

*Medium Voltage Vacuum Circuit Breaker with
Mechanically Interlocked Grounding Switch
(VDH/GSMI) Provides Better Safety and Reliability
for Wind and Solar Power Plants and Their
Personnel than Remote Transfer Trip*

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Abstract—The medium voltage vacuum circuit breaker with mechanically interlocked grounding switch (VDH/GSMI) and remote trip protection techniques provide unique forms of protection. In this paper, remote and transfer trip and VDH/GSMI protection techniques are compared, and the conclusion is that the VDH/GSMI is essential in the design and construction of wind power plants and solar power plants.

Damage due to faults in collection circuits happens fast. Remote transfer trip relays that protect the feeder circuit breaker are programmed to delay the trip signal, take more than seven cycles to operate, add deadly incident energy, or operate so quickly that destructive temporary overvoltage (TOV) occurs. This paper shows remote trip is a good protection technique; however, breaker designs that do not ground within wind power plants and solar power plants leave the collection circuit floating. This is a major problem.

If each feeder breaker on each collection circuit is interlocked with a grounding switch, most, if not all, of the problems seen with remote trip (including grounding transformers) are resolved. This paper reviews the background, design, and operation of the VDH/GSMI and remote and transfer trip with PSCAD and compares the performance of the two schemes. This paper shows that the VDH/GSMI is faster, significantly lowers the incident energy, and keeps the TOV duration under the prior duty curve of the lightning arrestors where other remote trip schemes do not. This paper concludes that the use of the VDH/GSMI in the design and construction of power-generating projects, such as wind power plants and solar power plants, constitutes the best practice.

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

1. INTRODUCTION

Although the interlocked-combine breaker grounding switch (VDH/GSMI) and remote and transfer trip provide protection, the interlocked-combine-breaker-grounding-switch is essential; this paper delineates the reasons why. Faults in collection circuits and the damage created happen fast. The interlocked-combine breaker grounding switch provides more forms of protection in a single unit with less delay than other types of breakers. The VDH/GSMI protects solar and wind power plants by reducing incident energy and eliminating temporary overvoltage (TOV). Elimination of TOV is an important feature of the VDH/GSMI. When TOV is eliminated during the opening of the circuit breaker, the lightning arrestors are operated below their prior duty curve, insulation coordination of the feeder circuit is maintained, and the equipment is more reliable. This paper discusses remote trip and the VDH/GSMI in terms of the TOV.

Feeder Breaker without Grounding Switch

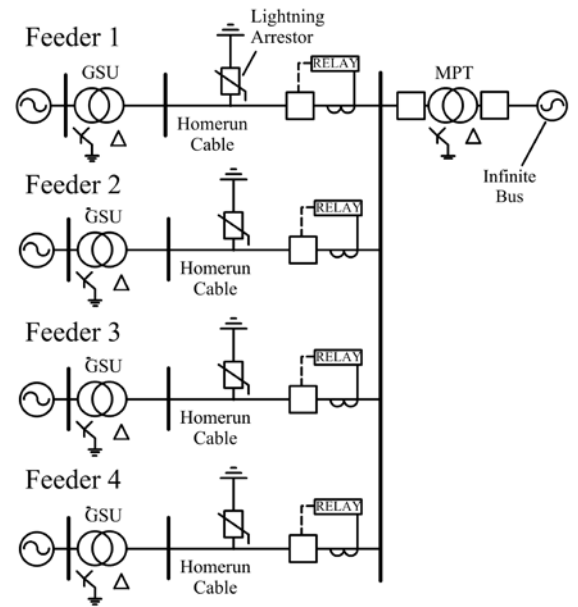


Fig. 1: Wind Power Plant or Solar Power Plant Single Line

First, we discuss remote trip for wind power plants(WPP) and solar power plants(SPP) and how delays caused by such a technique add to equipment damage and diminish the safety and reliability of the collection circuit with respect to arc flash, arc blast, temporary overvoltage, and incident energy. Second, we discuss the operation of the interlocked-combine breaker grounding switch in detail. We use PSCAD and ETAP simulations to support claims made concerning arc flash and remote transfer trip and to show where the VDH/GSMI overcomes such problems and provides superior protection compared with remote transfer trip.

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 a wind power plant or a solar power plant. Circuit breakers are mechanical switching devices that connect and break the current flowing in the circuit, which can be the nominal current or the fault current. Typical circuit breakers are composed of one switch that is either open or closed. Generally, some wind power plants and solar power plants only use non-grounding feeder (line) circuit breakers as shown in Figure 1.

In the collection circuit of a wind power plant or a solar power plant, a typical circuit breaker clears the affected feeder from the main station transformer (i.e., the transmission system) and the transmission system. However, such a design is limited and does not provide functionality, such as anti-islanding or temporary overvoltage mitigation, needed for today’s modern wind power plants and solar power plants.

Another special type of circuit breaker provides much more functionality and protection; this circuit breaker is called the VDH/GSMI; see [1] and [2]. The VDH/GSMI 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 from the initiation of a fault. With the impedance of the collection circuit (approximately 1/15th of the impedance of an individual wind turbine transformer) and with all three phases effectively bolted to ground, the voltage on the separated feeder quickly collapses.

The VDH/GSMI shown in Figure 2 is designed for the feeder collection circuits of wind power plants and solar power plants. The line side of the circuit breaker is composed of vacuum interrupters and bushings to connect to the 34.5 kV collection circuit. For information concerning 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 VDH/GSMI within wind power plants and solar power plants 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 breaker is commanded to open by the relay, 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 the clearing the fault and the feeder from the plant. As a result, improved anti-island functionality, superior TOV protection, and less incident energy into an arc flash or arc blast are provided.

In wind power plants and solar power plants, conventional breakers open and disconnect the affected feeder from the transmission system and then allow the delta connected collection circuit to operate without a ground reference unless a grounding transformer is connected. The grounding transformer cannot pass the active power anywhere, because it is an open circuit, but shares the zero sequence currents between each phase.

The VDH/GSMI, however, provides a better ground reference than a circuit breaker and opens with an electrical switching time of 4–12 ms, or less than one cycle, thus meeting the temporary overvoltage requirements for lighting arrestors.

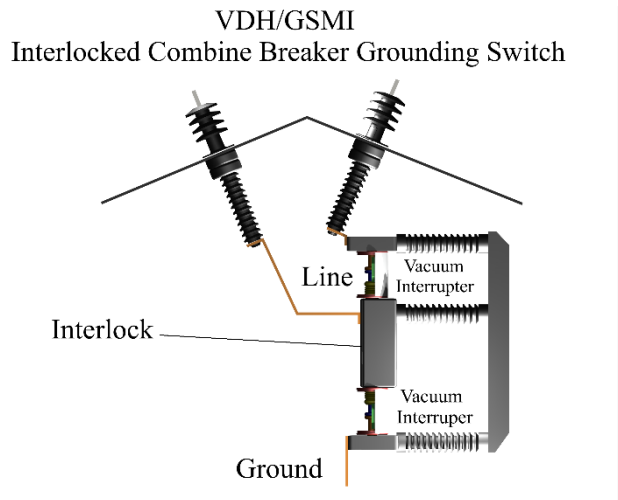


Fig. 2: medium voltage vacuum circuit breaker with mechanically interlocked grounding switch (VDH/GSMI (VDH/GSMI)). A set of three line-side phase vacuum interrupters and a set of three ground vacuum interrupters are interlocked and operate with one trip signal.

Feeder Breakers with VDH/GSMI

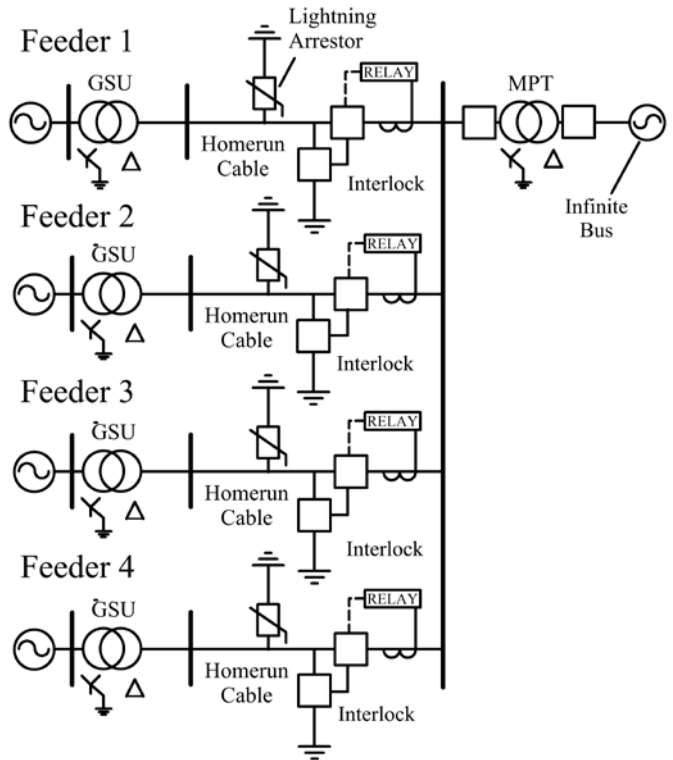


Fig. 3: Wind Power Plant or Solar Power Plant with VDH/GSMI Providing Protection at Each Feeder Circuit.

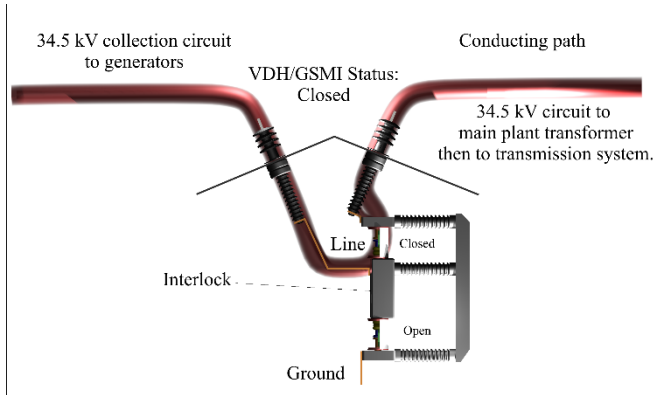


Fig. 4: VDH/GSMI Closed, Ground Switch Open.

With PSCAD simulations, in the next section of the paper, remote trip for wind power plants and solar power plants and how delays caused by such a technique create TOV or lethal arc blast situations is discussed. Consequently, remote trip may result in more damage to equipment, less revenue, and puts personnel's health and safety at risk. The paper and the PSCAD and ETAP simulations present claims concerning arc flash and remote trip and show that the VDH/GSMI overcomes such problems to provide superior protection compared with remote trip.

We then conclude with a discussion and comparison of the two techniques and with the conclusion that the VDH/GSMI constitutes a best practice concerning protection of personnel and equipment that work with collection feeder circuits within wind power plants and solar power plants.

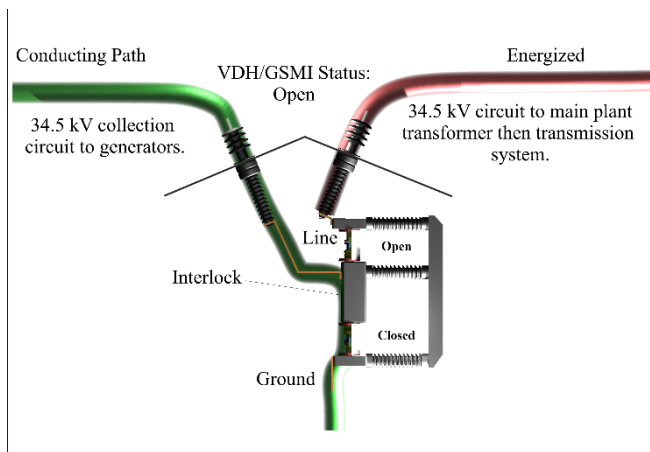


Fig. 5: VDH/GSMI Open, Grounding Switch Closed.

2. REMOTE TRIP

TOV according to IEEE 1313.1-1996 in part means “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.”

TOV limits peak voltage such as that specified for lightning arrestors, where such limits are found expressed as maximum continuous operating voltage (MCOV) in per-unit values for the root-mean-square (RMS) waveforms.

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]. In this article, we are concerned with remote trip and the potential for TOV for wind power plants or solar power plants, which is similar to this definition. However, wind power plants and solar power plants have a dedicated communication system within the plant.

The opening of a wind turbine or solar inverter circuit breaker from a remote location with a signal over a communication channel, such as fiber, takes time to complete; this delay is called latency. Delays from the initiation of a fault on the collection circuit to the time when the equipment is separated or isolated from the fault is called the clearing time (see IEEE Standard 551). Wind and solar power plants are made up of individual collector circuits. When protecting a collection circuit, there are two objectives: clearing the fault from the individual generators and clearing the fault from the plant. For remote trip, we focus on the timing of both.

As a solution, remote trip for wind power plants or solar power plants is a protection technique that has two options. In Option A, the feeder breaker is not delayed. The fault is cleared from the plant first and then from the generators. In Option B, the feeder breaker is delayed; therefore, the generators are cleared first and then the plant. Both techniques have dire consequences (see Figures 7, 8, and 9).

If Option A is chosen, the protection objective is to avoid or minimize the time personnel and equipment are exposed to the huge fault currents sourced from the transmission system. The feeder breaker operates first and clears the fault from plant. As a result, the engineers limit and reduce the incident energy and 15,000 amps of current sourced from the transmission system. However, TOV is now a problem.

If Option B is chosen, the protection objective is to avoid temporary overvoltage on the collection circuits. The generators are shut down first and the fault cleared. Then the feeder breaker opens, and the fault is cleared. However, now incident energy is now a problem.

In Option A and Option B, for a wind power plant or a solar power plant, a relay sends a remote trip with two signals, one to the generators and one to the feeder breaker. The signal to the generators is over a communication line, such as fiber, and runs from the substation (i.e., a remote location) over the fiber communication medium to each individual generator. A trip signal is sent to open the breaker of each generator and/or perform a soft shutdown during a fault.

However, both options have consequences. Figure 6 shows two collection circuits, one with a grounding transformer and one without. When the collection circuit is separate from the plant and the transmission system, the circuit's conductors are delta configured; consequently, the impedance to ground is very high. When the feeder breaker opens, energy supplied to the feeder by the generators (which are on-line and producing power) causes the voltage to increase in the separate collection circuit.

TOV occurs because the remote signal gets to the generators late. The delay is called latency. In a vain attempt to fix the problem of TOV, a grounding transformer is introduced to provide a lower impedance to ground, when the delta configured collection circuit separates. As the grounding transformer cannot pass active power during severe islanding, the transformer still has an excessive voltage increase; consequently, a grounding transformer is not found to solve the problem of temporary overvoltages.

The problem of TOV lies in the fact the generators are not shut down because of latency. Figure 7 shows some of the causes of latency, such as switches, fiber cables (or radio), the control system, and equipment. Standards identify the typical latencies one should expect when sending a signal for equipment to operate. IEC 61850 is a contemporary standard concerning the configuration of devices for electrical substation automation systems. This standard provides methods that allow different components to communicate with each other. Such protocols can run over TCP/IP networks or substation local area networks (LANs) using high-speed switched Ethernet to obtain the necessary response times of less than 4 ms for protective relaying.

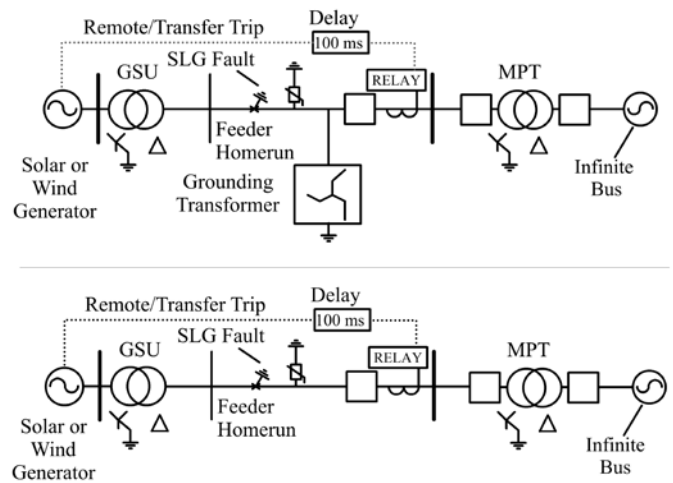


Fig. 6: Remote Trip with and without a Grounding Transformer.

In addition to latency, Table 1 lists the failure modes, which prevent the message from getting to the equipment. If such failure modes are not present and the message gets to the right device, then the typical latency times for remote trip introduce delays; they are shown in Table 2 [4]. In addition, [5] presents that feeder clearing times can exceed 122 ms when remote trip is used. Figures 7, 8, and 9 and Table 3 show that both techniques (delaying feeder breaker clearing or no delay in feeder breaker clearing) have consequences.

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

3. LIGHTNING ARRESTORS AND TEMPORARY OVERVOLTAGE (TOV)

Lightning arrestors come with a given temporary overvoltage curve called a duty curve which can be found on a graph supplied by the manufacturer that shows the (50–60 Hz) withstand voltage vs. time for arrestors. The time is usually given from 0.01 s to 100,000 s in RMS values in a per-unit rating. The duty curve and the prior duty curve should be higher than the continuous operating voltage of the collection circuit.

The Two Choices of Remote Trip TOV & Incident Energy

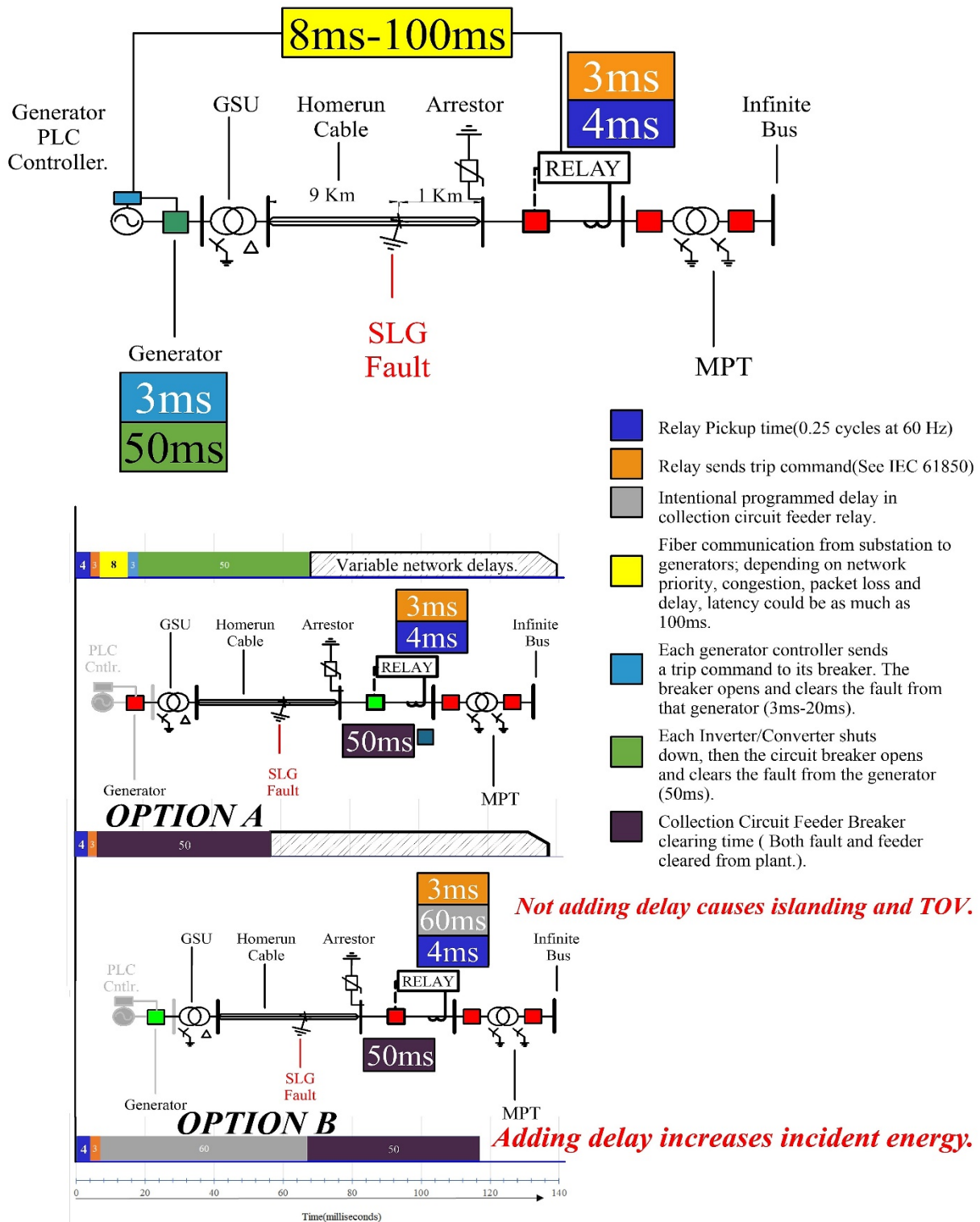


Fig. 7: Option A (TOV) or Option B (Incident Energy).

The prior duty curve is lower in per-unit voltage than the duty curve and represents that the lightning arrester can be repeatedly subjected to RMS voltages below that value and the arrester will continue to perform according to the manufacturer's specification. When the voltage exceeds the prior duty curve, the arrester is damaged, and its current voltage (I-V) characteristic changes.

Therefore, when the I-V characteristic is lost, the insulation coordination study for the collection circuit is no longer valid, and the entire plant is now at risk.

Without a lightning arrester on the collection circuit, the voltage increase would exceed the insulation capabilities of the collection circuit components. When a feeder breaker, which cannot ground the collection circuit, clears the fault (on that collection circuit) from the plant and the transmission system while the generators are producing power, the voltage quickly escalates along with the current through the prior duty curve of the lightning arrester. When a feeder is separate from the plant, PSCAD simulations with the generators still running show the TOV prior duty curve is typically exceeded regardless of the I-V characteristic used, due to the energy supplied to the collection circuit.

4. REMOTE TRIP AND AVOIDING INCIDENT ENERGY

When avoiding incident energy and using Option A, the relay clears the fault from the plant by opening the feeder breaker first. The relay is located at the substation, and the generators are 5 to 10 miles away. As generators are shutdown second as opposed to the breaker being opened first, the incident energy is far less; however, the TOV results in damage to the lightning arrestors and then a change in their I-V characteristic [14], which then damages other equipment. Figure 7 shows the timing diagram with Tables 1, 2, and 3 in mind, and Figure 8 shows the delays that occur when communication problems appear in the network.

When avoiding incident energy and enduring TOV (e.g., Option A), the relay clears the generators before the relay clears the feeder breaker. The relay is located at the substation, and the generators are 5 to 10 miles away. As the generators are shut down first before the feeder breaker opens, the delay allows the incident energy to build in the fault; consequently, damage to equipment is more severe, and the fault can be fatal to personnel (see section (043) and Table 4).

Remote trip techniques must be coordinated to protect the equipment within the plant. However, although relays are fast, they do not process information instantaneously. Time delays are always introduced in digital processing and communication equipment (see Figures 7, 8, and 9). When using remote trip, one must keep latency in mind.

Regarding latency, Tables 2 and 3 and Figures 7, 8, and 9 show the latency of the two signal paths where an engineer may add up the signal propagation delays from the substation to the generator. The process begins with the initiation of the fault through the sensing current transformer to the clearing of the fault. The figures start with a relay pickup time of 4 ms and a delay of 3 ms to issue the trip command. From there, the trip command has two paths, one to the feeder breaker and one to the generators.

Causes of Latency		
Item#	Device Operating Time	Milliseconds
1	Input debounce	2
2	Processors	4
3	IEC Message 61850	8-100
4	Misc. updates	4
5	Communication	4-32
6	Solar Inverter or Wind Turbine Breaker	50+

Table 2: Causes of Latency

If one includes a radio with a latency of 32 ms (net change 24 ms), the total latency with Table 2 in mind is between 72 ms and 146 ms. With such delays included with collection circuit feeder breaker operation, what are the consequences regarding TOV? Next, we look at two scenarios: The breaker is delayed from opening, and the generators are shut down first. If the breaker is not delayed from opening, and the generators are shut down second. What happens with arc flash and arc blast as they relate to incident energy and TOV?

5. REMOTE TRIP AND INCIDENT ENERGY

Option B introduces incident energy by opening the feeder breaker with a programmed delay, which results in little or no temporary overvoltage. For example, a wind power plant or a solar power plant, with a 230 kV to 34.5 kV main substation transformer, which is rated at 90 MVA with 8% impedance, is connected to the transmission system at the point of interconnection. The main plant transformer is Y connected and grounded on the 34.5 kV side. The main plant transformer is connected to a very strong transmission system, and the main station transformer is capable of sourcing 18,000 amps peak on the home run feeder cable, which has a faulted single line to ground. In addition, the other feeders may source between 750 and 1000 amps in the same fault. The longer the feeder breaker is closed, the more time 1800 amps feeds the fault.

OPTION A

Concerning TOV & Remote Trip TOV damages the lightning arrester and insulation coordination is lost.

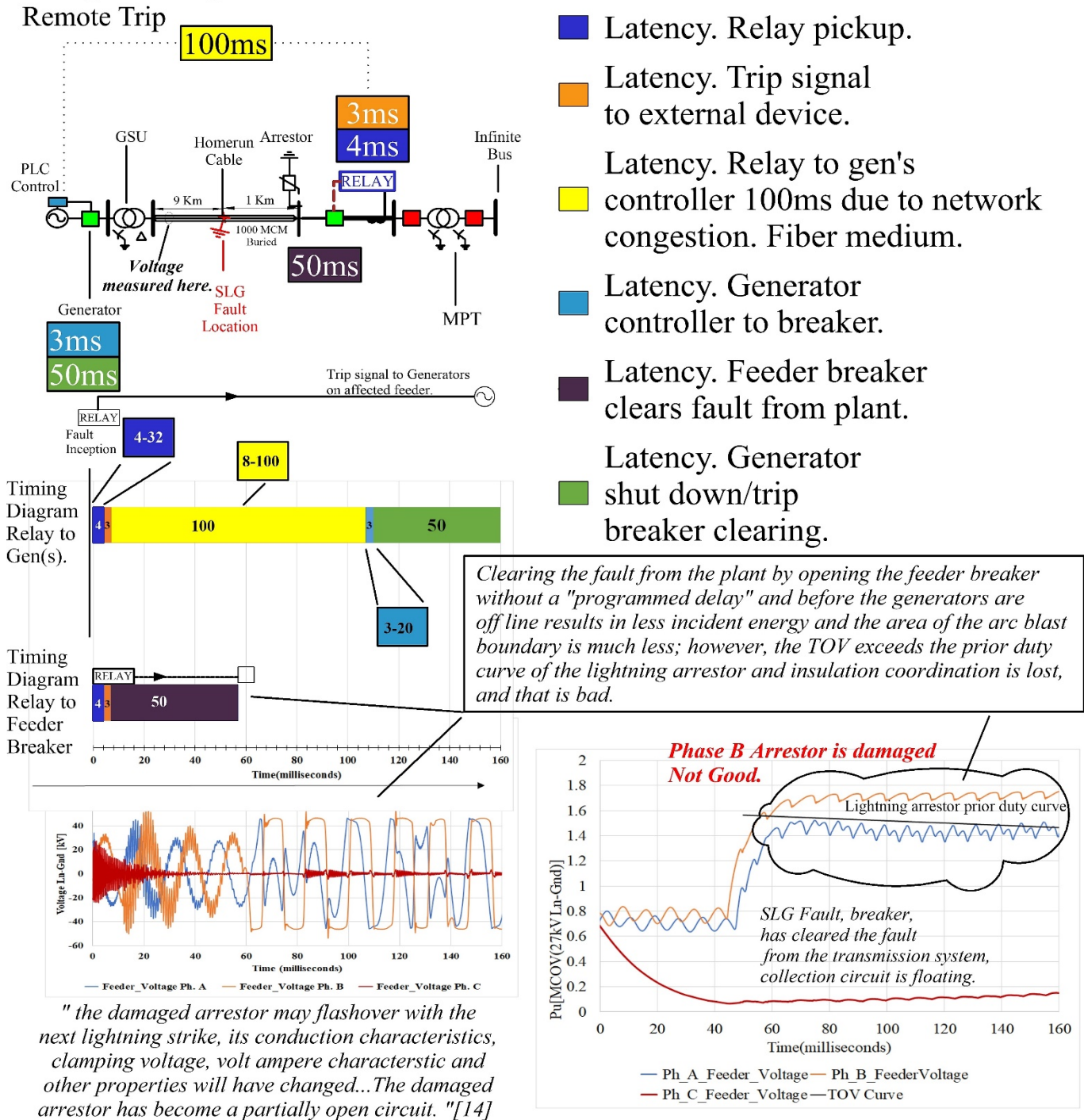


Fig. 8: PSCAD Simulation Option A, Remote Trip, and TOV.

Concerning incident energy and remote trip, the arc time and the resulting damage to equipment and injury to personnel are important to consider. Section 70E by the National Fire Protection Association describes procedures for arc flash studies. In this report, we use ETAP to calculate the incident energy due to arc flash.

Concerning arc flashes and remote trip, to protect the equipment on the feeder from temporary overvoltages, a delay is programmed into the feeder relay, which prevents the feeder breaker from opening for at least 117 ms or seven cycles from the start of the fault which exceeds 24 cal/cm² at a working distance of 36 in. When considering arc flashes, the increase in arc time is significant and adds to the risks personnel already take when working on such equipment.

Adding to the arc blast, the generators on the feeder collection circuit can also contribute energy while the fault is occurring. The generator’s current can be added to the fault current sourced through the main plant transformer to the fault location. When the circuit breaker clears the plant from the fault and interrupts the current, generators are still feeding the fault. Figure 9 clearly shows that as the best case faults can persist for as little as seven cycles. If the fault lasts longer, Table 3 shows at 36 inches after 200 ms the incident exceeds 40 cal/cm², which is lethal.

Because remote trip techniques allow for an increased arc time, arc flash, and arc blast, faults become increasingly dangerous due to the added incident energy. An ETAP model of a representative wind farm shows a fault on the transformer where personnel are present and are within the arc flash boundary. The arcing fault current in the ETAP model was approximately 12,000 amps RMS for between 3, 6, and 12 cycles. The results of the model are shown in Table 4.

According to NFPA 70E, annex K issued by the Virginia Division of Mineral Mining, concerning arc flash and blast even with proper personal protective equipment (PPE), severe injury may result from heat from the arc flash, and the resulting force of the pressure wave and shrapnel is lethal [6]. Therefore, it is imperative that the incident energy is minimized.

Concerning remote trip, minimizing incident energy from the transmission system may result in TOV.

Figures 7 and 8 show a timing diagram where the two signals race to the generators and the feeder breaker. In Figure 7, the signal is delayed to the feeder breaker and allows more incident energy. Figure 8 shows the trip signal to the feeder

Remote/Trip Relay Coordination and Latency			
(Option B) See IEC and Ref [5]			
Item#	Device	Remote Path (ms)	Breaker Path (ms)
1	Feeder Ground Fault	0	0
2	Feeder-Relay Pickup (1/4 cycle to 32 ms; see Ref. [5])	4–32	4–32
3	Relay Programmed Delay	x	11–120 PSCAD (60)
4	Relay processor time	3	3
5	Relay-Trip Signal Transport Lag (IEC 61850) [12], [13]	8–100	x
6	Wind Turbine Controller	3–20	
7	WTG Breaker Opens	50	X
8	WTG Clearing Time	68–205 PSCAD (160)	X
9	Feeder Breaker Opens	X	50
10	Feeder Clearing Time	X	68–205 PSCAD (117)

Table 3: Remote Trip, Relay Coordination, and Latency. Note: At 60-ms delay, incident energy exceeds 24 cal/cm² at a working distance of 36 inches. See Table 4.

breaker is not delayed; however, the variable latency present in both techniques suggests there is a likelihood of temporary overvoltage and islanding.

6. REMOTE TRIP IN SUMMARY

Figures 7, 8, and 9 and Tables 1, 2, and 3 show that either way there are dire consequences with remote trip when applied to wind power plants and solar power plants. Remote trip either delays the opening of the collection circuit feeder breaker and adds to the incident energy in the fault or opens the feeder breaker too soon and causes temporary overvoltages. Energy from the overvoltages rapidly consumes the useful life of the lightning arrestors or changes the I-V characteristic, such that the U.S. Nuclear Regulatory Commission states “the damaged arrestor has become a partially opened circuit” [14].

Option B Incident Energy

Adding Incident Energy to eliminate TOV increases the Areas of Arc Blast Boundaries which are Deadly.

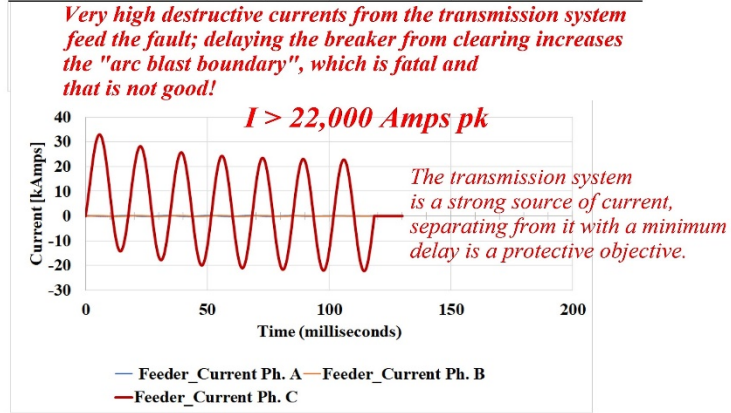
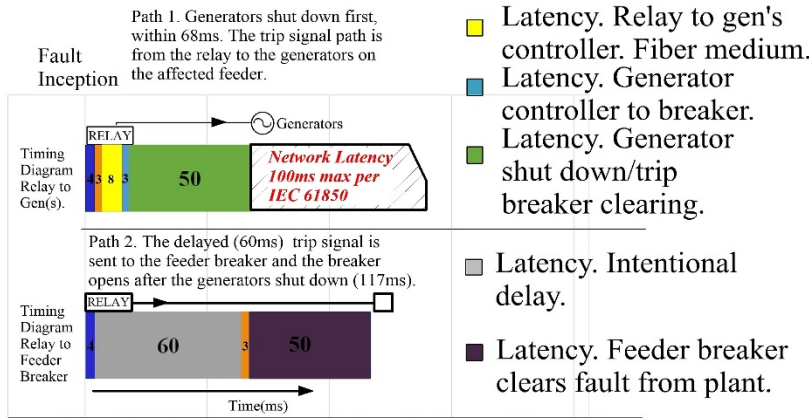
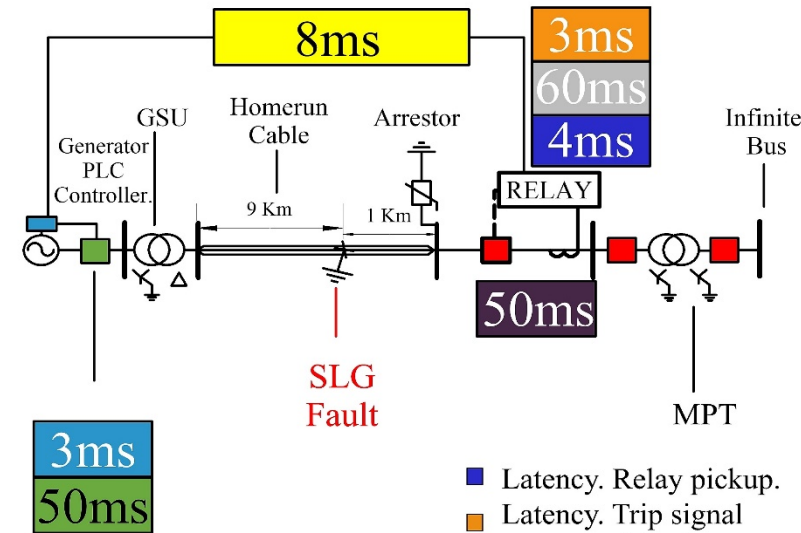


Fig. 9: PSCAD Simulation Option B Incident Energy (See Table 4).

One could presume that the insulation coordination is lost. Unfortunately, several causes of variable latency prevent wind turbines or solar inverters from getting the command at the right time or all the time from the relay connected to the feeder circuit breaker; whereas the resulting latency prevents the wind turbines or solar inverters from shutting down before the feeder breaker opens. When considering incident energy and assuming the relay does not require a handshake (e.g., acknowledgment of the action), the time to disconnect the affected feeder from the transmission system can exceed 100 ms or even 200 ms. Concerning safety, 100 ms to 100 ms at 36 inches away from a fault sourced from the transmission system will exceed the incident energy of 40 cal/cm² and can be fatal to personnel.

Item#	Incident Energy and Injury		
	Duration (ms)	Working Distance (in)	Incident Energy (cal/cm ²)
1	50	36	12
2	100	36	24
3	200	36	43

Table 4: Arc Blast/Flash Incident Energy

Because of the resulting arc flash and arc blast (even with proper PPE), severe injury may result from 1) heat from the arc flash, 2) the force of the pressure wave, and 3) shrapnel. Therefore, it is imperative that the incident energy be minimized. When it comes to remote trip, and with the above in mind, relay engineers cannot coordinate the relay for both cases without giving up some degree of protection. If they delay, they add incident energy and injure personnel. If they do not delay, they risk temporary overvoltage that can destroy equipment on the feeder. Therefore, one must keep in mind that delays and failure risks are associated with this technique.

There are devices that remote trip could be used in conjunction with; for example, the combined interlocked breaker grounding switch (VDH/GSMI) is a device that can reduce the incident energy. The VDH/GSMI does not require such delays and has been shown to keep TOV below the prior duty curve of a lightning arrester (see Figure 9). The VDH/GSMI provides a very low impedance path to ground, can clear a fault within 3.5 cycles or 50 ms, and coordinates well with generators and lightning arrestors on the feeder circuit.

7. GROUNDING BREAKER OPERATIONAL OVERVIEW

This is an operational overview of the VDH/GSMI for wind power plants and solar power plants. To describe the design and operation of the VDH/GSMI, the focus of this overview is on a feeder circuit within a wind power plant or solar power plant and the change in impedance that occurs

when a fault appears on the collection feeder home run cable (Figure 11). The PSCAD simulation for the operation of a grounding breaker demonstrates that it grounds the collection circuit.

Figure 10 shows the states of the VDH/GSMI: 1) Closed, the line breaker is closed, and the ground switch is open; 2) Transition, both switches are open; and 3) Open, the line switch is open, and the ground switch is closed. The grounding breaker operation has two distinct states of operation, open and closed. However, a transition state is included between the two.

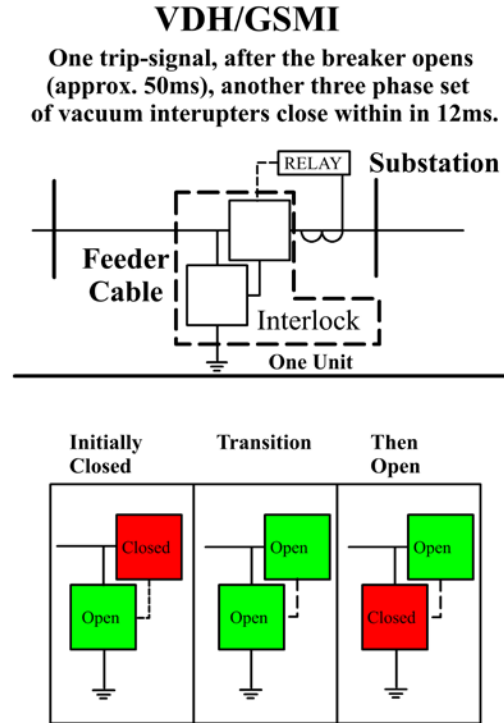


Fig. 10: VDH/GSMI States.

Therefore, there are three states in total. They are:

- Closed
- Transition
- Open.

Closed status means the line interrupters are closed, and the ground 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 (Figures 11). First, the line (breaker) vacuum interrupter start 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.

PSCAD VDH/GSMI OPERATING TIMING DIAGRAM

Single Trip Signal

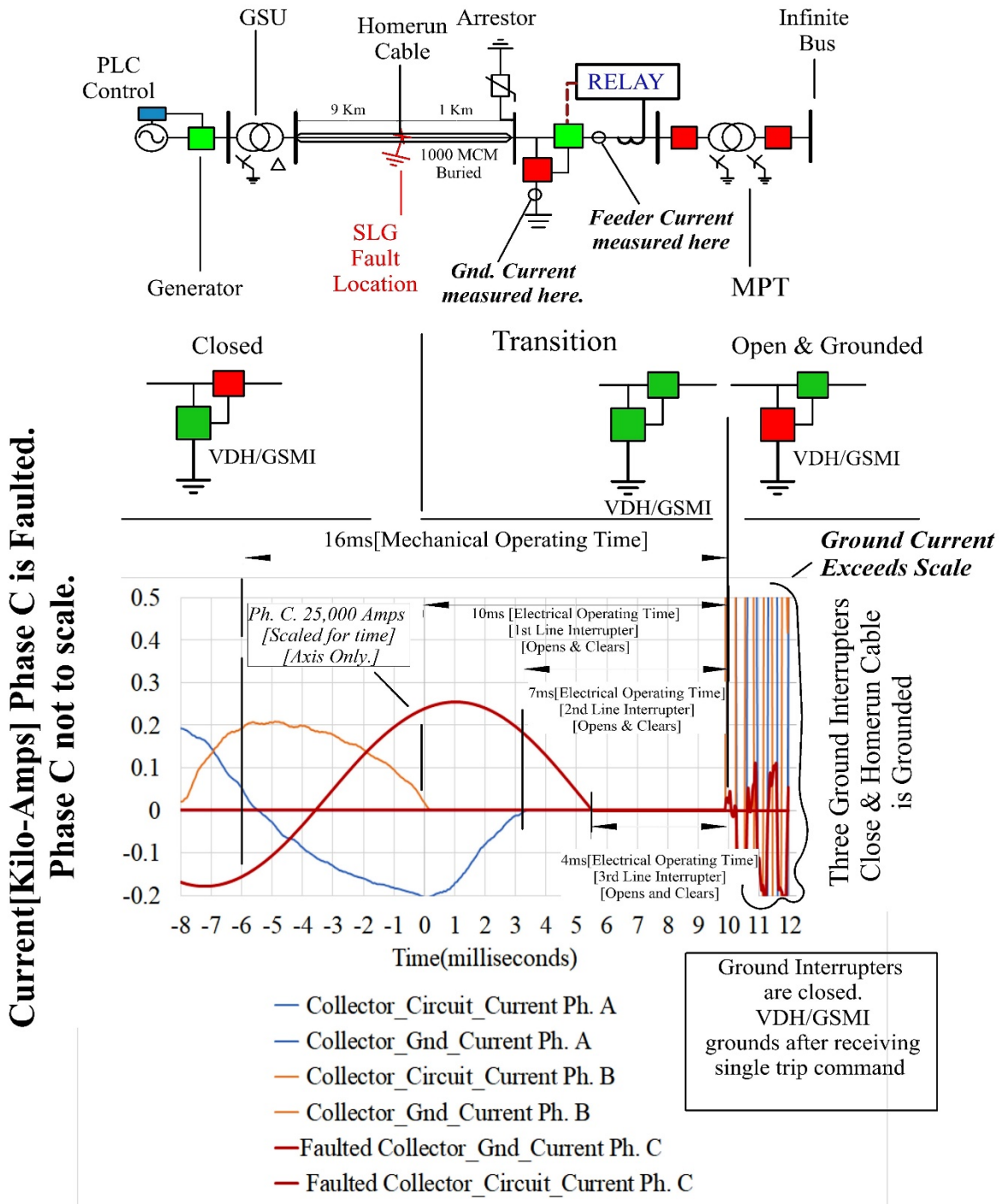


Fig. 11: PSCAD Simulation VDH/GSMI Timing Diagram.

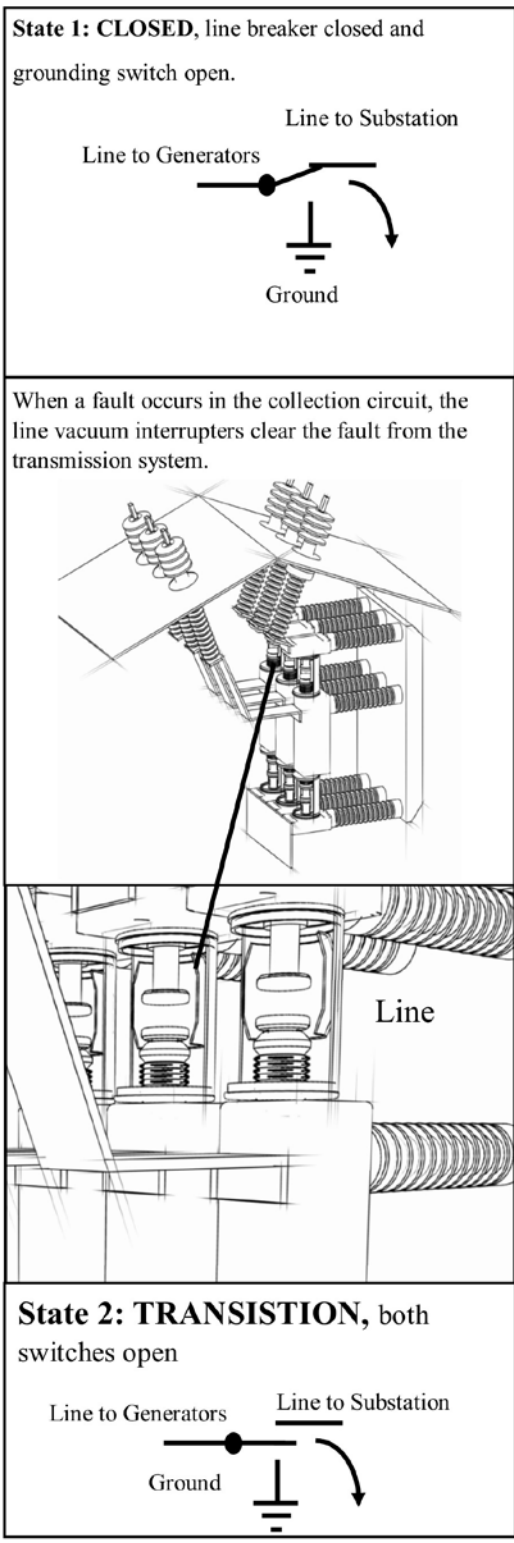


Fig. 12: VDH/GSMI Operating Sequence. The three-phase ground vacuum interrupters open first.

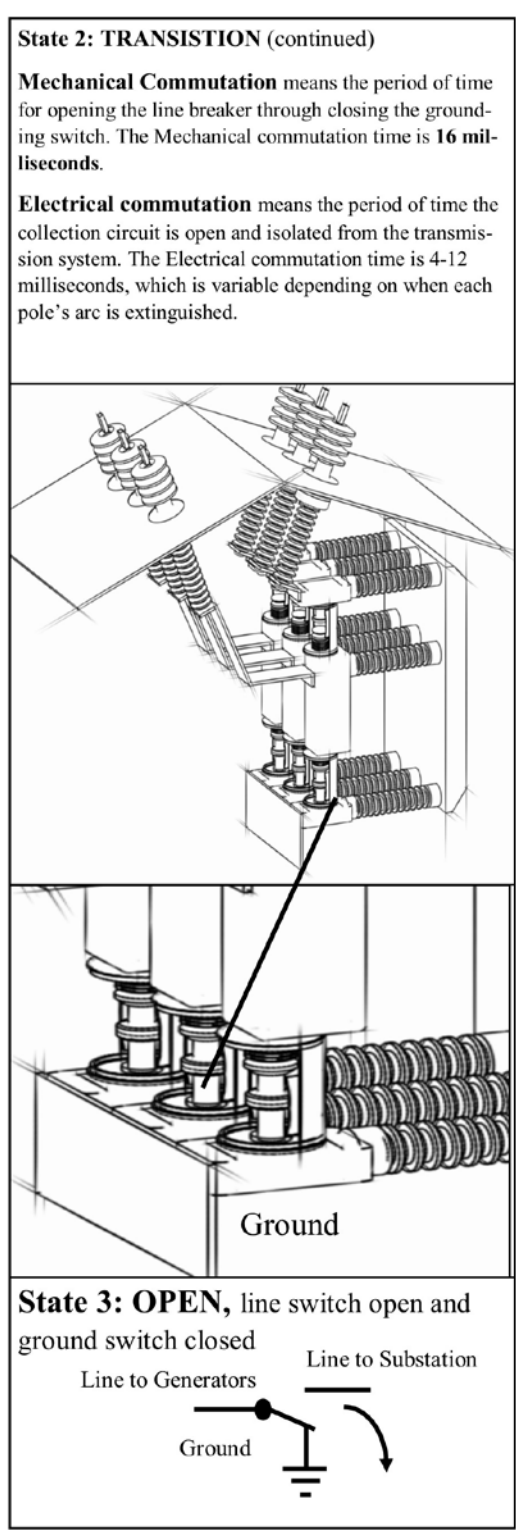


Fig. 13: VDH/GSMI Second Operating Sequence. The three-phase ground vacuum interrupter that closes the collection circuit is grounded.

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

Table 5: States of the VDH/GSMI

Open 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 5).

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 and according to the TP135-0 IEEE tutorial on vacuum switch gear:

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 11.)

Figure 11 shows that when the line-side breaker opens, the current stops flowing between 4 ms and 12 ms before the ground interrupters close. When the ground interrupters close, the current flows into a three-phase bolted ground.

8. CONCERNING PSCAD VDH/GSMI SIMULATIONS

Figures 14, 15, 16, and 17 each illustrate how the VDH/GSMI provides protection and shows how the VDH/GSMI protects the affected circuit by reducing incident energy and TOV.

The simulation starts with Figure 14. The PSCAD simulation initial power level is 24 MW, and the currents and voltages are symmetric and undisturbed. Figure 15 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.)

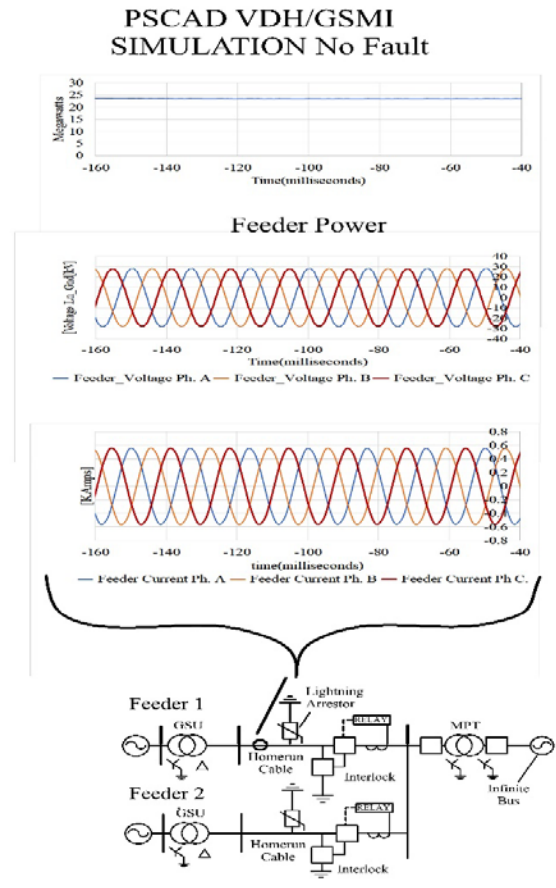
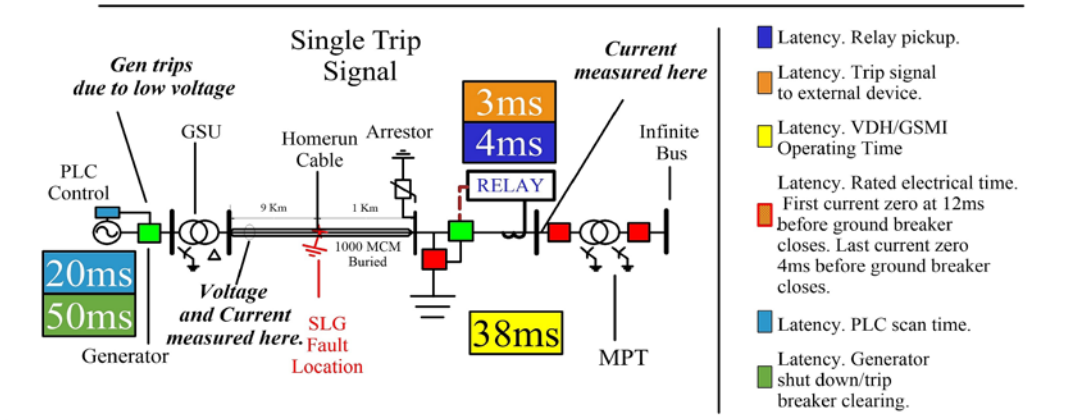


Fig. 14: PSCAD Simulation Start with No Fault and Symmetrical Feeder Current. Active power is around 24 MW.

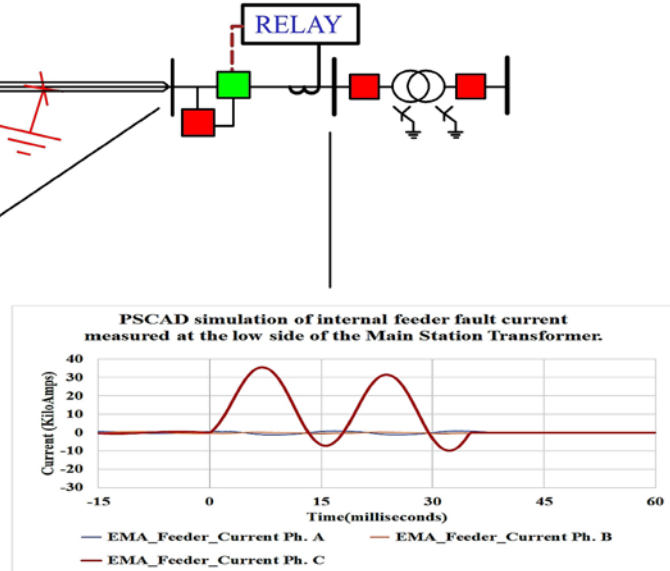
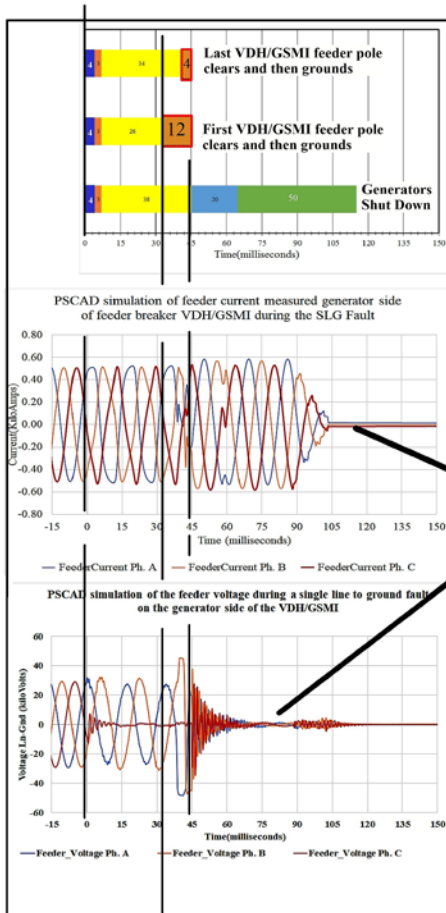
Figures 15 and 16 show the simulation with the relay picking up the fault within a quarter of a cycle or 4 ms. Then the same relay sends the trip command 3 ms later to the VDH/GSMI where the VDH/GSMI has opened and cleared the collection circuit within 26 ms. The total clearing and grounding time is approximately 30 ms. During the transition, the lightning arrestors clamp the voltage for a very short period of time, and the burden appears below the TOV prior duty curve.

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. Why? Because the operation of the breaker quickly transitions to ground, the collection circuit forms a three-phase bolted ground on the home run cable. This reduces the impedance looking into an end of the 10-km home run cable to near 1 j ohm to ground. Compare this to a generator step-up transformer with a positive sequence impedance of 25 ohms or a grounding transformer while it can share the zero sequence currents across the phases it is not designed pass active power in islanding conditions.

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



Fault Initiation



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/cm², and we conclude personnel are better protected.

Fig. 15: 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 arrester.

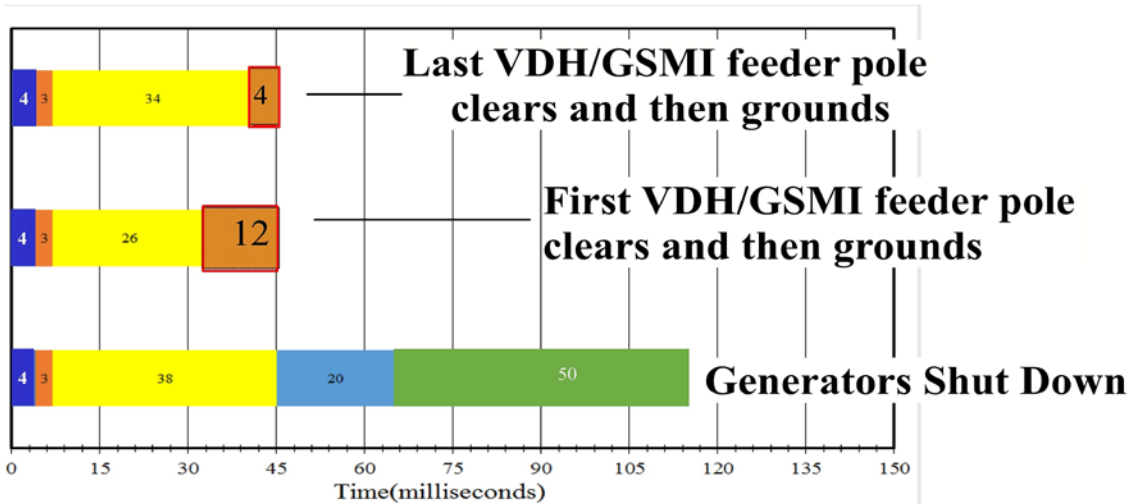
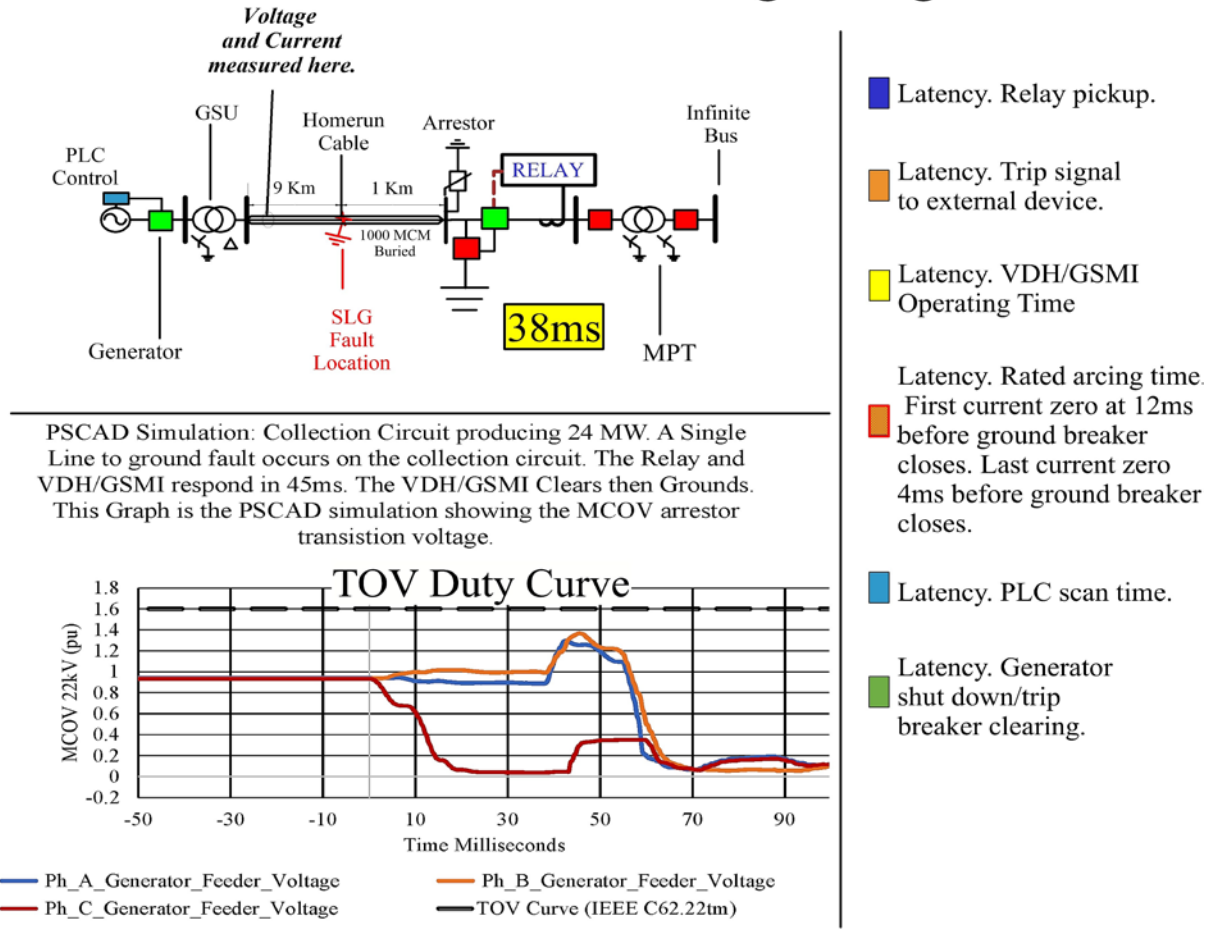


Fig. 16: PSCAD Simulation: TOV, Prior Duty Curve.

A Single Line to Ground Fault Occurs on the Collection Circuit which is producing 24 MW. The EMA VDH/GSMI responds by Clearing then Grounding the Collection Circuit. This is the PSCAD simulation of the Feeder Voltage.

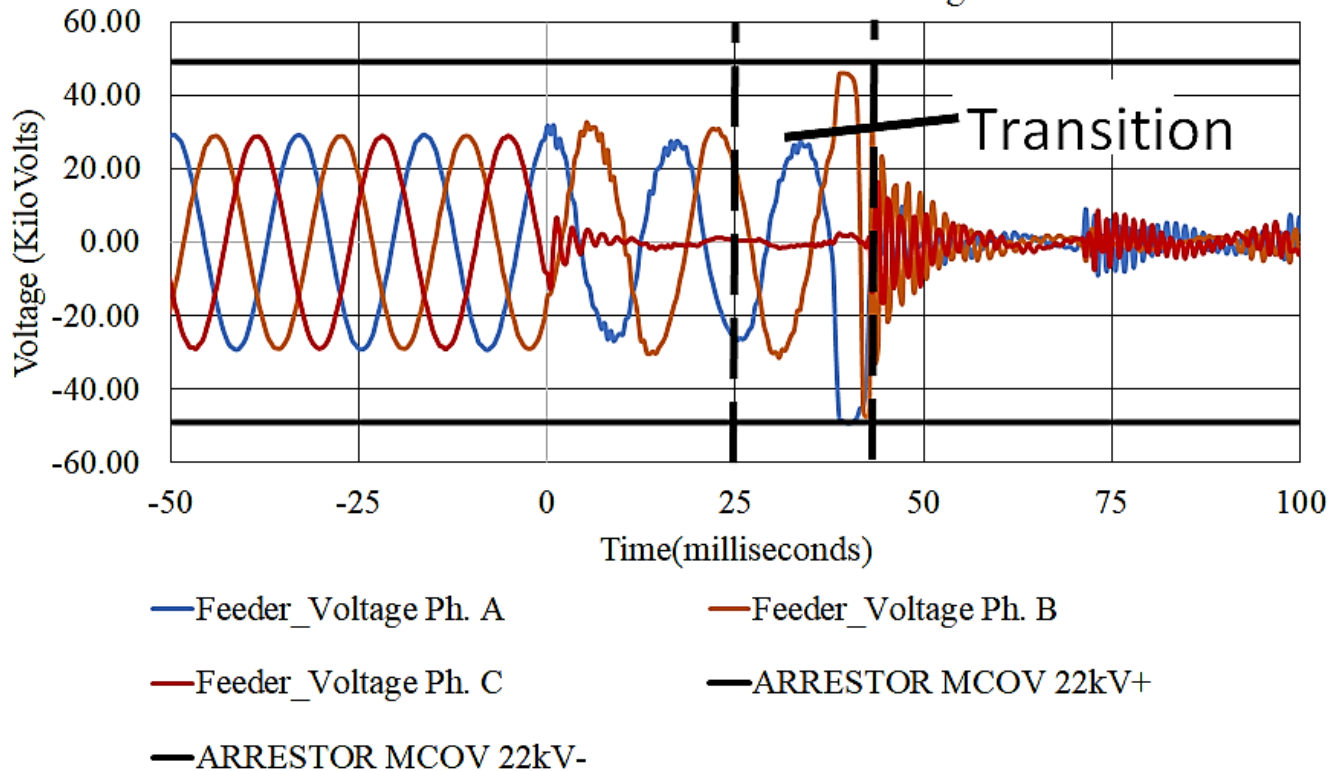


Fig. 17: PSCAD Simulation.

Figures 16 and 17 show the MCOV rating of the 27 kV lightning arrester. The line to ground voltage rating of the collection circuit is 19.920 kV. As the scale of the graphs is in the hundreds of milliseconds, the slope of the TOV curve is not evident.

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

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

In this case, as shown in Figure 17, when the VDH/GSMI switches feeder Phase C races up, however, the ground

interrupter closes fast enough to prevent the voltage from exceeding the prior duty curve.

In Figure 17, after the ground interrupters close, the feeder voltage drops significantly toward zero. There is a ringing of voltage with the change in impedance; however, within 20 ms, the voltage is clearly approaching zero.

The PSCAD simulation shows that the VDH/GSMI clearly can protect and make it easier for engineers to perform an insulation coordination study and feel comfortable about their assumptions. 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.

9. PSCAD MODELING

For emulating type 3 and type 4 wind turbines or inverters, Figure 18 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 transform that follows the voltage at the transformer mains. The plant is rated at approximately 100 MW. 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 home run cable is represented by an infinite pi model of varying distances. In PSCAD, the model is called a Bergeron model as shown in Figure 21. The VDH/GSMI is shown in Figures 18 and 20. The line breaker, remote trip, and grounding breaker relay model is 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 the ground fault occurs on the home run cable. 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 19 is a model of the timing of the relays used to open and close the appropriate breaker. For example, in a simulation, the Vac_Interruption_Line signal causes the line breaker in the VDH/GSMI to open. Then the Vac_Interruption_Gnd signal causes the VDH/GSMI grounding breaker to close. Concerning Remote_Trip, the delay provides enough time to shut down the generators within the wind power plant or the solar power plant (see Table 3) before the line breaker opens. Depending on the simulation, the Remote_Trip signal or the Vac_Interruption_Gnd signal may or may not be used in the simulation. An example of this is simulating the worst-case TOV and does not allow the feeder VDH/GSMI grounding 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 (see Figures 20 and 26) 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 a 34.5 kV 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.

Figure 22 shows the three-phase PSCAD cable model. Figures 23 and 24 provide R, X, and B for the cable. The impedance of the 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 the 1000 MCM direct buried cable. However, PSCAD can do this, and we use PSCAD's cable constant's positive sequence impedance XL, positive sequence resistance R, and susceptance B.

A. Calculations

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

$$I_{base} = \frac{S_{base}}{3\sqrt{3}V_{base}} \quad (1)$$

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

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

$$Z_{MPT} = Z_{base} * (Z_{[pu]MPT}) \quad (4)$$

For example, considering the 230 kV/34.5 kV main plant transformer with 8% (an 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

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

$$X_t = 0.08 * 13.225 = +1.05 \text{ jOhms}$$

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

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 a grounding transformer.

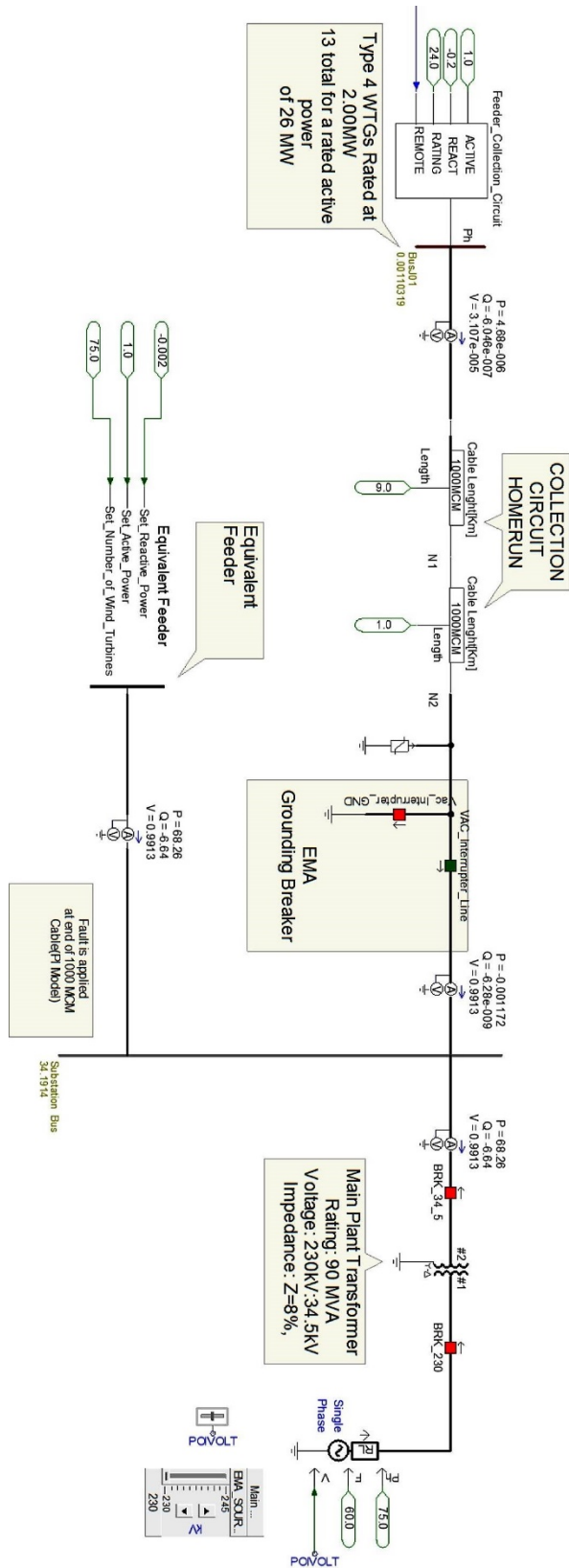


Fig. 18: PSCAD Model: Single Line.

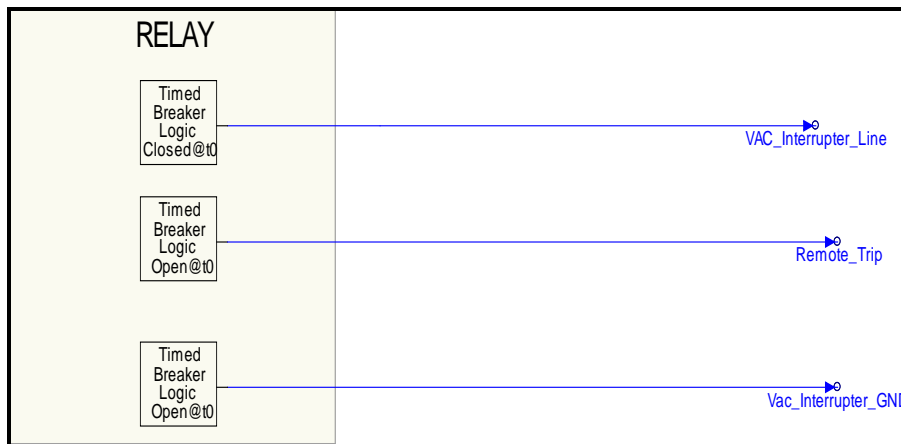


Fig. 19: Breaker(s) Timing.

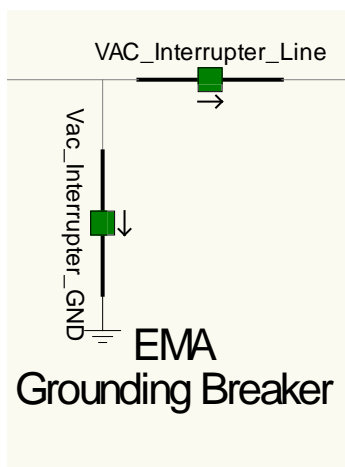


Fig. 20: EMA Line and Grounding Breaker Model.

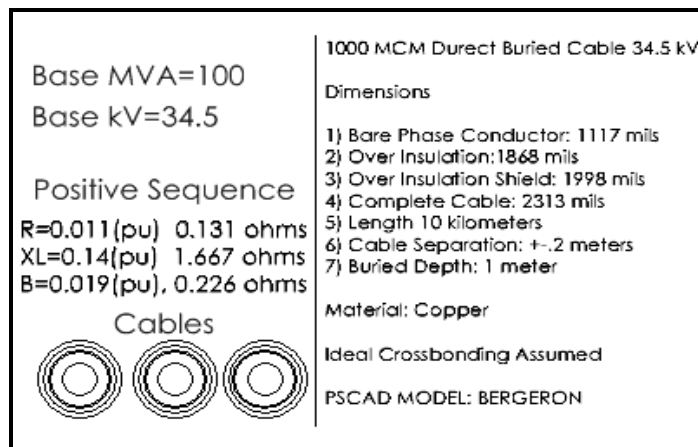


Fig. 21: PSCAD Line Constants Model 10 km (note for aluminum, the values are $R=0.014$ (pu), $XL=0.15$ pu (ohms), $B=0.228$ (pu)). In this this paper, we use copper where the values are nearly the same (see Figure 22). In the following figures, the cable is separated into 1 km and 9 km lengths.

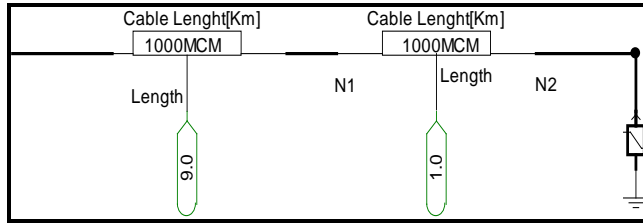


Fig. 22: PSCAD Cable Model (a 10-km model separated in 1 km and 9 km sections).

```

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. 23: 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. 24: 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. 25: 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. 26: MPT Transformer Parameters.

Why do we care about the impedance? Because the voltage rises across a padmount transformer 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 2.5 MVA which is calculated at $0.866 + j26.2$ ohms. The branch of the 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-km home run cable from PSCAD is $0.131 + j1.67$ ohms. The impedance of a grounding transformer is assumed to be the same as that of a padmount transformer.

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 grounding 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.

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 wind power plant when PSCAD is used for modeling and simulation. We use PSCAD 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 a wind power plant or solar power plant uses line breakers, grounding breakers, and remote trip protection arrangements.

GROUNDING TRANSFORMERS

Grounding transformers provide a ground reference for delta configured circuits. Unfortunately, these transformers also have an inductance to ground and provide an insufficient path for active power to flow during islanding. Wind power plant or solar power plant collection circuits with high-side delta configured transformers for each wind turbine generator or solar inverter use the limited path to ground provided by the grounding transformer to limit TOV; however, in certain cases TOV still occurs, with or without a grounding transformer.

Grounding transformers introduce an impedance to ground around 20 to 30 ohms for sharing zero sequence currents. When the line breaker opens, the main plant transformer (MPT) which provides less than 1 ohm to ground is removed. Now, with the

line breaker is open, we have a reference of 30 ohms and nowhere to put the active power.

When the (line) breaker opens, the ground reference from the MPT is lost. Immediately, temporary overvoltage is a concern, then dissipation energy through the lightning arresters is a concern, and then significant damage to the collection circuit is a concern. To make this next point, with the high impedance reference supplied by the grounding transformer causing the voltage on an islanding collection circuit to continuously go high enough to overburden the lightning arrester, if the lightning arrester burns open or changes its I-V characteristic, then the insulation coordination of each generator transformer is lost.

11. DISCUSSION

Generally, Figure 27 concerns type 3 or type 4 wind turbine or inverter-based generation. Figure 27 shows the sequence of events for a single line to ground fault and how the VDH/GSMI and remote trip respond to the fault differently and their impact on the collection circuit. With respect to the simulations, a wind power plant or solar power plant single line is presented either with or without a grounding transformer with PSCAD.

The simulations show that because remote transfer trip must delay the trip signal to the feeder breaker, greater amounts of incident energy are provided to a fault, where the VDH/GSMI does not have to consider such delays and operates quicker. When the remote trip signal fails to get the message to the generators, persistent temporary overvoltages occur. The simulations show that without the VDH/GSMI, there is a significant increase in incident energy which impacts the safety and reliability of equipment and personnel. From the simulation, we can infer the resulting arc blast is very dangerous. One should compare the seven cycles it takes remote trip to operate to the 3.5 cycles of the VDH/GSMI and compare the TOV from remote trip to that of the VDH/GSMI (see Figures 27 and 28).

In addition, a grounding transformer was connected to the single line in PSCAD to see what changes in the current and voltage would appear for the same circumstances. Regarding the grounding transformer and the TOV and incident energy of a fault, the simulation shows the grounding transformer did not improve the safety and reliability of the collection circuit in this specific case. This makes sense because there is no place for the active power to go. Therefore, it is safe to conclude the resulting line to ground reactance provided by the grounding transformer is insufficient for severe islanding. Whereas the VDH/GSMI shorts the phases to ground, and the impedance is significantly less.

Remote trip increases TOV and incident energy, causing overloaded or blown lightning arresters, and damages collection system equipment. Conversely, the PSCAD

simulation shows each time the collection circuit's voltage collapses after the VDH/GSMI operates. Whereas with the impedances and current limiting, it is clear the wind turbines would have a hard time increasing the voltage on a collection circuit if the VDH/GSMI were installed and open (e.g., open vacuum interrupter = open line / closed vacuum interrupter = grounded collection circuit).

A simple circuit approximation with the consideration that the current is limited by the inverter within each generator to approximately 1.1 pu to 2.5 pu [10] shows why this happens. For example, the 24 MW collection circuit and the resulting 1.1 pu current at 34.5 kV is estimated at approximately 500 amps. The resulting steady-state increases after the voltage collapses on the home run circuit is less than 1000 volts. The transient analysis in the PSCAD simulation shows the voltage dropping (Figure 27) below 0.15 pu on the grounded collection circuit. With the collector circuit voltage so low, it should coordinate well with low-voltage ride through and prevent islanding on the faulted collection circuit. Why? Because it bolts all three-phase conductors of the home run cable on the affected collection circuit to ground. One can easily see that, and if the generators' current limit is coordinated with the resulting impedance caused by the VDH/GSMI, the generators would have a clear signal not to ride through, and that is a good idea.

12. CONCLUSION

When it comes to protecting a wind power plant or a solar power plant, the VDH/GSMI is essential. Damage due to faults on collection circuits happen fast. Reports indicate remote transfer trip techniques can introduce a delay of more than 122 ms, and references indicate that the delay can be as long as 205 ms (Table 3) and are not 100% reliable. Although all faults create damage, remote trip delays disconnection from the transmission system and consequently allows high-magnitude fault currents sourced from the transmission system to persist.

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

Table 1 shows the likelihood that the transfer trip signal will not (emphasis added) reach all the wind turbines or solar inverters 100% of the time is a near certainty. Although protection schemes may race the signals to the generators and feeder breakers to trip both simultaneously, Table 2 and Table 3 show the delay is long enough to significantly add to the incident energy, where the VDH/GSMI limits it. In addition, if a disruption to communication occurs, there will be units on-line when the line breaker opens; consequently, temporary overvoltage and damage to equipment are very likely to occur.

Comparing Remote Trip to VDH/GSMI		
Topic	Remote Trip	VDH/GSMI
Incident Energy	Greater than 40 cal/cm ² at 36 in (lethal) @ 200 ms.	Less than 24 cal/cm ² at 36 in.
Temporary Overvoltage	Delayed message causes TOV and loss of insulation coordination.	Prevents TOV and maintains insulation coordination.
Lightning Arrestors	TOV will change the I-V characteristic and collection circuit will not be protected.	Voltage remains below prior duty curve; equipment is better protected.
Generator step up transformer	TOV and loss of insulation coordination will damage the transformer.	Voltage remains below prior duty curve; equipment is better protected.
Dangers to personnel	Blast from 40 cal/cm ² is lethal.	At 24 cal/cm ² PPE is available.
Islanding	Trip signal does not get to the generators in time; they produce power into an open circuit causing TOV which damages equipment.	Grounds the home run cable of the collection circuit providing a very low impedance for the generators to produce.
Grounding Transformer	Ineffective at preventing TOV.	VDH/GSMI either eliminates the need or complements existing installations and improves protection.
Under Voltage Ride Through	Delayed or unreliable trip signal TOV is present, and ride through could cause islanding.	Collapses voltage in most cases below 15%.

Table 6: Comparison, Remote Trip vs. VDH/GSMI.

A VDH/GSMI once grounded will create a bolted three-phase ground on the home run cable. This, in turn, will create 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 km long. If we compare the home run 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.

With the home run cable grounded by the VDH/GSMI, and even if we had some semblance of proper operation on the three-phase grounded feeder (which we do not have), 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.

The maximum current (amps) magnitude for all 12, 2 MW generators during the fault, which are current limiting, is approximately 500 amps, and the resulting voltage increases across the home run cable at j2 ohms is less than 1 kV. Consequently, each generator is hard-pressed to keep its AC mains voltage above 10% with the VDH/GSMI creating a bolted three-phase ground on the home run cable.

PSCAD Comparison of Remote Trip to VDH/GSMI

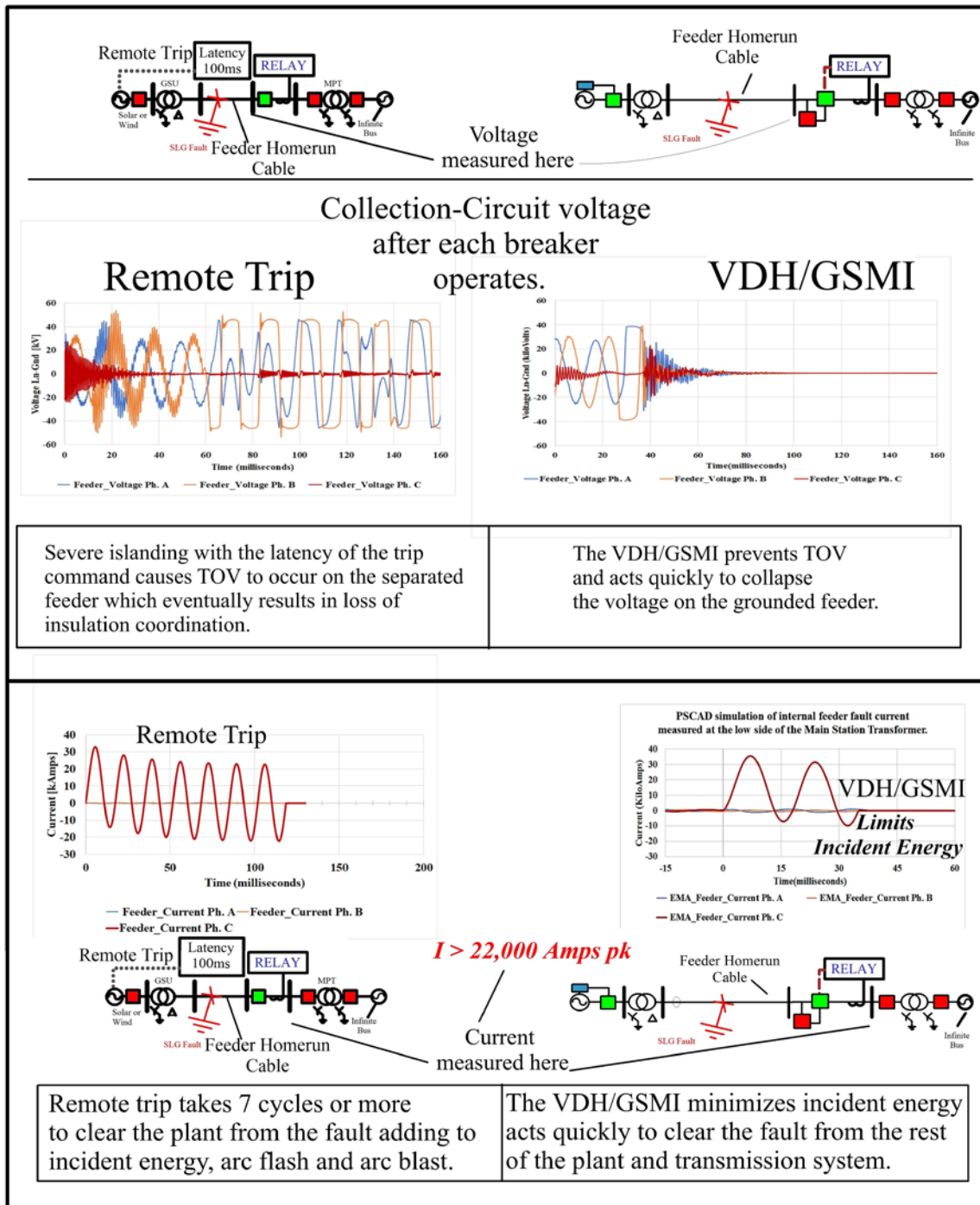


Fig. 27: Comparison of PSCAD VDH/GSMI and Remote Trip (Incident Energy and TOV).

PSCAD Comparison of Remote Trip Delay to Fast Action of the VDH/GSMI

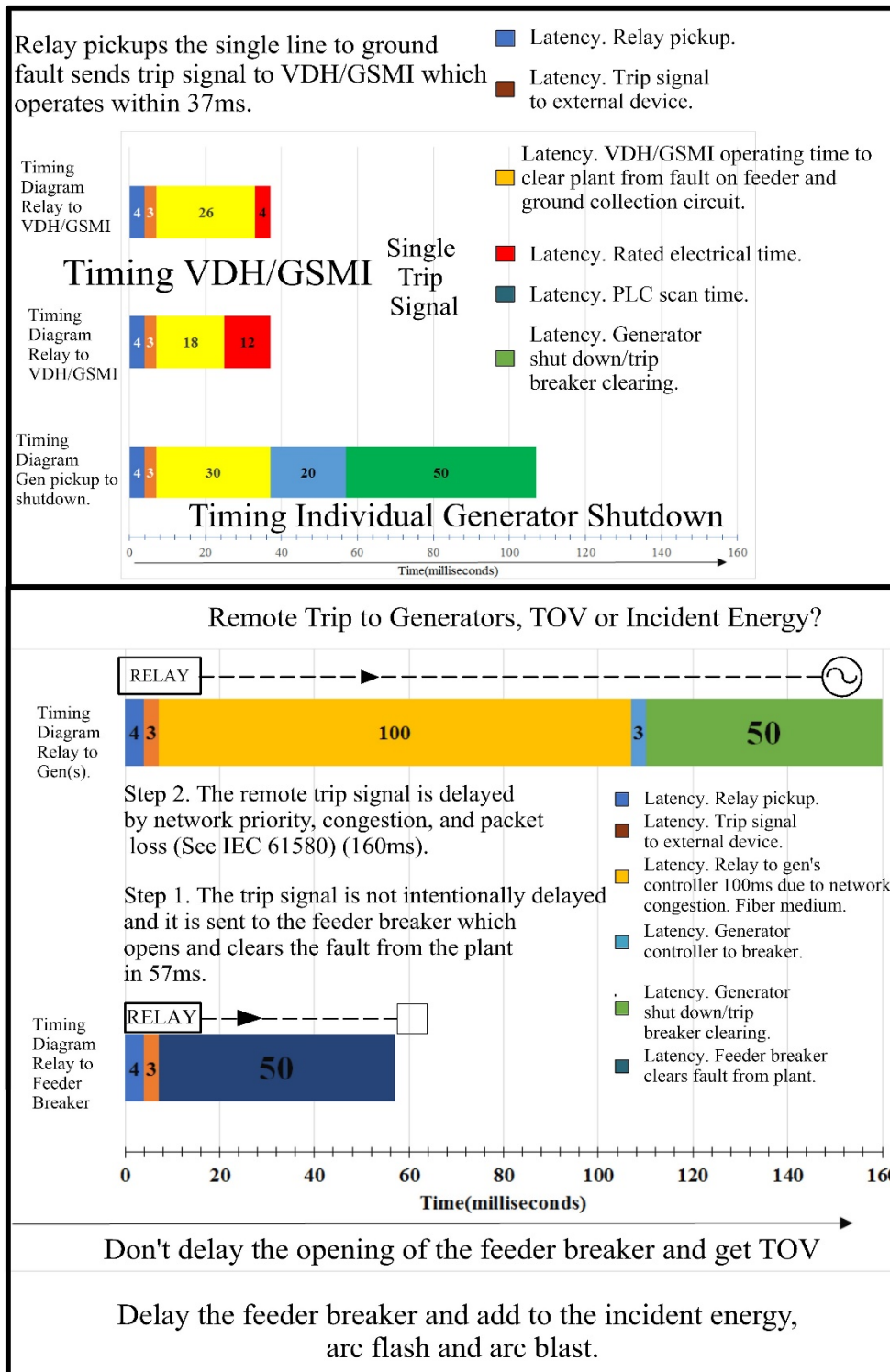


Fig. 28: Comparison between Remote Trip and TOV, Timing.

At that point, each generator should trip offline, and islanding should not occur. In addition, and as an aside and with the above in mind, each generator should coordinate well with low-voltage ride-through requirements.

In this paper, a sequence of events and an operational overview concerning the VDH/GSMI for wind power plants and solar power plants are presented. With the VDH/GSMI in mind, we draw the following conclusions:

1. The VDH/GSMI operates two vacuum interrupters with an interlock; therefore, the VDH/GSMI operates with at least one trip signal.
2. There are three states with respect to impedances during the operation of the breaker.
3. In the VDH/GSMI, the line interrupters open first, and the ground interrupters close second. With the VDH/GSMI, a faulted feeder is disconnected from the transmission system first, and then the faulted feeder is bolted to ground.
4. The transition state of the VDH/GSMI where both vacuum interrupters are open is from 4 to 12 ms.
5. The operation of a VDH/GSMI demonstrates a clear change in impedance as the VDH/GSMI operates. Generators can detect such a change and act on it.
6. 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 km).
7. TOV duration is minimized by the combination of the fast transition state of the VDH/GSMI and the lightning arresters. 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 reference to ground than a grounding transformer and consequently reduces the burden on lightning arrestors.
10. Given the typical design variations of wind power plants and solar power plants and the generators with current limiting capability, the VDH/GSMI should provide a 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 offline to prevent islanding. (See the low-voltage ride-through paper.)

11. With fewer modes of failure, the VDH/GSMI is more reliable than remote transfer trip.

The PSCAD simulations show the VDH/GSMI resolves issues of temporary overvoltage and incident energy, where delays are not needed to clear the fault from the plant. The VDH/GSMI completely operates within nearly 50 ms to separate the affected collection circuit and ground it, so it collapses the voltage. The VDH/GSMI relieves the lightning arrestor and keeps the resulting TOV below the prior duty curves. As a result, we conclude that the use of the VDH/GSMI in the design and construction of generating projects, such as wind power plants and solar power plants, constitutes a best practice.

13. ACKNOWLEDGMENT

The authors thank all of those who work with EMA for their support to produce this paper concerning the design and operation of the VDH/GSMI for wind power plants and solar power plants.

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