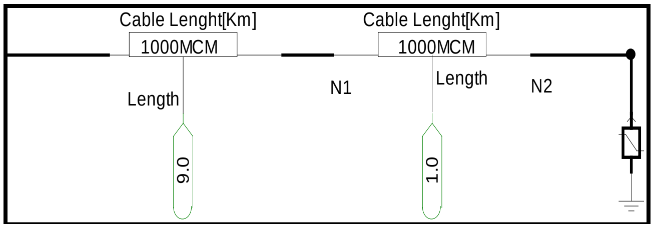
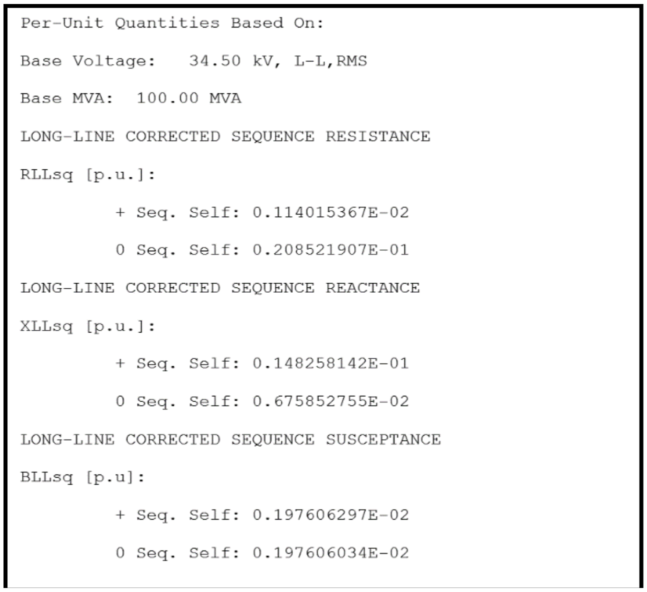
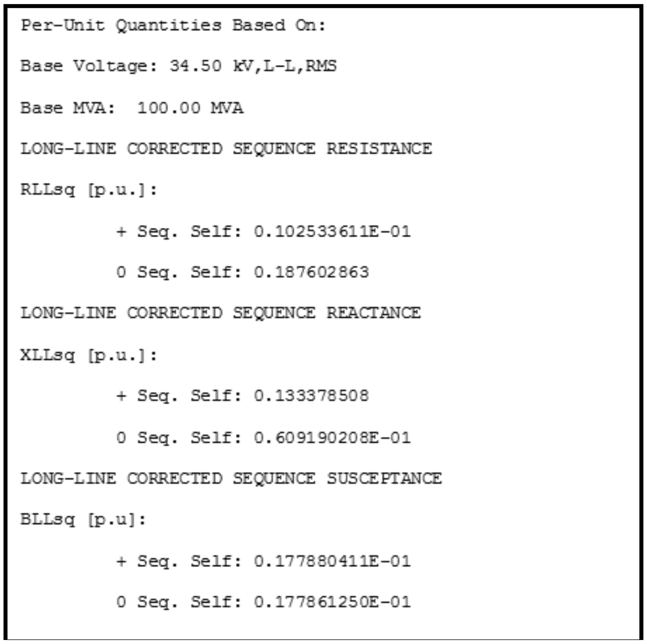


Fig. 23. PSCAD cable model (10 km model separated into 1 km and 9 km sections).



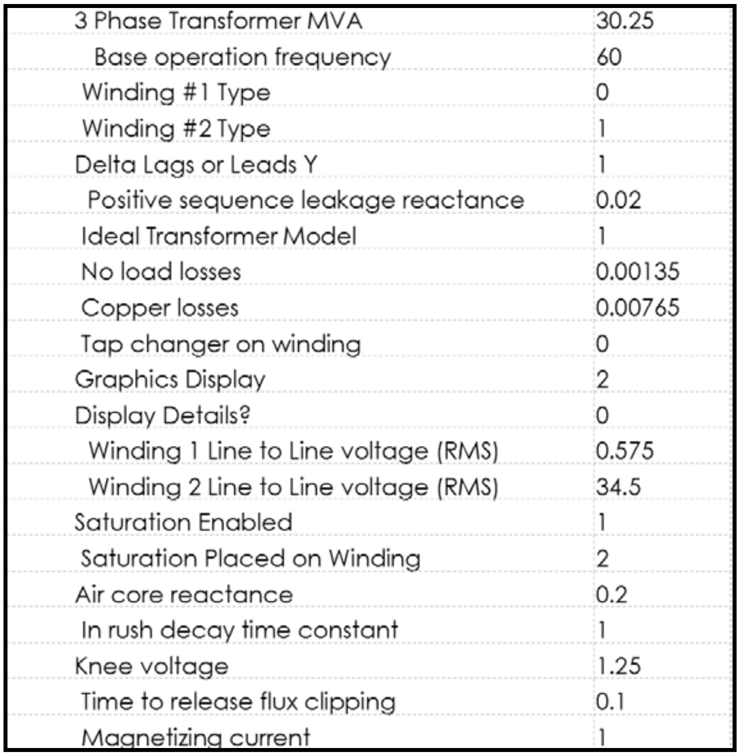
```
Per-Unit Quantities Based On:

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. 24. PSCAD 1 km 1000 MCM cable parameters.



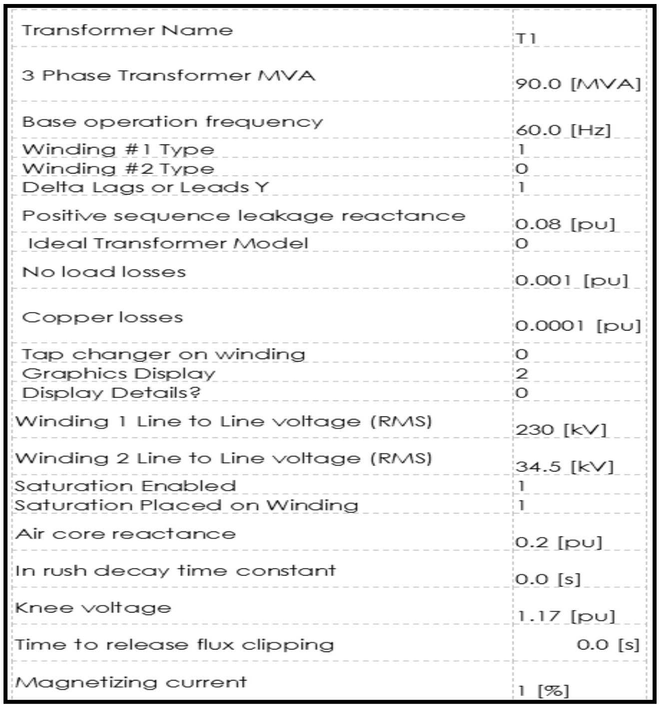
```
Per-Unit Quantities Based On:

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. 25. 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. 26. 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. 27. MPT transformer parameters.

We care about impedance because voltage rise across the padmounts transformer is due to the current and angle across the transformer impedance, which dominates in value over the branch impedance when the homerun 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 2.5 MVA, which calculates at 0.866+j26.2 ohms. The branch feeder impedance is assumed to be much less than the transformer impedance and is estimated at 1.4+j1.3 ohms. The impedance of a 10-kilometer homerun cable from PSCAD is 0.131+j1.67 ohms.

The calculations show that the VDH/GSMI provides a relatively low impedance when it opens and shorts the homerun cable to ground. Within a range of fault locations on the cable, the impedance of the cable remains low compared to the impedance of each transformer at each wind turbine. The wind turbines or inverters are thus hard pressed to remain online when the grounding breaker closes. When the ground breaker operates and is in state 3 (see figure 14) the impedance is so low that a type 3 or type 4 generator [10] and[19] that is limiting its current will be hard pressed to keep its voltage up and will trip offline because the voltage is so low.

10. PSCAD TRANSIENTS AND MODELING METHODOLOGY

The focus of this paper concerns the grounding breaker and remote trip and how each can protect a collection circuit within a WPP or SPP. We used PSCAD to model switching transients and other electro-dynamic and control system events. The simulation focuses on the impacts of various faults on a specific collection system feeder circuit where the WPP or SPP employs the use of line breakers, grounding breakers, and remote trip protection arrangements.

Our simulations used an individual control at each generator, similar to what is prescribed in [19]. The paper took the approach that using an inverter with a crowbar would be too detailed for a dynamic simulation because the collection system designer may not be aware of every detail or nuance of every generator manufacturer's inverter. Thus, this paper will take the (extreme) position that the longest trip point (however unrealistic) within each generator is presumed to be common to most inverters [see 18].

With the above in mind, this paper uses controlled current sources on each phase to inject current into the collection circuit. The current sources are controlled by a mechanism that aggregates the generators into one generator with an aggregate commanded active power and reactive power. The active power control and reactive power controller use a proportional integral (PI) regulator to generate an individual active and reactive power command. This is sent to a current controller that employs Clark/Park transforms with a phase-locked loop to generate the commanded current for the individual phases. This control also uses the phase-locked loop to reproduce the [average] measured voltage and provide a clean signal to calculate the currents with the commanded active and reactive power.

This simulation uses the technique derived from the generalized circuit theory provided by [15] and [20], in which the [clean] instantaneous voltage measured at the mains of each generator with the commanded active power and reactive power, **id** and **iq**, are generated and then transformed into their respective instantaneous phase currents ia, ib, and ic.

Since the phase-locked loop operates and may or may not requires constant synchronization to another voltage source at either the high side or the low side of the generator (wind or solar), and because it operates to provide the desired line currents on each phase, this technique provides under voltage ride through at the mains of the generator at the high or low side of the its step-up transformer. This technique is also for simulating a short-term separation from the transmission system. While different techniques may be used to create or simulate an inverter as a generator, it is known in the industry that each inverter manufacturer will have the proprietary method of programming and controlling its inverter. The technique described within is just one of many [see 19 and 20].

It is critical to note that when it comes to protection, the VDH/GSMI provides a three-phase bolted ground on the homerun cable of a collection feeder and thus relieves WPP and SPP designers from guessing what the inverter manufacturer chooses to do. Instead, the inverter manufacture can rely on the VDH/GSMI to work the same way every time.

11. DISCUSSION OF SIMULATION RESULTS

This article incorporates the topics discussed in [19] and several methods of modeling the inverter and control techniques. This speaks to the nature of the grounding transformer's limitations. The grounding transformer primarily provides a zero-sequence path for ground currents to flow. It is not found to provide a clear signal to the inverters to shut down. It is, however, found to reduce the energy burden on lightning arrestors.

[19] shows several methods for modeling an inverter. However, modeling shows that with tuning the phase-locked loop, the Clark/Park controller for id and iq and the transformation of the individual line currents coupled with the response of the collection circuit creates a response that is difficult to control and implies that such control is unpredictable if the programmers programming control of the inverters do not coordinate with the engineers designing the collection system. Therefore, the VDH/GSMI is found to provide flexibility and independence between the engineering requirements for the two groups.

This section discusses the PSCAD simulation results. The simulations indicate that during severe islanding the grounding transformer does not shunt the majority of the power of the generator away from the lightning arrestors. If the feeder breaker is opened before the generators are offline, the lightning arrestors become overburdened and may fail over time during severe islanding. IEEE 62.22™ indicates that if the TOV exceeds more than 100 milliseconds, thermal runaway of the lightning arrestor is possible. A grounding transformer without a lightning arrestor reduces the BIL; however, the transient value may not be low enough to meet existing insulation requirements. Figures 10 and 28 illustrate this concept. Finally, we compare the performances of the VDH/GSMI and the grounding transformer

Figure 6 shows the collection circuits with and without a grounding transformer. When the collection circuit is separated from the plant and transmission system, it is delta configured. Consequently, the impedance to ground goes from 1 to 2 ohms to a very high impedance with no path for the real power to flow. When the feeder breaker opens, energy supplied to the feeder by the generators (which are online and producing power) causes the voltage to rise on the separated collection circuit. PSCAD results in Figure 6 show that during severe islanding, a grounding transformer on the collection circuit with the feeder breaker does lower the voltage and allow the lightning arrestors to share the burden.

PSCAD simulations show that during severe islanding, when the collection circuit is separated and the generators are producing maximum power, the lightning arrestor lowers the peaks to approximately 1.6 pu of its MCOV rating of 22 kV, with the grounding transformer included. Lightning arrestors have a heavy energy burden, however, as the energy passing through and aggregate arrestor at 24 MW exceeds ratings and most likely will overheat. If the TOV of 1.6 pu continues for more than 100ms, the lightning arrestor will become thermally unstable and will be damaged. Its I-V characteristic will then be unknown for later operations. If the current carrying capability is reduced due to repeated overstressing, the clamping voltage on the collection circuit will likely increase, during islanding and decreased current carrying capability. Simulations indicate that if the generators remain online after the feeder breaker opens, excessive energy will be shunted to ground by the lightning arrestors.

Generally, multiple lightning arrestors are connected to a collection circuit: a station class arrestor at the substation and heavy-duty arrestors at the end of the circuit. Manufacturers usually design arrestors exceed the recommendations of IEEE standard 62.22™ concerning TOV. However, PSCAD simulations show that during severe islanding of an affected feeder, even lightning arrestors with TOV curves that start at 1.65pu for 0.1 seconds are damaged. Over time, a damaged arrestor may pass less energy to ground and cause the voltages on the collection circuit to move higher and higher. Over time, possibly over years if subjected to such abuse (see Figure 8 and Figure 9), the lightning arrestor will fail short and will be replaced. Without measurements of the collection circuit voltage and current, however, the integrity of the insulation is unknown.

The grounding transformer provides a zero-sequence path for the current to flow from ground to the phase conductors. Such current flows during a single line-to-ground fault. However, PSCAD simulations show that when islanding occurs for a type 4 generator or an inverter-based generator (such as photovoltaic generator), the grounding transformer lowers the voltage spikes of the islanding-affected feeder from more than 200 kV to 150 kV without the aid of a lightning arrestor. However, both may exceed the WPP or SPP basic insulation levels.

The PSCAD model indicates that during islanding of a collection circuit, the resulting voltage spikes exceeded 150 kV and 200k without lightning arrestors and with and without a grounding transformer. The model confirms that grounding transformers do alleviate the stress of islanding collection circuits. The protection provided may not be enough, however. We have shown that if islanding occurs, lightning arrestors with or without grounding transformers on the separated collection circuit will be subjected to voltages that exceed the manufacturer's specified TOV curve. The arrestors will be damaged, their I-V characteristic will change, and their insulation coordination will be lost.

Figures 6, 9, and 28 show PSCAD simulations of an inverter-based generation and how the grounding transformer does not adequately protect an affected collection circuit. Figure 28 shows that the grounding transformer on its own does not prevent damage to the lightning arrestors and collection circuit during severe islanding. Conversely, PSCAD simulations of the VDH/GSMI show that it does protect the collection circuit by providing a three-phase bolted ground.

The PSCAD simulations show that the grounding transformer increases the TOV endured by the lightning arrestor because of the remote transfer trip's latency. Because the VDH/GSMI does not have to endure such delays, it operates more quickly (see Figure 28). The simulations show that without the VDH/GSMI, there is a significant increase in voltage and stress on the insulation system. A remote trip takes 7 cycles to operate, compared to the 3.5 cycles of the VDH/GSMI. The TOV from the remote trip is also significantly higher than that with the VDH/GSMI (see Figure 28). The simulation also shows that in terms of the TOV and incident energy of a fault, the grounding transformer does not improve the safety and reliability of the collection circuit. This makes sense, since the 60Hz impedance of a grounding transformer most likely is not designed for islanding. In addition, with the fault and the transient conditions, the pulsing current or voltage at higher frequencies does not lower the inductive reactance. Thus, it is safe to conclude that even though the grounding transformer provides a return current path for single line-to-ground faults and reduces triple harmonics, it does not appear to shunt large amounts of power to ground. The VDH/GSMI, on the other hand, shorts the phases to ground, providing a method to reduce potentially damaging over voltage on the separated collection circuit.

This section discussed the PSCAD simulation results. The simulations indicated that during severe islanding, the grounding transformer does not shunt a majority of the generator's power away from the lightning arrestors. If the feeder breaker is opened before the generators are offline, the lightning arrestors are overburdened and thus may fail over time. IEEE 62.22™ indicated that thermal runaway of the lightning arrestor is possible if the TOV voltage is exceeded for more than 100 milliseconds. In addition, even though the grounding transformer without any lightning arrestor reduces the BIL, the transient value may not be low enough to meet existing insulation requirements. This concept is illustrated in Figure 28. Finally, we compared the performance of the VDH/GSMI to the grounding transformer.

12. CONCLUSION

The VDH/GSMI is essential for protecting a WPP or SPP. Damage due to faults on collection circuits can happen quickly. Reports indicate that remote transfer trip techniques can introduce a delay of more than 122 milliseconds, such a delay may lead to damaging and dangerous conditions. While any fault creates damage, the remote trip delays disconnection from the transmission system and, consequently, allows high magnitude fault currents sourced from the transmission system to persist.

If properly coordinated, a VDH/GSMI can separate the affected feeder from the transmission system and WPP or SPP within 3.5 cycles. This is less than half the time of a remote trip and guarantees a great ground reference for the feeder. If the remote trip is not operating, the generators may island. In addition, TOV can occur and persist for longer periods of time on the feeder collection circuit.

Once grounded, a VDH/GSMI will create a bolted three-phase ground on the homerun cable. This, in turn, will create an impedance on the homerun cable of less than 2 ohms, as seen from the junction box to the VDH/GSMI for a 1000 MCM cable that is 10 km long. If we compare the homerun cable impedance to that of the generator-step-up transformer impedance, which is j28 ohms at 34.5 kV, the ratio is approximately 15 to 1. Even with some semblance of proper operation on the three-phase grounded feeder (which we don't have), with the homerun cable 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 1.1kV.

When it comes to insulation coordination, the VDH/GSMI provides a three-phase bolted ground on the homerun cable of a collection feeder. This relieves WPP and SPP designers from guessing what the inverter manufacturer chooses to do. Instead, the engineers will have control of how the WPP or SPP performs over the long term.

	Comparing Grounding Transformer to VDH/GSMI	
Topic	**Grounding Transformer**	**VDH/GSMI**
Collection circuit fault	Feeder breaker is delayed, preventing islanding; added incident energy is destructive.	Operates quickly, prevents TOV with arrestors; incident energy is significantly reduced.
Lightning arrestor	Allows current and energy to be shared, reducing the burden on lightning arrestors (see figure 28)	Voltage remains below duty curve for equipment. (see figure 28)
Fault at generator-step-up transformer	With possible severe islanding during a fault, delayed trip will destroy transformer.	Operates quickly, lowering incident energy into a fault at the transformer, where transformer may be repairable
Islanding	Delayed trip signal for remote trip increases incident energy. Grounding transformer helps share the load between arrestors.	Grounds the homerun cable of the collection circuit, providing a very low resistance and collapsing the voltage
LVRT	Cannot help distinguishing between internal or external faults of a WPP or SPP	Can assist with distinguishing between internal and external faults.

Table 6: Comparison, remote trip vs VDH/GSMI

This paper presents a sequence of events and an operational overview concerning the interlocked combine breaker grounding switch (VDH/GSMI) for WPPs and SPPs compared to grounding transformers (see Table 6). We can draw the following conclusions:

1. The grounding transformer splits the current and energy burden between lightning arrestors during a fault where the feeder breaker has opened and allows the energy to be shared.

2. During severe islanding, where the generators have not received a trip signal and shut down, the grounding transformer on the separated collection circuit will not shunt the active power to ground and will not keep the voltage below the MCOV of the lightning arrestor.

3. The VDH/GSMI operates two vacuum interrupters with an interlock and operates with at least one trip signal.

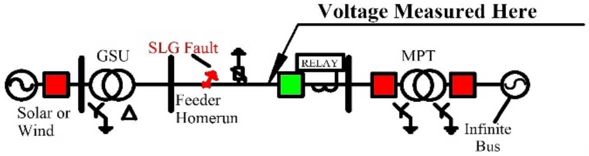
4. The transition state of the VDH/GSMI where both vacuum interrupters are open is from 4 to 12 milliseconds.

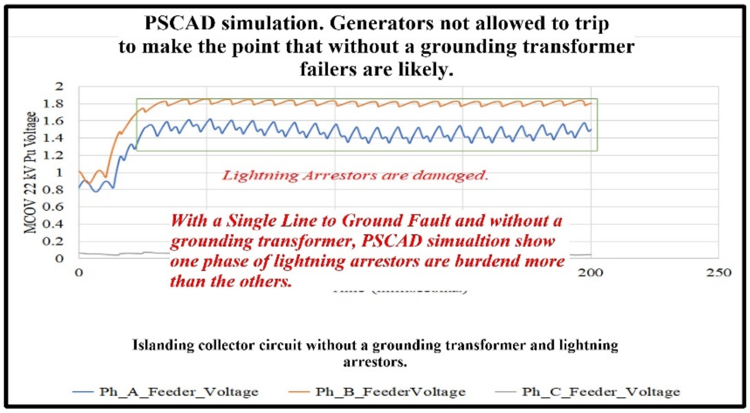
5. A VDH/GSMI demonstrates a clear change in impedance as it operates. Generators can detect such a change and act on it. (*List continues on following page*)

CONCLUSION

From the PSCAD simulation(s) the graphs below show during SLG fault on the collection circuit that a grounding transformer works to lower the voltage and TOV on a separated feeder circuit with lightning arrestors, but it may not be enough. However, the VDH/GSMI with a lightning arrestor provides a three-phase bolted ground and no observed TOV during the very short period of islanding; as a result, the VDH/GSMI provides a clear signal for the generators to turn off and the collection circuit is well protected.

Islanding without a grounding transformer, TOV is really bad & dangerous.



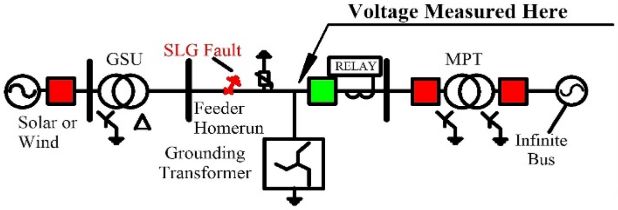

PSCAD simulation. Generators not allowed to trip to make the point that without a grounding transformer failers are likely.

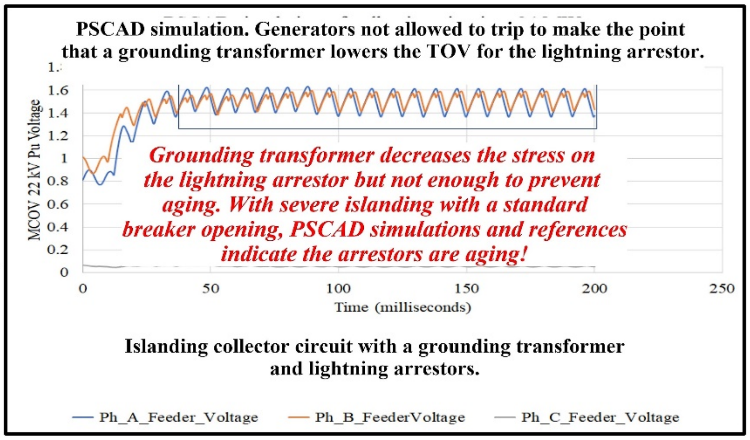
Lightning Arrestors are damaged.

With a Single Line to Ground Fault and without a grounding transformer, PSCAD simualtion show one phase of lightning arrestors are burdend more than the others.

Islanding collector circuit without a grounding transformer and lightning arrestors.

Islanding with a grounding transformer, TOV is present but reduced, anticipate accelerated aging.

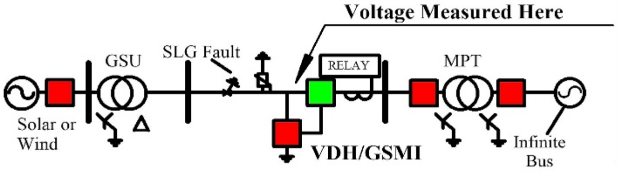



PSCAD simulation. Generators not allowed to trip to make the point that a grounding transformer lowers the TOV for the lightning arrestor.

Grounding transformer decreases the stress on the lightning arrestor but not enough to prevent aging. With severe islanding with a standard breaker opening, PSCAD simulations and references indicate the arrestors are aging!

Islanding collector circuit with a grounding transformer and lightning arrestors.

Islanding with a VDH/GSMI and without a grounding transformer. No observed TOV, coordinates well with lightning arrestors and other protection.



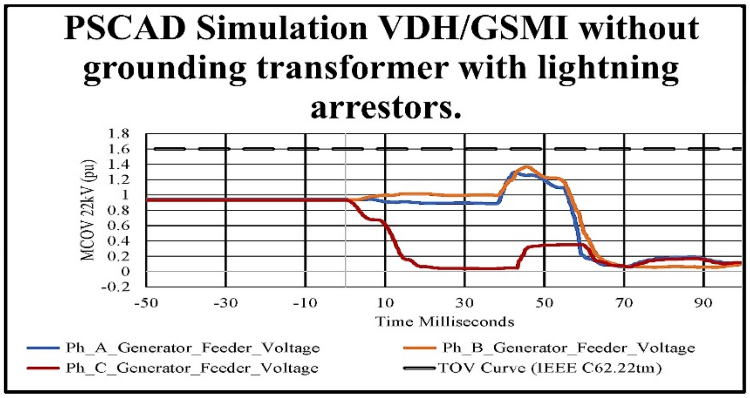

PSCAD Simulation VDH/GSMI without grounding transformer with lightning arrestors.

Fig. 28. Comparison of islanding voltages with or without a grounding transformer.

6. When closed to ground, the VDH/GSMI results in a very low impedance of the homerun cable to less than 2 ohms measured from a junction box (1000 MCM less than 10 km).

7. TOV duration is minimized by the combination of the VDH/GSMI's fast transition state and the lightning arrestors. Note: Without a VDH/GSMI, the arrestors can be destroyed by other protection schemes. After that, if the arrestor is not replaced, expensive collection circuit equipment is damaged thereafter.

8. A VDH/GSMI significantly lowers the energy burden on lightning arrestors, and engineers can easily coordinate.

9. The VDH/GSMI provides a better path for active power to flow to ground than a grounding transformer.

10. Given the typical design variations of WPPs and SPPs, and the current-limiting capability of generators, VDH/GSMI should provide a very low impedance on the feeder circuit, cause the AC mains voltage at each generator to go below minimum operating voltage, and force generators offline to prevent islanding.

11. The VDH/GSMI protects the lightning arrestor.

12. The phase-locked loops and the Clark/Park transform used for commanding active and reactive power from each individual [inverter] generator are found to not respond or control active/reactive power reliably or in a predictable way to open circuits caused by feeder breakers. However, they respond better with a three-phase bolted ground provided by the VDH/GSMI.

13. While the grounding transformer reduced the burden on lightning arrestors when a feeder breaker opens, it is not found to coordinate with all forms of different programs running in inverter controllers.

The PSCAD simulations show that the VDH/GSMI resolves both issues of TOV and incident energy where delays are not needed for clearing the fault from the plant. The VDH/GSMI completely operates within nearly 50 milliseconds to open and clear the close and ground the affected collection circuit, and thus it collapses the voltage. The VDH/GSMI relieves the lightning arrestor and keeps the resulting TOV below the duty curves. As a result, we can conclude that the use of the VDH/GSMI in the design and construction of generating projects such as WPPs and SPPs constitutes a best practice.

13. ACKNOWLEDGMENT

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