THE VDH/GSMI REDUCES ENERGY REQUIREMENTS FOR LIGHTNING ARRESTERS AND PROVIDES FAST, CLEAR AND RELIABLE NEEDED SIGNAL TO “INDIVIDUAL GENERATORS UNITS” TO EITHER SHUT DOWN, OR CONTINUE TO RIDETHROUGH FOR BOTH HIGH AND LOW VOLTAGE RIDETHROUGH CONDITIONS

EMA ELECTROMECHANICS

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1 EXECUTIVE SUMMARY

EMA asked Thomas Wilkins and Miles Downing to simulate and review with PSCAD the cases that ask the questions: "*Will Lightning Arresters interfere with the inverter's "high voltage shutdown threshold" at each individual generating unit(IGU) concerning PRC-024-02 for the transient case where the point of interconnections voltage swings from 0.95pu to near 1.199pu*? *Should generator owners be concerned*? *If there is a problem does the VDH/GSMI resolve it*?

This report begins to answer the question by providing a background concerning Arresters. Then discussing the differences between lighting surges and longer surges such as Temporary Over Voltage (TOV) which can last a million times longer than a lightning strike (100 us vs 10,000 seconds). Then the paper discusses the very low 12-millisecond islanding time provided by the VDH/GSMI (See Figure 1) and how the VHD/GSMI provides superior protection for Lighting Arrestors and Insulation Coordination. However, it is very important for the reader to see the difference between the time period of a Lightning-Surge and the time period of a Temporary Over Voltage (TOV) Surge. Where the VDH/GSMI is found to reduce Temporary Over voltage times caused by a typical Feeder Circuit Breaker. A typical Feeder Circuit Breaker can cause Generator islanding from 12 milliseconds to 100s of milliseconds (Figure 1).

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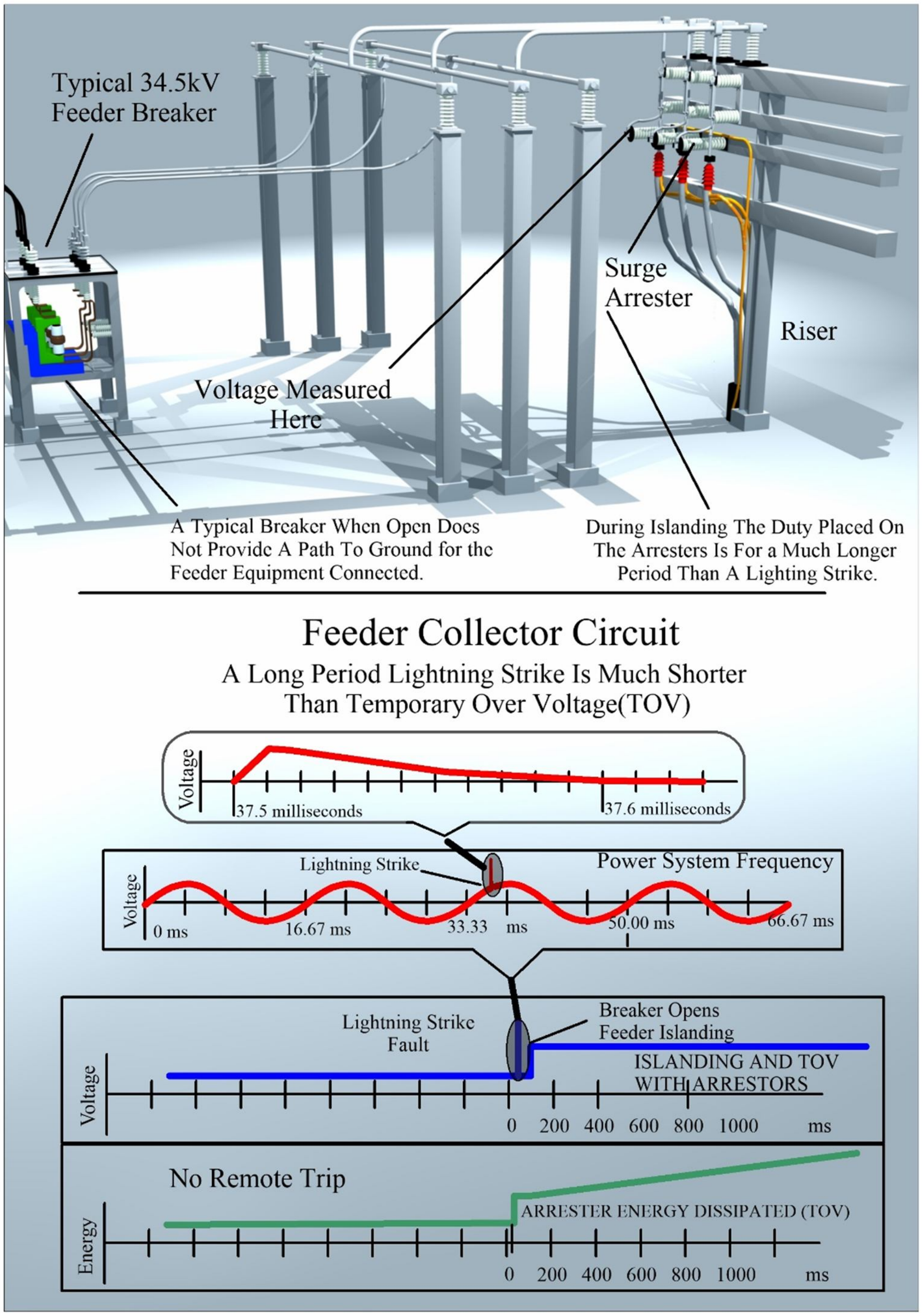

Figure 1, Lightning Period vs VDH/GSMI Islanding Period.

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In this report, with TOV in mind, PSCAD simulations indicate the Lightning Arresters as well as local transformer saturation will interfere with the IGU Inverter's "local" capability of detecting when to ride-through or shutdown which can cause islanding. Therefore, plant owners and operators should be concerned because of the resulting delays and uncertainties from remote signaling; where such delays are in excess of 200ms. PSCAD simulations also show that the VDH/GSMI resolves this problem by providing a "faster" and "clearer" signal than a typical Feeder Circuit Breaker or Remote-Trip-Signal "locally" to each inverter (at each individual generating unit) to either Ridethrough or shutdown.

The simulations clearly show that for a typical solar power plant (SPP) during high voltage Ridethrough, the voltage within the plant can exceed 1.4 pu. Tabulated data from several simulations show that the TOV V-I curve and not the Lightning Arrester's V-I curve should be used when determining Ridethrough capability for a SPP. The TOV V-I curve of the Lightning Arrester may clamp the voltage and not let it go high enough for an inverter to detect an island event (please see Table 2 on page 11).

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PSCAD simulations also show that the VDH/GSMI resolves this problem by providing a three-phase bolted ground on the affected feeder where the bolted ground causes a low voltage signal during a high voltage event, thereby providing a clear signal for each individual generating unit to shut down.

More specifically, the phasor calculations with PRC-024-2 High Voltage Requirements in mind indicate or project that the voltage rise to the back to the low side of the Generator Step Up Transformer (GSU) at an individual generating unit will exceed 1.4 pu. If a typical breaker opens, PSCAD simulations show that saturation may prevent the a 1 to 1 per unit voltage rise through the GSU. In addition, after a typical breaker opens, PSCAD simulations project under certain circumstances the voltage can exceed 1.6 pu on the separated collector. Where the Lightning Arresters are found to clamp the voltage at this level. PSCAD simulations also project, depending on generating conditions, one generator may be at lower production than the others, and consequently its voltage may stay low enough during islanding that the high voltage threshold is not exceeded. Therefore, it remains on-line until it receives an external command to shut down. This can take over 100-200 milliseconds.

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PSCAD simulations project that concerning Ridethrough, if the high voltage trip relay setting at an individual generating unit is set lower than 1.4 pu and there is a requirement for Ridethrough above 1.4 pu, the calculations project it may not ride through. PSCAD also projects the VDH/GSMI solves such operational challenges.

The VDH/GSMI provides a solution for both Islanding and High Voltage Ridethrough detection issues because it will ground out the feeder, thereby providing a clear signal to the relay at each generator to shut down during both islanding or if the voltage exceeds the Ridethrough requirement at the POI (We presume all VDH/GSMIs within the plant will operate at this point).

During islanding, if the voltage does not rise above 1.4 pu (this is usually the high voltage threshold to shut down the individual generating unit) the VDH/GSMI, should it operate, will cause the voltage to go low on the Collection Feeder Circuit and the units will go offline, whereas a typical circuit breaker cannot do this. In addition, if the high voltage trip is set above this value, the inverter (generator) may island when it should not. The VDH/GSMI resolves this problem by grounding all three phase conductors should the POI voltage go too high. Therefore, for high voltage Ridethrough the VDH/GSMI can operate and shut down the units by grounding the feeder if the POI voltage exceeds 1.2 pu.

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Figure 2 projects what happens when the VDH/GSMI grounds the feeder for PRC-024-2 conditions. Table 1 shows the calculated voltages across the collection system cable, and Table 2 shows the problem caused by a typical feeder breaker. Table 3 provides the resulting values when the problem is resolved by the VDH/GSMI.

This paper looks at the voltage rise across a feeder during Ridethrough conditions as specified by PRC-024-2 and describes how the VDH/GSMI could be set up to assist with providing PRC-024-2 functionality for solar power plants.

In past papers we simulated inverter-based resources without a fast-high voltage turn off during islanding. In this paper we start to talk about this set point and how the collection system can cause unwanted islanding. In this paper we include the high voltage Turn Off set point and show that the VDH/GSMI is very much needed in large SPPs and can protect inverter-based resources during islanding where a typical breaker cannot.

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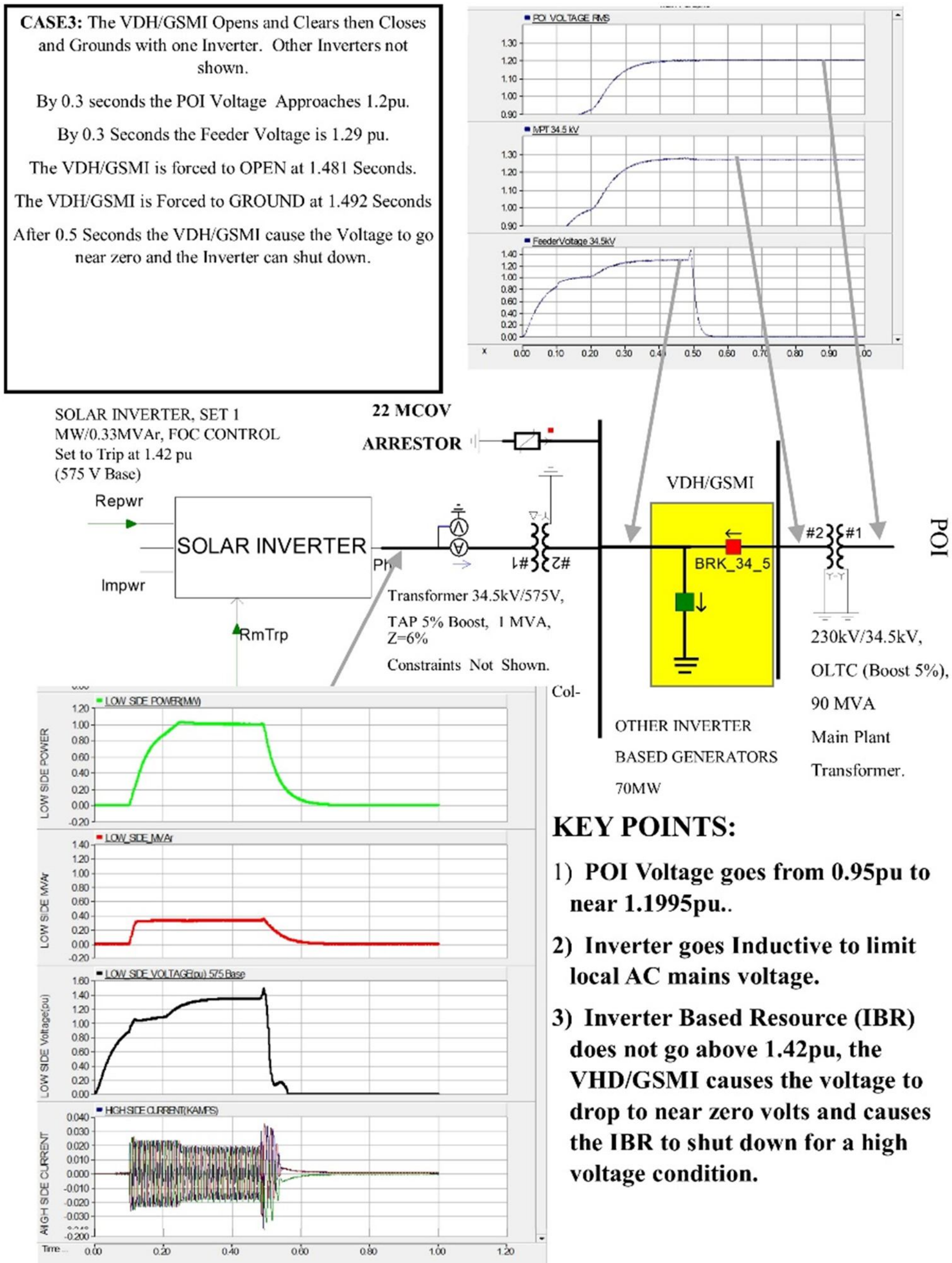

Figure 2(Same as Figure 17). VDH/GSMI Provides a Faster and Clearer Signal Than a Typical Feeder Circuit Breaker For PRC-024-2 High Ride-Through Compliance

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Table 1. Calculated PRC-024-2 Voltage Rise at an Inverter in a Solar Power Plant (SPP).

P,Q,V TABLE (13 Gen. Units/Feeder, 4 Feeders).Homerun cable for each feeder included in calculations.				
	POI **Location (1)** 1	**34.5 kV Sub** **Location (2)** **OLTC BOOST 5%** **(52 units)** 2	**34.5kV High_Side GSU** **Location (3) (13 Units)** **(partial equivalence)** 3	**690 V Low_Side GSU** **Location (4) (1 unit)** **All tap to boost 5%** **(partial equivalence)** 4
P	100 MW	100.05 MW	25.05 MW	1.93 MW
Q	33 MVAR	39.15 MVAr	7.1 MVAr	0.61 MVAr
V	V=1.199	1.29 pu	1.304 pu	1.38 pu+2% Phase Imbalance

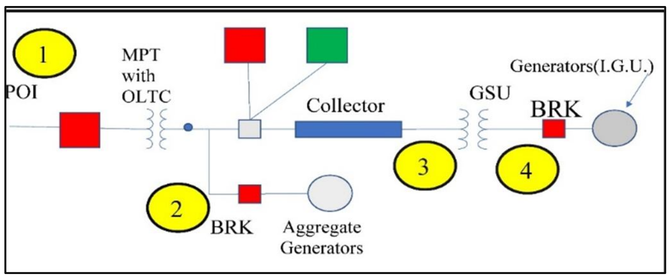


Table 2. PSCAD Islanding Caused by a Typical Feeder Breaker in PRC-024-2 Conditions.

High Voltage RideThrough PSCAD Simulation with a **Typical Breaker. I.G.U** (GSU) Transformer is in saturation Its Tap is set at 5% Buck.							
I.G.U. Plant Power Setting	I.G.U. Trip Set	Interconnect Voltage. Location 1	**Collector 22MCOV**		Low Side IGU		
			CLOSED Locations 2 & 3	SWITCHING Locations 2 & 3	CLOSED Location 4	SWITCHING Location 4	Result
100%	1.42 pu	1.199 pu	1.25 pu	1.53 pu	1.20 pu	1.44 pu	Shutdown?
50%	1.42 pu	1.199 pu	1.25 pu	1.54 pu	1.19 pu	1.44 pu	Shutdown?
25%	1.42 pu	1.199 pu	1.25 pu	1.54 pu	1.18 pu	1.41 pu	Islanding
13%	1.42 pu	1.199 pu	1.25 pu	1.53 pu	1.18 pu	1.40 pu	Islanding
The 22 MCOV Arrestor Clamps the Voltage to below 1.53 pu on the Collector. PSCAD shows at all power levels Islanding is possible without a VDH/GSMI							

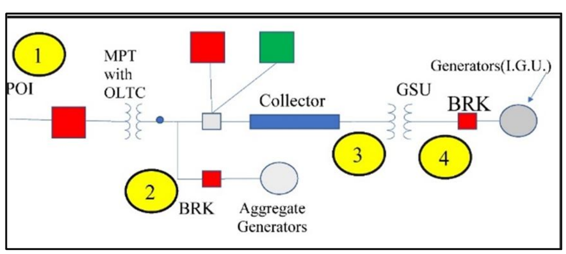
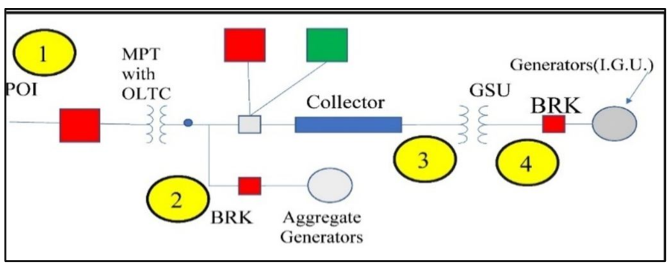


Table 3. VDH/GSMI Helps Meet the Conditions in Table 1 and Resolves the Problems Shown in Table 2.

High Voltage RideThrough PSCAD Simulation with a VDH/GSMI. **I.G.U** (GSU) Transformer is in saturation its Tap is set at 5% Buck.

I.G.U. Plant Power Setting	I.G.U. Trip Set	Interconnect Voltage. Location 1	**Collector 22MCOV**		Low Side IGU		
			CLOSED Locations 2 & 3	SWITCHING Locations 2 & 3	CLOSED Location 4	SWITCHING Location 4	Result
100%	1.42 pu	1.199 pu	1.25 pu	1.49 pu	1.20 pu	1.40 pu	Shutdown
50%	1.42 pu	1.199 pu	1.25 pu	1.43 pu	1.19 pu	1.34 pu	Shutdown
25%	1.42 pu	1.199 pu	1.25 pu	1.44 pu	1.18 pu	1.34 pu	Shutdown
13%	1.42 pu	1.199 pu	1.25 pu	1.40 pu	1.18 pu	1.30 pu	Shutdown

The 22 MCOV Arrestor clamps with the help of the VDH/GSMI, the voltage to below 1.49 pu on the Collector. VDH/GSMI prevents Islanding.



In this paper we provide several cases and calculations showing PRC-024-2 requires the individual generating units within a SPP to operate up to and above 1.4 pu.

A solar plant's inverter-based resource is required to operate at much higher voltages than historically. So, in this paper we consider Ridethrough and islanding

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with these higher voltages in mind. We will show through simulations how a typical Feeder Circuit Breaker will not clamp the voltage on the feeder to zero. We will also show that the VDH/GSMI provides for clamping the voltage down to near zero volts on all three phases within 12 milliseconds. We will show that the VDH/GSMI prevents islanding of inverter-based resources that are forced to have higher instantaneous high voltage shut down due to PRC-024-2 requirements.

The paper next provides several PSCAD simulations that show how, because of Ridethrough requirements and the Ridethrough settings at the low side of the GSU of an individual generating unit, it may not turn off and island with a typical collection circuit breaker. We will discuss how a Lightning Arrester can make the problem worse. This paper also provides the voltage rise calculations across a feeder circuit to show the consequential operating voltage during Ridethrough to support the claim concerning the high voltage conditions on the feeder.

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2 VDH/GSMI & ARRESTERS

2.1 Introduction

Introduction, this section describes Lighting Arresters and Surge Arresters how they are really the same thing, where surge period is much longer than the Lightning period (See Figure 1). This section also discussed the operation of the VDH/GSMI with Arresters. Then this section discusses condition monitoring of Arresters and how current techniques do not provide a complete picture concerning Arrester health. This section ends with a discussion concerning failure modes of Arrestors and how the VDH GSMI may prevent such failures.

2.2 Lighting Arresters vs Surge Arresters, where does the VDH/GSMI provide protection?

Concerning protection from excessive voltage in the circuit, the words "Lightning" or "Surge" are used for the most part, interchangeably. But, the words “Lightning” or “Surge” are not enough to describe what we are doing and how we are trying to protect a circuit. With that said, Industry may use the two terms interchangeably, and as a result, this may lead to misunderstandings. However, we will keep in mind, a "Surge Arrester" or a "Lightning Arrester" performs the similar functions of "clamping the voltage" and "dissipating the surge energy"; thus, allowing the

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circuit to function properly after the surge. The primary difference between the words “Lightning” or “Surge” is time(seconds)(See Figure 1). A Lighting Strike is impulsive energy usually occurring within a period of time of 40us-100us (us=microseconds) or less. This is 0.000040 to 0.00010 seconds. The time period of a surge can be in the milliseconds (0.001 seconds) to 10,000 seconds. Therefore, a Surge can be from 1000 times to over millions of times longer than a lightning strike.

When considering the word or phrase “Lighting Arrester” or “Surge Arrester” we should focus on the ratings of the "Arresters" to tell us the intent of the manufacture. This includes the MCOV rating, Energy Rating (kJ/kV), Temporary Over Voltage Duty Curve, Prior Duty Curve, the V-I curve for Lightning Arrester and the V-I curve inferred from the V-I Duty curve" or from the Prior Duty Curve, where “longer period V-I curves” may be inferred from the energy rating of the Arrester.

As commonly known, a surge in general is a transient or spike in level or magnitude of Voltage or Current(Amps)) from a normal or standard value and may

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beyond the design limits of the circuit. We know surges typically lasts thousands to millions of times longer than lightning strikes.

Also, concerning the VDH/GSMI and its application to Feeder Collection Circuits we have to clarify the type of surge where we now include “Islanding Surges". Surges and "islanding surges" are similar, however there are important differences between the two. An "Islanding Surge" is a source driven surge after the Breaker has separated the Inverter Based Resource (IBR) or Generator from the Power System. During an “Islanding Surge” we account for the period of time that the source (i.e. Generators) will remain on line, after the circuit separates from the power system and integrate (e.g. sum up) energy delivered by the source during the islanding period. This energy is dissipated by the Arresters. Also, concerning “Islanding Surges” we should account for the zero, positive and negative sequence paths where the energy can be dissipated from the circuit. Typically, a Lightning Arrester will provide at least two paths, but we will need to size it properly for the type of surge expected through the Arrester.

So, in this paper we focus on three classes of surges that we can differentiate and relate by time and energy dissipated. They are:

1) Lightning Surge 8/20us 10/100us, may have the highest power dissipation but for a short duration where the energy content varies significantly from 1 kiloJoules to 100s of kiloJoules.

2) General Surge. General in nature and can last in the range of milliseconds (1,000s of micro-seconds) to 10,000 seconds (See TOV Duty Curve), energy dissipated can be in the 100's of kilojoules.

3) Islanding Surge. Heavy Duty Source driven surge into the arrester and can last from 1ms to 200ms. The Energy dissipated can be as high as the 100's of kilojoules. Islanding is not a typical surge, because it is actively source driven. Therefore, with the above in mind, we conclude that there are similarities and difference between Lighting Arresters and Surge Arresters where one is encouraged to look at the specifications of each Arrester to find if the design meets the circuits designer’s needs.

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2.3 Operation of the VDH/GSMI and Arresters

With the above in mind, we now include in our discussion the operation of the VDH/GSMI. Figure 3 shows the single line for a wind power plant or solar power plant, with the VDH/GSMI where the interlock and grounding switch are on four collection circuits or feeders. Figure 3 shows the home run cable and the Generator Step Up Transformer (GSU) where the GSU is the equivalent of many generators. Figure 3 shows where the VDH/GSMI is located within the plant and the PRC-024-02 HVRT requirements. Figure 3 also shows the single line for a wind power plant or solar power plant, with the VDH/GSMI where the Figure 3 shows the two interlocked breakers on each of the four collection circuits or feeders. Figure 3 shows the home run cable and the Generator Step Up Transformer (GSU) where the GSU is the equivalent of many generators. Figure 4 shows the VDH/GSMI when it is closed (the ground switch is open). The blue bold line indicates the electric path from the generators on the feeder to the main plant transformer. Figure 5 shows the 12-millisecond transition period for the VDH/GSMI. Figure 6 shows the VDH/GSMI Open and Grounded where the feeder is grounded as shown with the green path. For Figure 6, the home run cable's three phases are bolted to ground so the entire feeder circuit is grounded.

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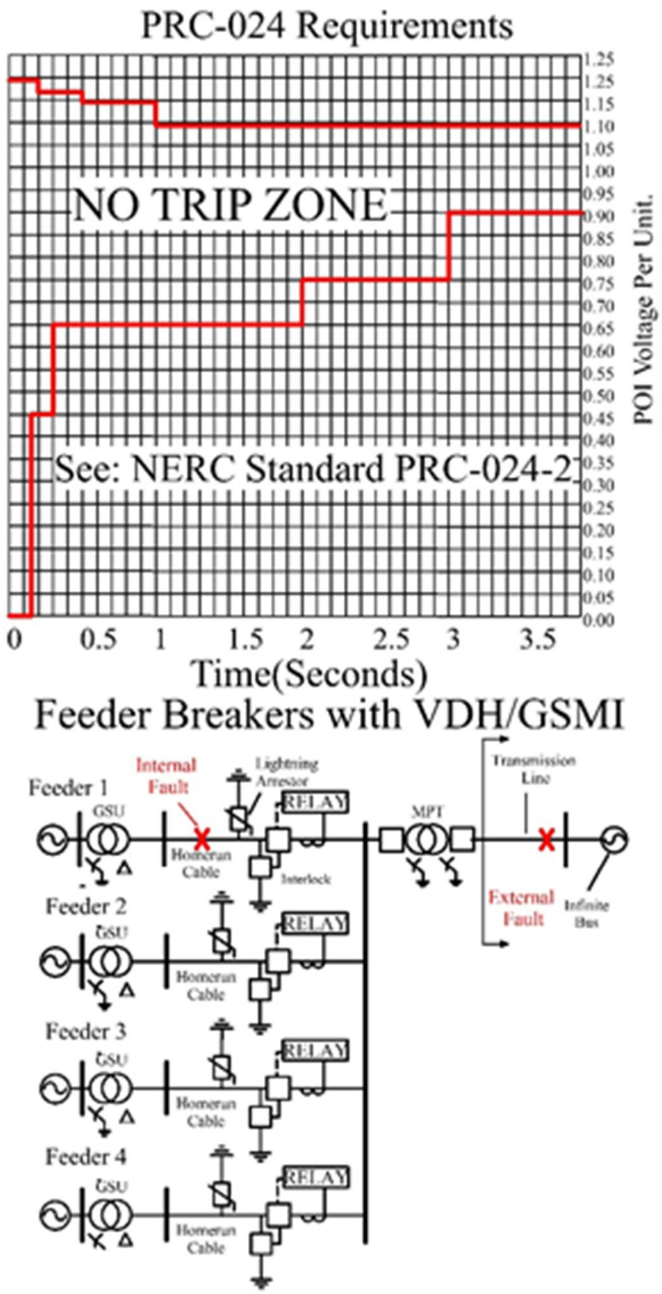
PRC-024 Requirements
NO TRIP ZONE
See: NERC Standard PRC-024-2
POI Voltage Per Unit.
Time(Seconds)
Feeder Breakers with VDH/GSMI
Feeder 1
Feeder 2
Feeder 3
Feeder 4
Internal Fault
Lightning Arrestor
RELAY
Homerun Cable
MPT
Transmission Line
External Fault
Infinite Bus

Figure 3

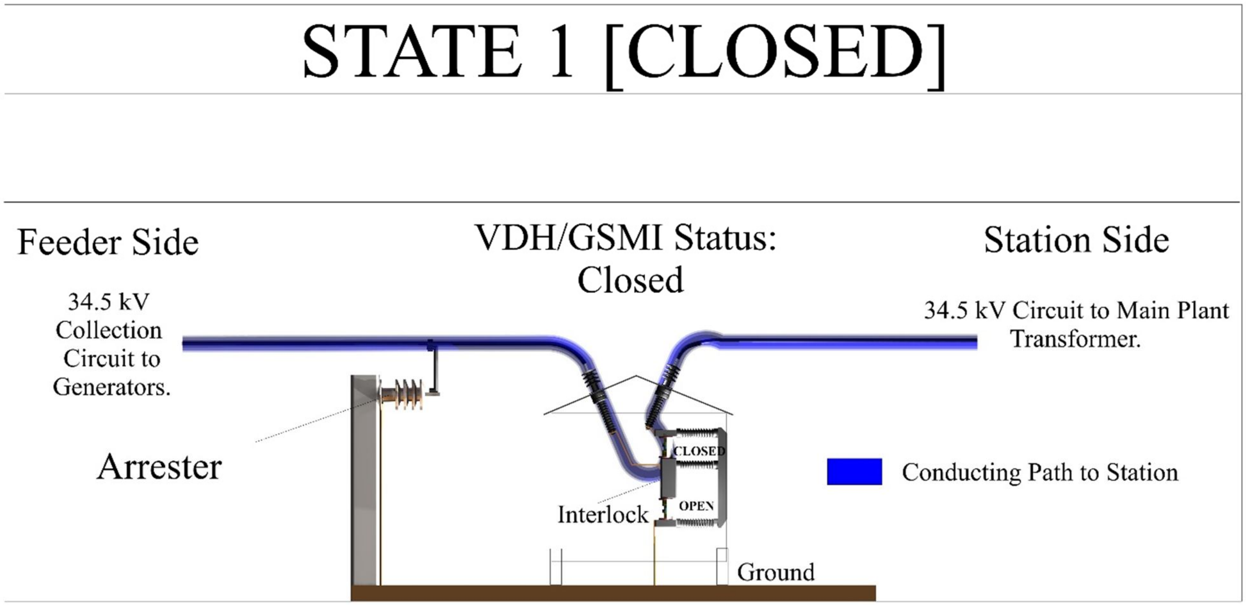

Figure 4 VDH/GSMI Closed

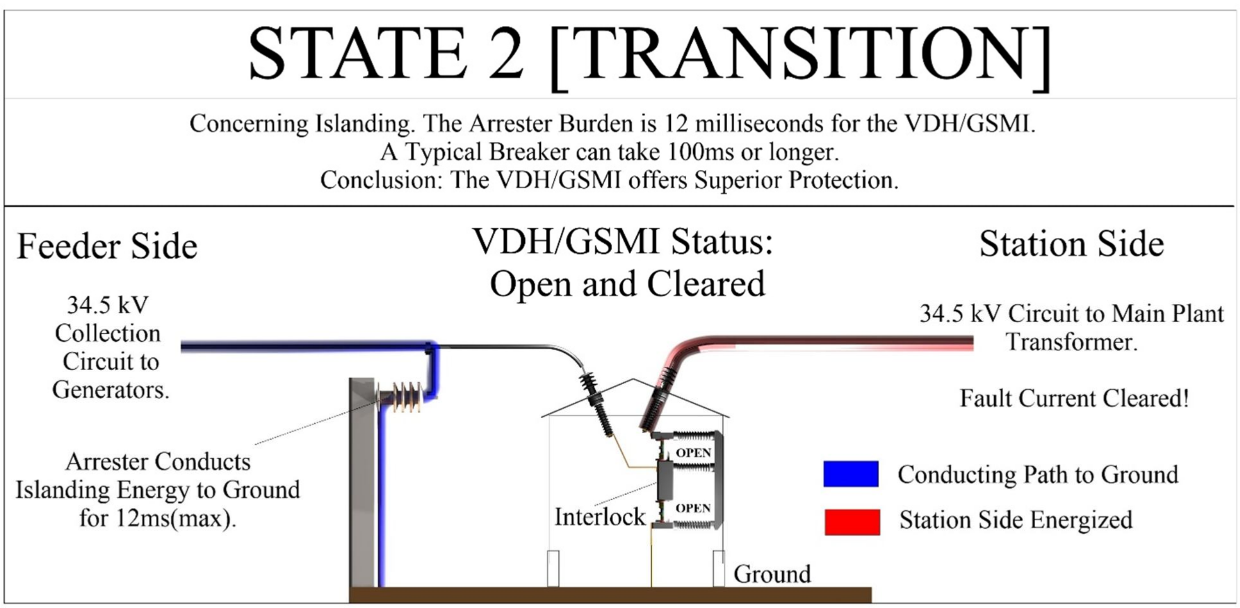

Figure 5 VDH/GSMI Transition

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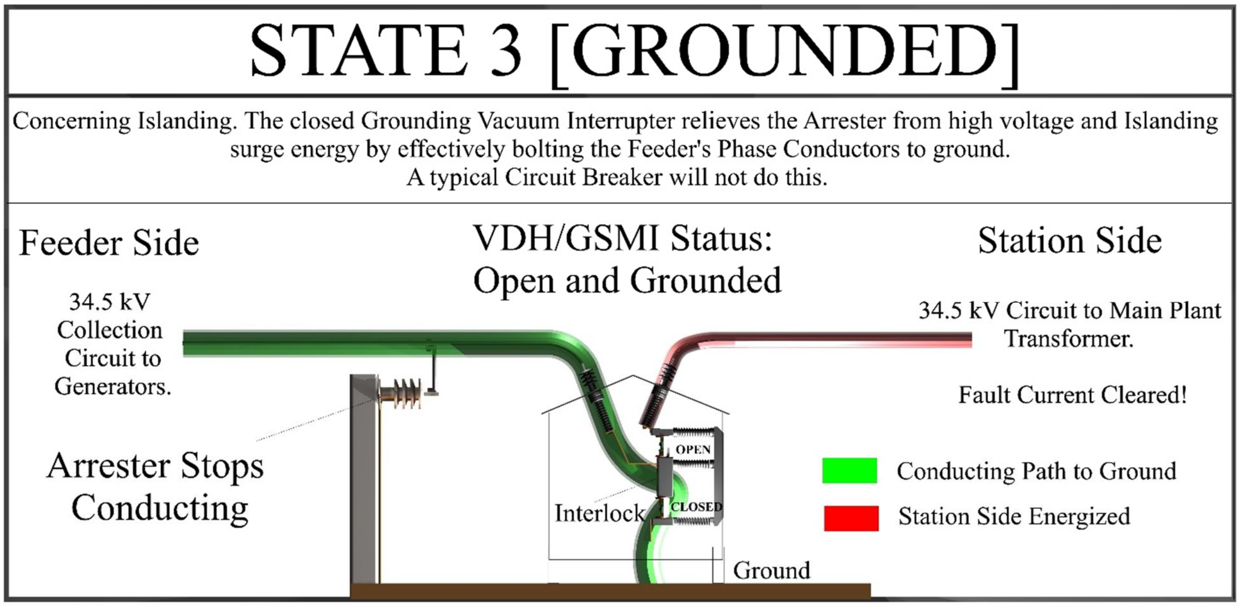

Figure 6 Feeder Grounded

Figure 3 through 6 project and suggest in part how the VDH/GSMI provides support for a generation plant regarding PRC-024-2 and ride-through capabilities for the many types of faults. After the VDH/GSMI opens and then closes, the line to ground impedance on the home run cable is significantly reduced. With that in mind, the VDH/GSMI provides "easy" islanding capability where the voltage remains very low. As PRC-024-2 requires nine cycles of ride-through capability, with zero voltages at the point of interconnect, the VDH/GSMI provides engineers and designers with an option they do not have with a typical feeder breaker.

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

2.4 The Operational Relationship between the VDH/GSMI and Arresters.

Concerning a particular Feeder Collection Circuit, the Arrester protects the VDH/GSMI and the VDH/GSMI protects the Arrester. The Arrester clamps the voltage when the VDH/GSMI opens and clears but remains open for approximately 12 milliseconds to make certain all the ground vacuum interrupters have ceased conducting current supplied by the plant, then closes and grounds. During this 12ms, we assume that all the Inverter Based Resources (IBRs) or Generators never shut down and island at full power. With that in mind, the energy for 12ms is presumed to be going to go through the Arrester, where it is relatively easy to project the energy dissipation requirement of the arrester.

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For example, concerning a very cursory calculation, 25MW Collection Feeder Circuit is at maximum power and islanding for 12ms where we presume the voltage goes up to approximately 1.5 pu (Arrester is limiting the voltage) and the current is 1.0 pu since the inverter can regulate the current output (1.5 * 19920(Volts)*500(Amps) 0.012 s) =172kiloJoules. However, what does this mean? Are there other technologies that we can use to compare the VDH/GSMI too? The answer is yes. Let's compare it to grounding transformer.

In this case the VHS/GSMI is not in the circuit and one uses a grounding transformer with a typical breaker. The islanding could be 6 cycles or longer. If the IBR islands without shutting down, and since the Grounding Transformer only presents a zero-sequence path, the Arrester now (depending on extreme worst-case conditions) is required to take 8 times the positive and zero sequence islanding surge energy than if a VDH/GSMI has been used. Therefore, the Grounding Transformer is found to place a much greater surge burden on an Arrester than VDH/GSMI for the same Feeder Circuit design, where the VDH/GSMI significantly reduces such a burden by 8 times. This is one of many reasons we find the VDH/ GSMI is very useful for improving the operation of Wind or Solar Power Plants.

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2.5 Condition monitoring for Arresters

Concerning protection and condition monitoring of Lightning Arresters there are devices known as counters where they measure 1) total leakage current,2) surge current, 3) impulse current 4) 3rd harmonic analysis of leakage current 5) leakage current harmonics, 4) temperature, and 5) condition indication. However, here is what they are not found to measure:

1. CONDITION MONITORS ARE NOT FOUND TO MEASURE THE CLAMPING VOLTAGE OF THE ARRESTER!

2. CONDITION MONITORS ARE NOT FOUND TO MEASURE THE V-I CURVE OF THE ARRESTER DYNAMICALLY!

3. CONDITION MONITORS ARE NOT FOUND TO MEASURE THE ENERGY DISSPATED BY THE ARRESTER DURING THE SURGE.

4. CONDITION MONITORS ARE NOT FOUND TO KNOW THE TYPE OF SURGE.

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In addition, one needs to keep in mind the time for the count and the maximum current they can measure. Counters may not provide all the necessary information because counters are limited by the current transformer's (CT's) limitations.

Therefore, Arresters may be damaged because the counter did not provide the information necessary for the operators to make a proper determination of as to the condition of the Arrester.

Islanding Surges are part of this example, where if the current goes beyond the maximum values of the Counter's CT operators will not know. As a consequence, if the Arrester is damaged or altered the V-I characteristic may change. If the V-I characteristic changes and either moves up or down, the operation of the entire plant may be thrown out of spec either way. If the Arrester ages or changes the V-I curve moves up the insulation is damaged. If the V-I curve moves down due to overheating there is a risk of not riding through when the plant is required.

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2.6 Aging of Arresters

If one wanted to know if there is arrester premature aging or how the plant was performing and to perform a root cause analysis concerning insulation coordination, Arrester Health, or ride through one could use condition monitoring. However, a better way not usually performed is to use a Potential Transformer(PT) located on each phase on the medium voltage 34.5kV feeder located on the feeder side of the Collection Circuit Feeder Breaker and close to it. This addition, even though costly would give technicians and engineers the capability of knowing each time the voltage and energy dissipated after the feeder breaker opens, and allow for the characterization of the following:

1) Improved analysis of generator's performance during islanding. (Note: we found that generator manufactures will not guarantee islanding performance. Even if they did and most of the time they "could", it is far better to use a VDH/GSMI as insurance.)
2) Improved analysis as to the consequences of failed Remote trip.
3) Improved root cause analysis of insulation stress or failure.
4) Improved characterization of Arrester's performance and aging.
5) Improved analysis for preventative maintenance of a feeder circuit.

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2.7 Failure modes of Arresters

One of the consequence of Arrester Aging is it can "fail open" of "fail short" or "partially fail short". Where concerning partially failed short means a disk within the arrester has failed short and the others have not. If an Arrester has failed short, it is like connecting a cable from the phase conductor to ground. If it has failed open it is like placing an insulator between the phase conductor and ground and the Arrestor is not long providing protect to the Feeder Collection Circuit.

It would be expected a counter or condition monitoring may pick up if an Arrestor has failed short or open. However, this requires a counter or condition monitoring on every arrester on the feeder circuit and personnel to inspect or interrogate the monitors. While this approach is becoming more common, it is not fully or consistently in practice.

However, a good point to bring up is when a Lightning Arrester fails short it will be immediately replaced because the operators will not be able to bring the feeder collection circuit back into service until they do so. However, if the Lightning Arrester fails partially short or open it may not be detected for some time without

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condition monitoring. If a Surge or Lightning Arrester "fails open" it means that the Lighting Arrester will not protect the Collection Feeder Circuit for that phase and without condition monitoring operators will not know they are unprotected. In other words, if there is no condition monitoring, it may not be detected until inspected and found by the plant operator or until some catastrophic event occurs because there was not any Lighting Arrester in place to protect the very expensive feeder collection circuit.

2.8 Summary

In this section we discussed the operation and aging of Lighting Arresters and Surge Arresters how they are really the same thing. Where surge period is much longer than the Lightning period (See Figure 1). In this section we also discussed the operation of the VDH/GSMI with Arresters. Then this section discusses condition monitoring of Arresters and how current techniques do not provide a complete picture concerning Arrester health. This section ends with a discussion concerning failure modes of Arrestors and how the VDH GSMI may prevent such failures.

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3 IBR TOV GROUNDED AND UNGROUNDED SYSTEMS

Just because you have a wye grounded transformer on the high side of your collection circuit does not mean you will not experience temporary overvoltage (TOV). Concerning solar plants and their installation, there is a significant investment associated with underground cables and equipment. Clearly, we want to protect this equipment due to the high costs associated with replacement. So, we demand the best available protection from the effects of TOV. This is critical for solar collector systems. With PRC-024-2 in mind, we know that high voltage swings and TOVs were common in the past. In the future they are going to get worse. PRC-024-2 will require the SPPs to endure even higher overvoltages. Such overvoltages increase the risk of damage to the feeder cable, transformer, and inverter-based resources, resulting in potentially expensive outages. Modern SPP feeders can be both ungrounded delta or grounded wye; however, as far as this paper is concerned, TOVs will occur on both types. In this paper we will simulate delta low side and grounded wye on the high side in PSCAD to show why TOV is a danger. Figure 7 below shows a typical TOV curve for a medium voltage arrester.

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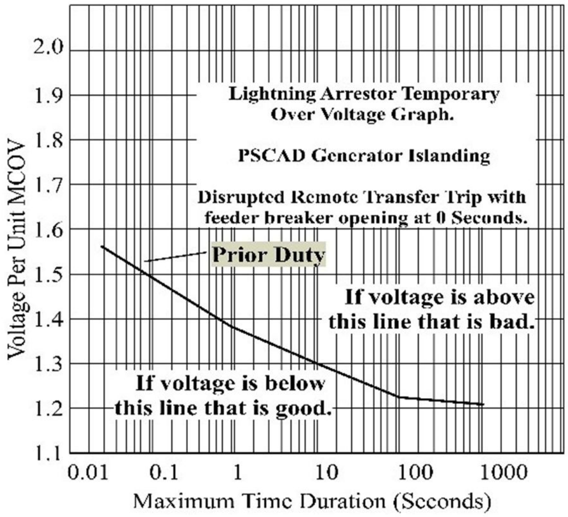

Figure 7. Prior Duty Curve.

This section concerns Lightning Arresters and how their TOV curve is exceeded and consequently how Lightning Arresters are stressed on a separated and islanding collection circuit within a solar power plant. The purpose of the Lightning Arrester is to limit the voltage rise during transient overvoltage that occurs during a switching event or a lightning strike. Lightning Arresters also provide protection for TOVs with longer durations than transient overvoltages. The Institute For Electrical and Electronic engineers (IEEE) standard C62.11 defines a temporary overvoltage 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 Arresters limit the peak voltage on collection circuits within the SPP or WPP and on the interconnected transmission system. They come with a given

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TOV curve called a “duty curve” that can be found on a graph supplied by the manufacturer. The graph shows the 50hz–60hz thermal stability of the Lightning Arrester relative to an applied withstand voltage vs. time. 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 Arrester’s duty conditions. The test includes several voltage levels applied across a sample of the representative arrester 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 loss of watts. There are five to six TOV tests performed for periods 0.01 seconds, 0.1 seconds, 1 seconds, 10 seconds, 100 seconds,1000 seconds, and 10,000 seconds. Each sample passes when it exceeds the manufacturer’s specified duty curve and demonstrates thermal stability. When a feeder is separated from the plant with the generators still running and attempting to produce approximately 20 MW, the PSCAD simulations show that the TOV duty curve is typically exceeded regardless of the V-I characteristic used, and the path to ground for that “attempt” of power production would be through the

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Lightning Arresters. At this point, the arrester can fail short or open, depending on failure mode.

Concerning failures, thermal stability of the Lightning Arrester is critical. If the voltage applied across the arrester from line to ground causes it to burn up, the results could be disastrous. So Manufactures test Lightning Arresters with applied overvoltages and watch them heat up. The Lightning Arrester is subjected to overvoltage during testing, and it gets hot. If the temperature runs away within 100 milliseconds with the applied voltage, the arrester is found to be thermally unstable, and damage is likely. The United States Nuclear Regulatory Commission reports that a station class arrester typically does not fail open when it exceeds the given TOV specifications. However, the arrester will be damaged, and its V-I characteristic will change. Thus, we must consider that the insulation coordination for the affected feeder would be lost when the Lightning Arrester is damaged. See Figure 7 above.

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3.1 Not All V-I Curves Are the Same

Lightning Arresters come with a V-I curve representing an 8/20 microsecond lightning strike [1][1]. We find the residual voltage applied for a Lightning Arrester's V-I curve is higher than the same Lightning Arrester's TOV curve. This point is important: not all V-I curves are equal.

This makes sense, since the TOV voltages are applied to the arrester for periods of time that are longer than a lightning strike. A Lightning Arrester has a certain energy rating, given in kilojoules per kilovolt. For example, a station class arrester rated at 22 MCOV has an energy rating of 10 kiloJoules per kiloVolt. This means that the energy rating of the arrester is 220,000 Joules. This rating is derived from testing the Lightning Arrester's thermal stability. "Thermal stability" refers to the energy (in this case Volts × Amps × seconds) that can be applied to the Lightning Arrester until temperature within the arrester climbs rapidly and the arrester is damaged. What TOV testing does is to test for thermal runaway. A TOV test is performed for thermal stability over time at an applied voltage. The higher the applied voltage, the hotter the Lightning Arrester is going to get until it reaches thermal runaway.

[1] Diaz R., Fernandez F., Silva J., "Simulation and test on surge arresters in high-voltage laboratory", Paper presented to IPST 2001.

Why is this important? To answer, let's return to the lightning strike. Residual voltage due to a lightning strike manifests as a traveling wave and not a standing wave Voltage. The traveling wave is of shorter duration than a TOV and the Lightning Arrester has little time to heat up. However, even with lightning strikes they still get hot.

Standing waves occurs in a TOV event. We must make a distinction between the two, or that lightning strikes causes a traveling wave and TOV is so long in duration they are seen as part of the standing wave. Here we are focusing on TOV events. We estimate the current from the applied voltage and the resultant heating of an arrester for these longer-term events which are measured and tested for up to 10,000 seconds. We find the V-I curve by knowing the prior duty curve for a given Lightning Arrester and correlate it to its published energy handling capability in kJ/kV. In other words, we can estimate the tested TOV current through the Lightning Arrester by knowing the outcome of these tests.

So how do we do this?

We take the continuous operating voltage of the Lightning Arrester and multiply that value by the "kiloJoules per kiloVolt" specified by the manufacture and divide that by the thermal stability limit in seconds to get the power dissipated through the arrester for that test.

Then we divide this result by the applied voltage in the prior duty curve. This will give us an approximation of the current through the Lightning Arrester. When we do this the V-I curve for the arrester is much lower than the published V-I curves for lightning strikes. This means the Lightning Arrester will dissipate more energy and at lower voltages for TOV. An example calculation is given to estimate the current for TOV conditions using a typical prior duty V-I characteristic for a 24MCOV Lightning Arrester.

$$\mathbf{I_{TOV} = [10kJ/kV \cdot 24(MCOV)kV \cdot V_{PU\text{-}MCOV(Time\text{-}prior\text{-}duty)}] \div Delta_{Time\text{-}prior\text{-}duty\ (1)}}$$

Taken from a published prior duty curve, Table 4 below provides the estimated current through the Lightning Arrester to maintain thermal stability[2].

Why is this important? The published V-I curves for Lightning Arresters are for an 8-microsecond/20-microsecond pulse. TOV is from .01 to 10000 seconds and

[2] Data from Cooper Power Systems UltraSILTM polymer-housed VariStarTM surge arrester data sheet – 235-5, August 2014

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may lead an engineer to expect that a wind power plant (WPP) may ride through when it will not. Table 4 shows the difference in values.

Table 4. V-I Characteristics Calculated vs. Lightning
For the same Voltage, Temporary "TOV" energy dissipated
is much greater than lightning energy dissipated.

Prior Duty Curve 24MCOV				Lightning	
	Vpu (MCOV)	Time (Seconds)	Estimated Current (Amps)*	Vpu (MCOV)	8/20 µs Pulse (Amps)
1	1.518	0.01	658.7615283	1.518	10
2	1.436	0.1	69.63788301	1.436	1
3	1.359	1	7.358351729	1.359	0.01
4	1.286	10	0.777604977	1.286	0.0003
5	1.217	100	0.082169269	1.217	0.0001
6	1.151	1000	0.008688097	1.151	0.00007
7	1.089	10000	0.000918274	1.089	0.000005
***Double this current to estimate peak for one power pulse less than 0.01 seconds**					

Table 4 shows that the feeder voltage will be clamped below 1.436 at near 70 Amps. Considering a 34.5 kV feeder circuit, this corresponds to a power level of 6 MVA. If there are parallel arresters conducting at higher or lower currents with all collection circuit feeder circuits closed(Generally 3 to 5 Feeders per Plant), we will find that the power dissipated at these voltages is cumulatively higher.

For example, if there are 5 feeders, then there will be at least 5 arresters per phase where we know that one arrester would take most of the burden. However, we could say there would be an "average dissipation of energy" to perform a simple

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analysis. For example, if we have station class arresters on five feeders on each phase with 10 kJ/kV rated at 24 MCOV, each arrester would be rated to dissipate 240,000 Joules. This is tabulated in Table 5.

Table 5. Arresters' Cumulative Dissipation of Energy.

Prior Duty Curve			
	Vpu(mcov)	Time (Seconds)	Estimated Current (Amps) 5 Parallel Arresters
1	1.518	0.01	3294
2	1.436	0.1	348.2
3	1.359	1	26.79
4	1.286	10	3.889
5	1.217	100	0.4108
6	1.151	1000	0.04344
7	1.089	10000	0.004591

Concerning high voltage Ridethrough, the worst-case calculated voltage rise on a feeder collection circuit is 1.31 pu on a 19.920 kV base. Concerning a 22MCOV arrester, this value equals 1.19 pu with a 22kV base. The current is estimated to be near 0.8 Amps and total power dissipation by all arresters would be 64 KW. This may cause a relay to pick up on a ground fault and the SPP may not ride through. So the engineer may go to the next higher MCOV value which is 24 MCOV to reduce the arrester current during Ridethrough.

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3.2 Transformer Wye or Delta Does Not Matter

Concerning islanding and TOV (long periods of several cycles of islanding), we find that, if the feeder breaker opens regardless if the converter is configured to delta or wye, the energy and overvoltage components that result are both stressful to the equipment's insulation. The results are nearly the same: either the Lightning Arrester will not allow the voltage to rise high enough to allow Ridethrough, or if it does, islanding may still occur if the feeder circuit is not grounded.

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4 EQUIVALENCING HIDES TOV AND THE VALUE OF THE VDH/GSMI

Industry and government both promote equivalencing the impedances of the collector system that makes up either a solar plant and wind plant, a practice which masks certain constraints and prevents engineers from peering deeper into the consequences of their design. This method can masks certain TOV's on the collection system.

Even with very little equivalencing, we can calculate a voltage rise of 1.4 pu with the PRC-024-2 high voltage Ridethrough requirement of 1.2 pu at the POI. If an engineer were to use equivalencing of the collection system of a WPP or SPP and use one transformer and one generator, he Or she may not calculate the voltage rise-up to 1.4 pu. Instead he Or she may come up with a lower number such as 1.3 pu voltage as an average or aggregate number[3].

This incorrect lower number will in turn prevent engineers from analyzing, discussing, and designing the proper protection for a WPP or SPP that includes a

[3]For equivalencing, see Generic Equivalent Collection System Parameters for Large Wind Power Plant.

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VHS/GSMI and coordination of Dynamic Reactive Power provided by the several inverter-based resource(s) within the plant. The next sections explain why.

In an effort to simplify analysis, several articles have offered to the industry techniques to develop an equivalent representation of the collector system that accurately finds the P and Q consumption within the WPP or SPP. However, such techniques may not point out the specific and complete range of high or low consequential voltages within the WPP or SPP. In the next section we provide a simple circuit theory to show how an equivalent circuit, either in series or parallel, can mask the voltage rise and reactive power flows.

4.1 Series Equivalencing Masks the Importance of a VDH/GSMI

In the simple equations below, a given I (Amps) is known as well as Z1, Z2, and Z3 on a given feeder. Where Z1 represents the feeder home run cable, and Z2 and Z2 are branch cables impedances on the same feeder connected in series with wind turbines or inverter based resources connected. We wish to find the change in voltages across the three impedances as the current flows through.

$$\Delta V = I(Z1+Z2+Z3) \quad (2)$$

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Z1 is at the beginning of the string and Z3 is at the end. We can equivalence the string and then find ΔV.(3)

$$Zeq=Z1+Z2+Z3 \quad (4)$$

$$\Delta V=I(Zeq) \quad (5)$$

We do not know what the voltages across Z1 and Z2 are. We presume for good reason they are less than the voltage at Z3. However, there are other items to consider, such as the tap position of a GSU at Z1 and Z2 and Z3, not all which may have been considered. Why not? Because it is a general practice to equivalence the feeder collection circuit. This could create a difference in voltage of over 8% across a GSU, given that an inverter-based resource is dynamically limiting its reactive power, causing a difference of 0% to 5% from the equivalent model. The difference in taps settings across the feeder could create a difference of 5% from the equivalent model. Concerning an equivalent model, individual tap settings are by definition not evaluated in the analysis. The consequence of this is that the error in voltages could exceed 10% for steady state conditions.

Because of the Western Electric Coordinating Council (WECC) REGC model, it is at least known that if equivalencing is used, the error in dynamic reactive support from an inverter-based resource is significant. An individual generating unit could

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actually be dynamically inductive when the equivalent generator model showed it was dynamically capacitive and we do not account for individual tap setting.

WECC provides for this limitation in their REGC[4] model of a dynamic resource. In addition, if an entire collection circuit was simulated with REGC in mind, it is expected the model would provide a more accurate answer. If the collector was equivalent, then some information would fall through the cracks.

Regarding the On-Line-Tap-Changer (OLTC) on the main plant transformer, equivalencing does not include the tap setting of every GSU in each feeder collection circuit. Consequently, there may be individual generator units that are dynamically "reactive limiting" in order to keep their voltages within a desired operating range and do not provide the reactive power anticipated. Because the method of equivalencing was used, the engineers are unaware of the severity of this dynamic constraint. If the OLTC is included to an equivalent model and the operator locks out the OLTC after the plant is commissioned, the steady state error could go significantly higher.

[4] WECC Second Generation Wind Turbine Models, January, 2014.

4.2 Equivalencing and the VDH/GSMI

So how does equivalencing the collector system hide key features of a VDH/GSMI? To answer the question, we will first discuss what the VDH/GSMI provides. The VDH/GSMI protects both the bulk electric system (BES) and the equipment within the WPP or SPP by opening and clearing and then closing and grounding a faulted feeder circuit. The first part of a single operation protects the balance of the WPP or SPP and the BES. The second part of the same operation protects the individual generating unit on the affected feeder by forming a three-phase bolted ground during both high and low voltage Ridethrough conditions. Equivalencing may incorrectly tell the Engineers that the voltage at certain Generators is projected lower than actual, therefore the Engineer may not choose to use a VDH/GSMI when he Or she needs one.

4.3 Indirect Benefits Provided by the VDH/GSMI

Some benefits provided to the BES by the VDH/GSMI are indirect. The VDH/GSMI, regardless of high, low, or zero voltage Ridethrough conditions at the POI, provides the engineers who are programming or setting the protective relays the opportunity at each individual generating unit to trust that a very low impedance and a low voltage will appear at the terminal of each unit when the affected feeder separates from the BES. This is unlike other typical breakers which open and provide uncertainty during islanding conditions(See Figure 1).

4.4 Over-Optimistic Equivalent Preliminary Models

Generally, the engineer uses a generic equivalent model of the collector system for preliminary power system studies of WPPs and SPPs connected to the BES. The model incudes the main plant transformer (MPT) and an equivalent model of the sum of the individual generator units(IGUs). The equivalencing does not include individual tap setting or cable conditions. The results may include an increase in significant modeling errors in plant performance during high voltage Ridethrough conditions. Such errors may include lower simulated voltages and overestimating dynamic reactive support during high voltage Ridethrough conditions. Actual values of voltage within the plant may be higher and the reactive power support significantly lower than predicted in the preliminary study. A preliminary study using equivalencing may cause engineers to under-design the WPP or SPP, mis-coordinate protection settings, and purchase the wrong equipment. This may include choosing Lightning Arresters with an MCOV rating that can be either too high or too low to protect a collection circuit feeder that is separating from the BES.

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4.5 Feeder Separation and Lightning Arresters

For reasons previously presented, the single line phasor model used for calculation do not reveal or predict the burdens placed on the individual generating units during high voltage Ridethrough conditions. For example, the calculated voltage during high voltage Ridethrough conditions at the point of interconnection is 1.2 and the worst-case feeder voltage is projected to exceed 1.3 pu before the feeder separates and an equivalent model that does not include the collector system and individual taps settings. As a result, an equivalent model may erroneously show this value to be lower. In PSCAD we model short collection cables that make up the feeder and two IGUs with different sizes and Tap settings where the collector cable and the different Tap setting impact the voltage seen at each inverter. In addition, we can make one inverter smaller than another, so we can look at different cases normally not considered.

However, concerning both the calculated model or the PSCAD models, a typical Lightning Arrester is not expected to conduct even if the generators are producing 100% active power. Yet, the more detailed calculations that include the collection cable show the voltage at the low side of the GSU is expected to exceed 1.4 pu. This means the PSCAD model should show nearly the same for steady state conditions and show an individual generating unit is expected to remain on line and support the BES. with the inverters trip threshold voltage higher than 1.4 pu.

With the above inn mind, what the PSCAD simulation re expected to show is the voltage rise during transient conditions that calculations will not, and the subsequent conducting or a Lightning Arrester.

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5 PSCAD SIMULATION

The PSCAD simulations are presented to show how the VDH/GSMI provides superior protection over a typical circuit breaker. The PSCAD simulations illustrate how the VDH/GSMI provides better Ridethrough and anti-islanding functionality than a typical circuit breaker for a solar power plant. The PSCAD model projects a typical breaker will cause islanding where a VDH/GSMI will not.

5.1 PSCAD Simulation Cases

Concerning the two configurations, we simulate a few scenarios. The first case begins with a high voltage Ridethrough simulation of the POI voltage going from 0.95 to 1.2 pu. We see what happens to the inverters within the SPP when all breakers remain closed during high voltage conditions. In the 2nd case we look at the voltage rise and islanding that occurs with a typical breaker. For the 3rd case we look at is how the VDH/GSMI solves the islanding problem.

Last, we provide several cases with several PSCAD simulations that project the switching voltages at both the high and low side of the GSU or at the main terminals of the inverter caused by the switching (opening) under load of a typical

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breaker, or by the switching of a VDH/GSMI with various ratings of a Lightning Arrester's MCOV.

5.2 PSCAD Model

Figure 8 below is for Cases 1 and 2. It shows along with Figures 14, 15, and 16 what happens during high voltage Ridethrough at the POI of 1.2 pu and the switching transients caused by the opening of the typical breaker. We use two different MCOV ratings of a Lightning Arrester to simulate the voltage magnitude of the switching transients.

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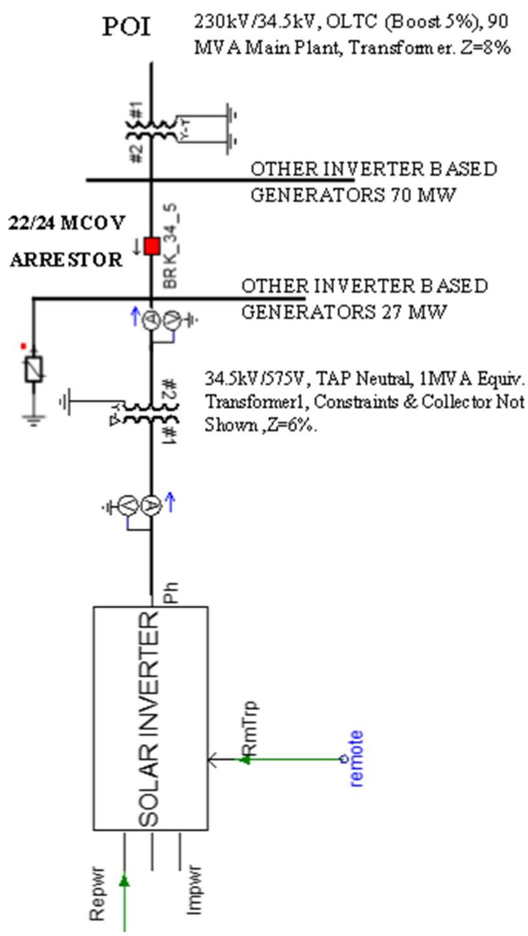

Figure 8. PSCAD, High Voltage Ridethrough Configuration (POI Near 1.2 pu).

Figure 9(next page) depicts Case 3. We see with figure 14 in mind how a VDH/GSMI prevents prolonged islanding of a feeder circuit(Approximatly 12ms). The circuit is very similar to 8, except that we use the grounding capability of the VDH/GSMI.

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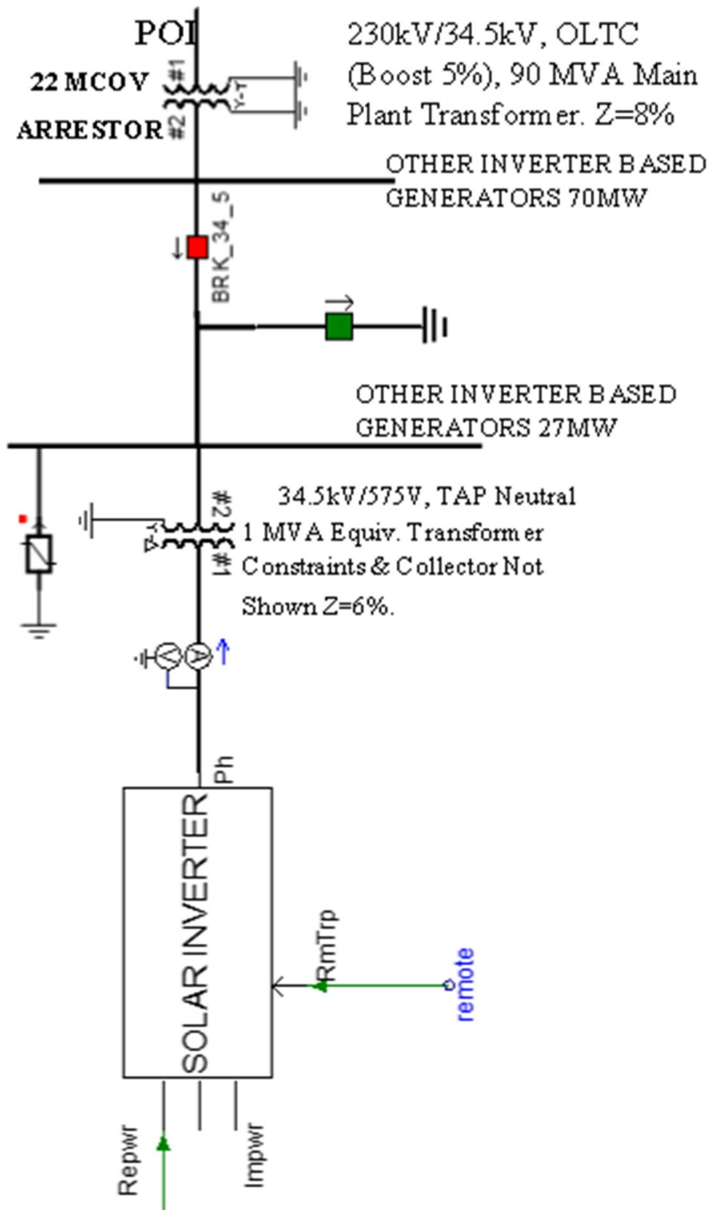

Figure 9. PSCAD VDH/GSMI Configuration.

Concerning the PSCAD simulations, we have one feeder circuit divided into two circuits. We then use two equivalent feeder circuits for a 100 MW plant. Turning back to our feeder circuit we are simulating, we see it has two circuits. One has a 1MW inverter and the other has an equivalent circuit with an aggregate 27MW inverter-based resource (IBR). The two are joined by a 1000mcm feeder collector cable that goes from the coupled IBR to a collection circuit feeder breaker. The collection circuit feeder breaker is either modeled after a typical breaker (Figure 10) or a VDH/GSMI (Figure 11). The inverter's step-up transformer is configured delta on the low side and wye grounded on the high side. (See Figure 3 and Figure 4.)

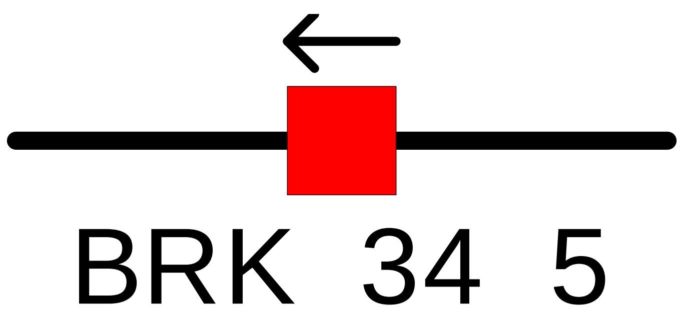

Figure 10. PSCAD Typical Breaker.

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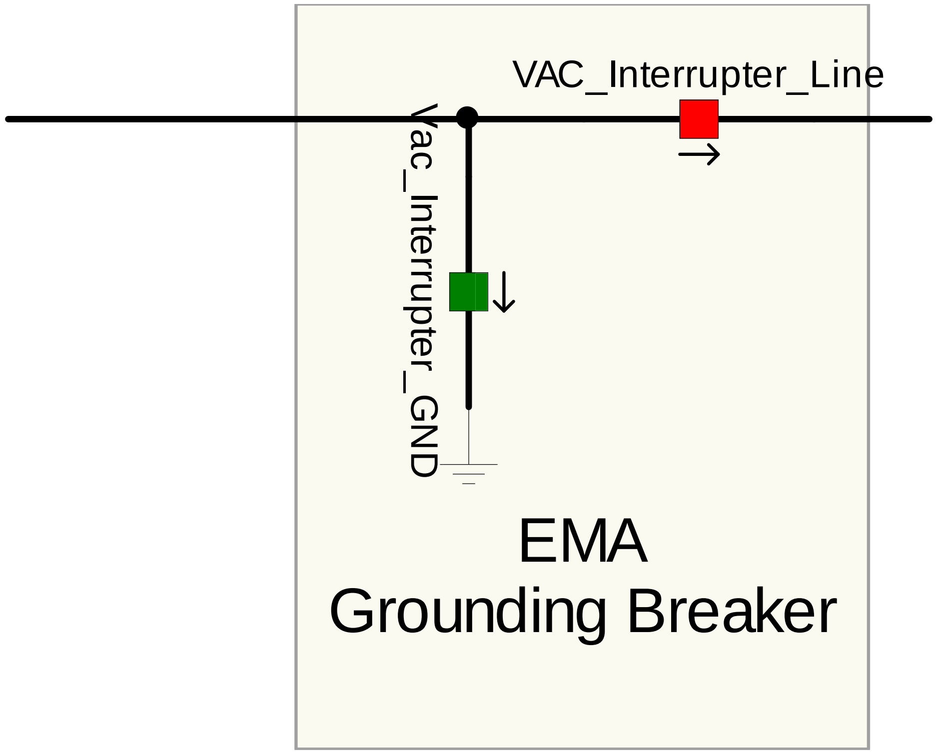

Figure 11. PSCAD VDH/GSMI.

Concerning emulating the solar inverters, Figure 8 and Figure 9 show a PSCAD near equivalent single line for each simulation. The model emulates the IBR of a SPP. The inverter model as a generator uses 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 approximate to a 75MW group of feeders, and the other is 28 MW. The feeder where we open the main circuit breaker could be a VDH/GSMI or a typical circuit breaker

Figure 12 is a model of the timing of the relays used to open and close the appropriate breaker. For example, in a simulation, the Vac_Interrupter_Line signal

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causes the line breaker in the VDH/GSMI to open. Then the Vac_Interrupter_Gnd signal causes the VDH/GSMI grounding breaker to close. The time between switching is approximately 12 ms.

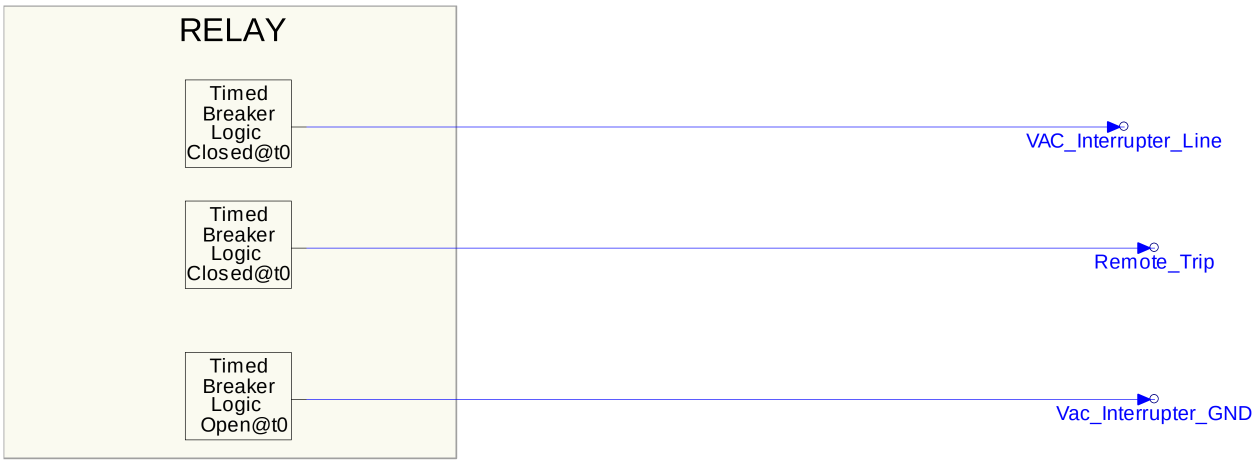

Figure 12. PSCAD Setup to Control the Breakers.

The model begins with a very strong source rated greater than 1000 MVA with the voltage either at 1.199 pu or above to model PRC-024-02 Ridethrough conditions. In addition, we simulate the 0.95 POI low voltage case, and after a given time the voltage rises up to 1.2 pu on the POI with the main plant transformer (MPT) boosting the collector system voltage by 5%. The MPT (Figure 13) 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

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MW, and the faulted feeder is set to produce at up to 28 MW. Reactive power is set to flow anywhere from near zero to 30% sourcing capacitive to an inductive load. Depending on the simulation, that value is adjusted. The voltage at the POI is set at anywhere from 0.95 pu to 1.2 pu.

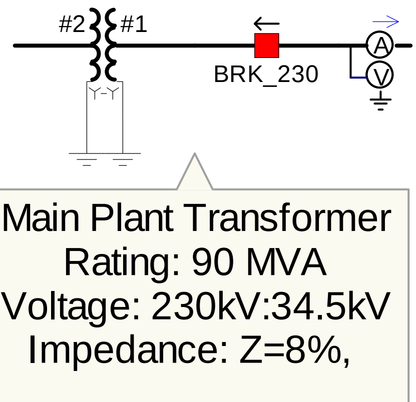

Figure 13. PSCAD MPT Model.

5.3 PSCAD Simulation Results

Case 1. Multiple inverters are grouped into one block, we use a Typical Circuit Breaker with the POI voltage rising to 1.2 pu to evaluate the voltages on the Collection Feeder Circuit when a typical medium voltage (34.5 kV) circuit breaker opens. We use two different MCOV ratings of a Lightning Arrester to simulate and project the voltage magnitude of the switching transients. The results (Figure 14) for Case 1 show that the GSU transformer saturates, and the voltage on the low side of the GSU does not rise high enough to guarantee that the Inverter Based

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Resource will know to shut down. The voltage at the inverter rises to about 1.35 pu. This is below the expected and calculated value of 1.4 pu. These results suggest that the inverters may ride through; however, the next case shows that we need some other method of signaling when to ride through a high voltage event and when a typical collection circuit feeder breaker will not work.

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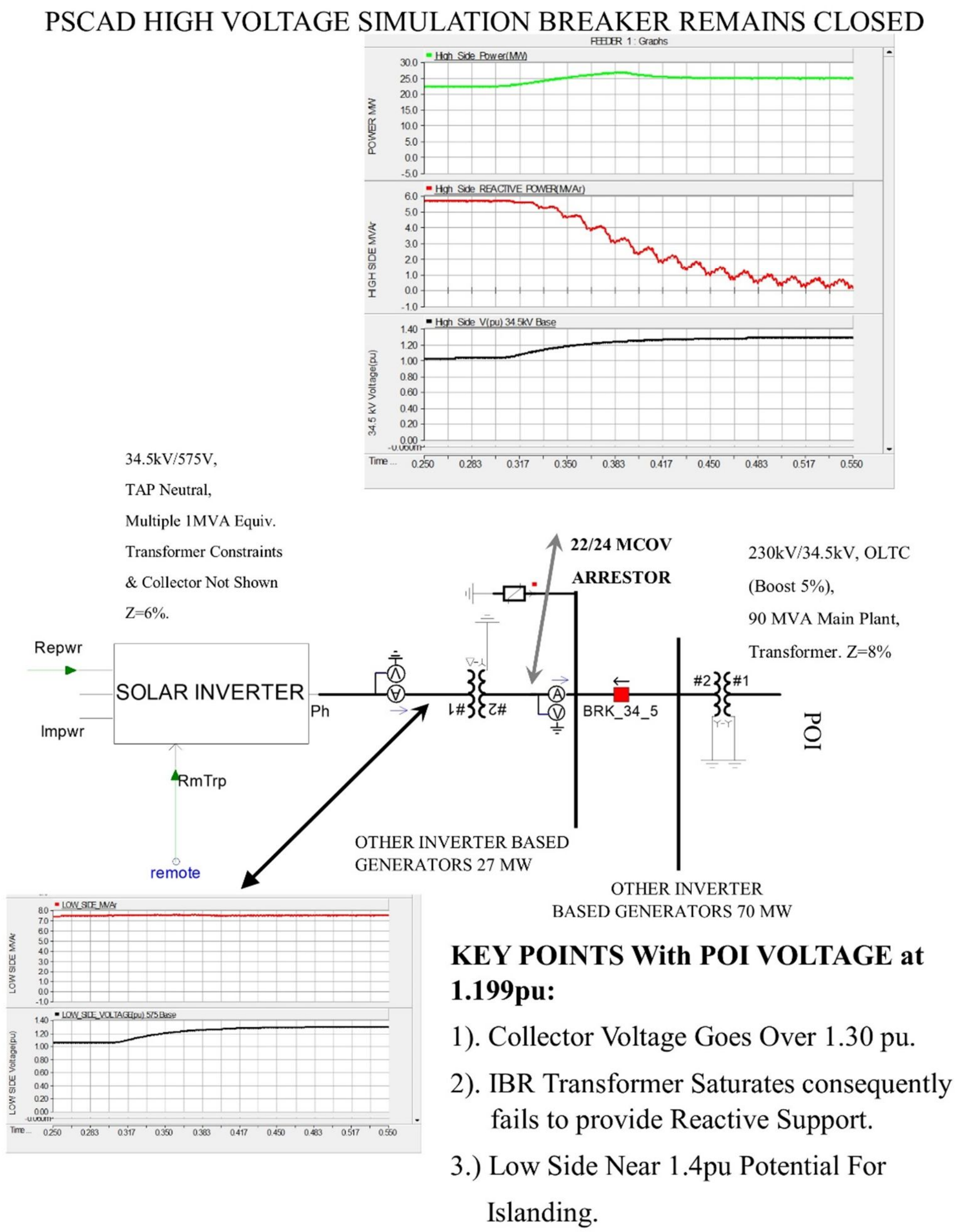

Figure *14.* PSCAD Simulation Results*:* High Voltage *Ridethrough*, Breakers *Remain* Closed. Notice the Transformer Saturation.

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Case 2. (See Figure 15.) Is a simulation focused a single 1 MW inverter where we use a Typical Circuit Breaker with the POI voltage rising to 1.2 pu to evaluate the voltages on the Collection Feeder Circuit when a typical medium voltage (34.5 kV) circuit breaker opens. The results show that the inverter is around 1.4 pu when a typical breaker opens. This voltage is below the calculated voltage rise for Ridethrough. These results suggest that the inverters will require some other method of signaling when required to ride through or shut down and prevent islanding. These results show that a typical collection circuit feeder breaker will not work, because it may not turn off an island.

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PSCAD HIGH VOLTAGE SIMULATION TYPICAL BREAKER OPENS

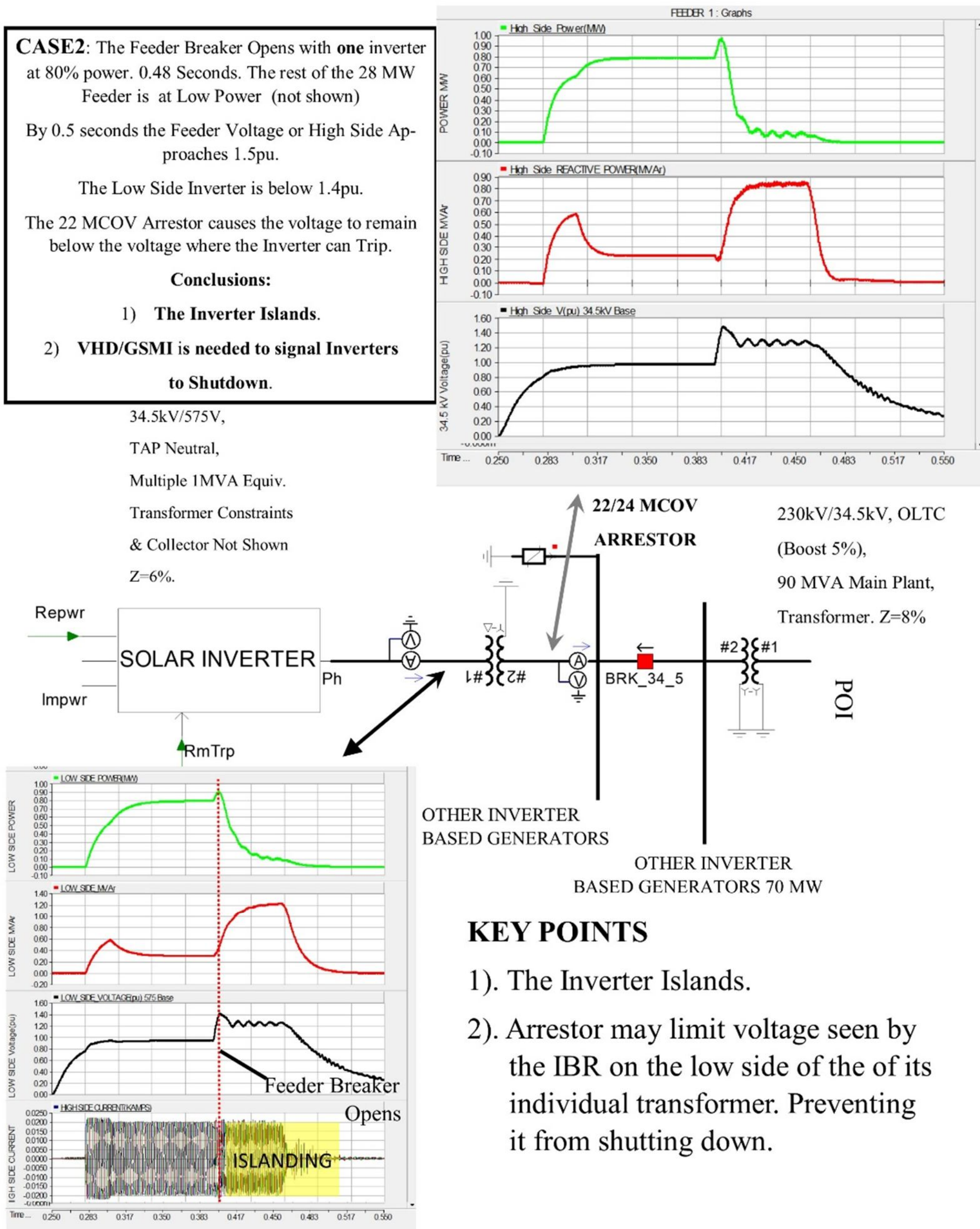

Figure *15.* PSCAD Simulation with Typical Breaker and Islanding *Due* to *Ridethrough* Requirements.

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Case 3. (See Figure 16.) In this simulation we change out the typical breaker for a VDH/GDMI and where the PSCAD simulation resolves islanding. The results show the inverter's voltage at its mains is around 1.2 pu when the VDH/GSMI operates and grounds. The results show the VDH/GSMI will work for both Ridethrough and prevent islanding of a feeder collection circuit. Figure 17 is the same configuration however this time the voltage for the POI, 34.5 kV Substation and 34.5 kV Feeder are shown in the Graphs on the upper right corner. Notice they are at 1.3pu as predicted in the calculations. Again, the VDH/GSMI does what is expected and that is very good thing, because the VDH/GSMI causes the Voltage to quickly collapse on the Feeder once it Grounds. A typical Circuit Breaker will not do this.

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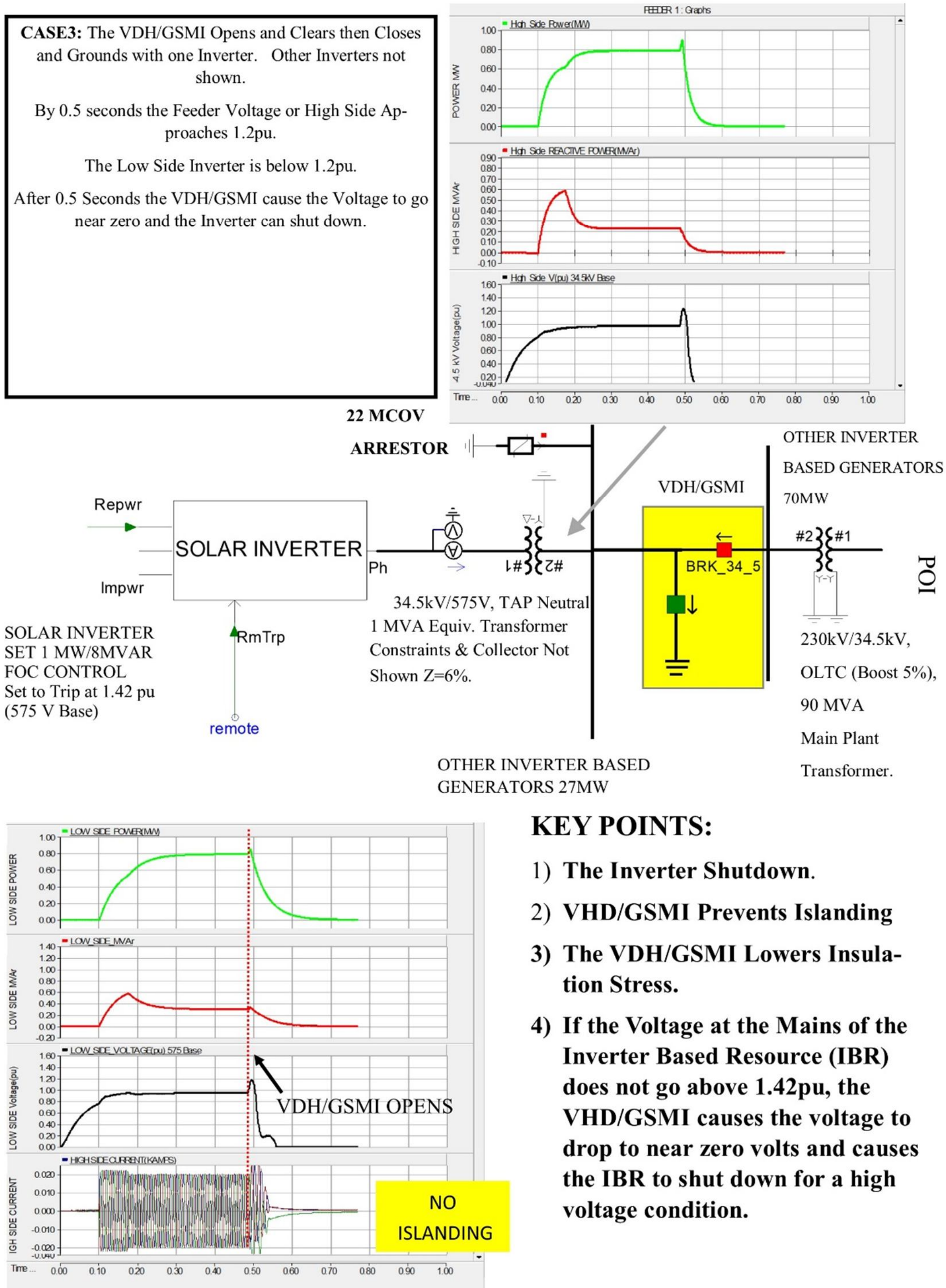

Figure 16. PSCAD Simulation of a VDH/GSMI. No Islanding.

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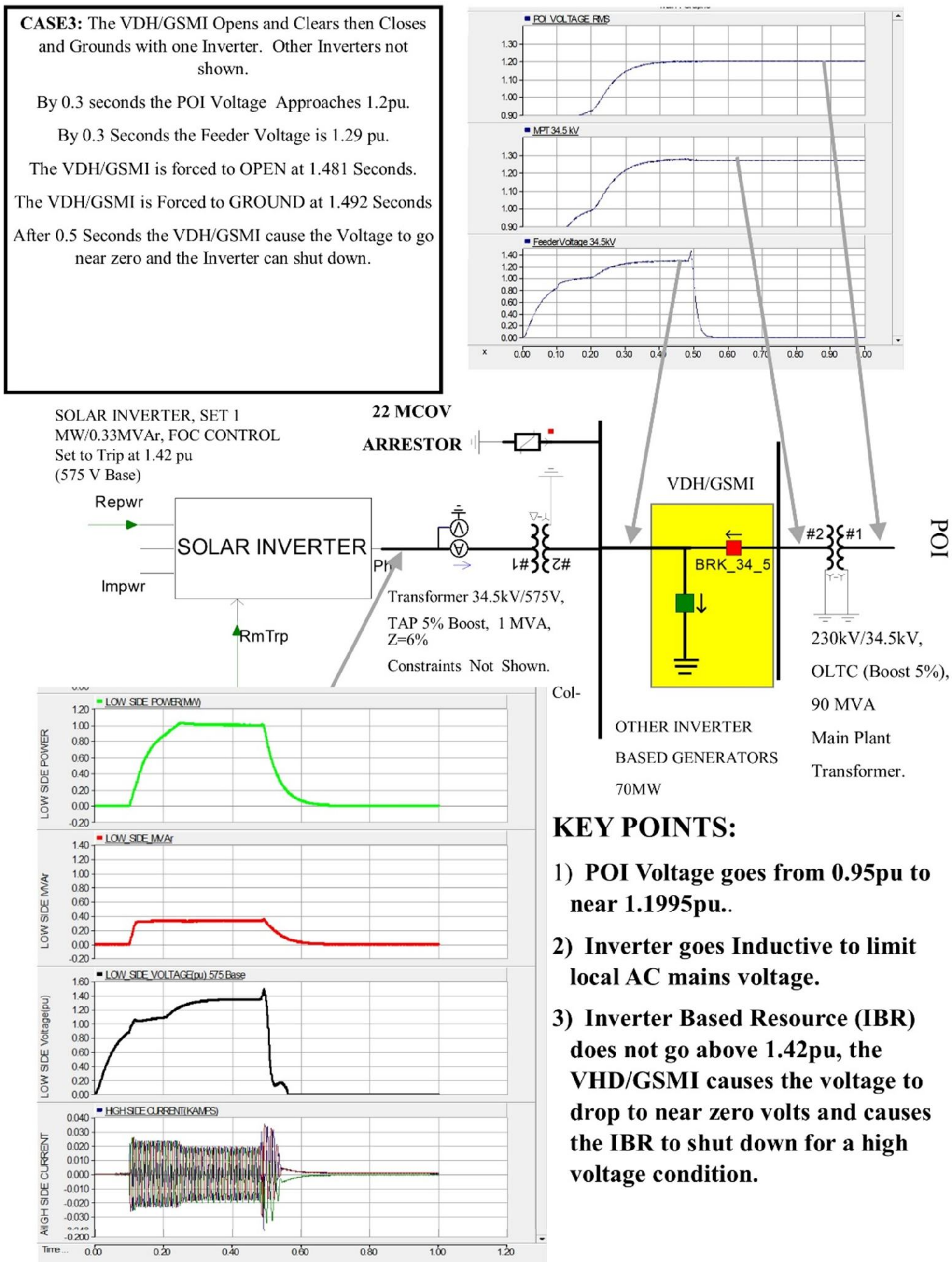

Figure 17. VDH/GSMI Provides a Faster and Clearer Signal Than a Typical Feeder Circuit Breaker For PRC-024-2 High Ride-Through Compliance

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5.4 PSCAD Lightning Arrester Model

This paper shows that, for a given Lightning Arrester's V-I curve, the TOV V-I curve is much lower. Depending on the operating conditions of the Lightning Arrester which protects the insulation of a WPP or SPP, they may cause nuisance tripping of the plant during PRC-024-2 high voltage Ridethrough conditions. This paper uses a lower V-I characteristic for the Lightning Arrester model.

5.5 Several Cases Tabulated

The tabulated cases below (Table 6 and Table 7) are derived from the PSCAD simulations. They show the difference in the performance between a typical breaker (Table 6) or VDH/GSMI (Table 7). The tabulated PSCAD simulations show that a typical breaker is plagued with high voltage Ridethrough-related islanding problems. They also show the VDH/GSMI lowers transient voltages, thereby protecting the insulation and preventing islanding.

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Table *6. High Voltage Ridethrough Simulation with a Typical Breaker.*

High Voltage RideThrough PSCAD Simulation with a **Typical Breaker. I.G.U** (GSU) Transformer is in saturation Its Tap is set at 5% Buck.

I.G.U. Plant Power Setting	I.G.U. Trip Set	Interconnect Voltage. Location 1	**Collector 22MCOV**		Low Side IGU		
			CLOSED Locations 2 & 3	SWITCHING Locations 2 & 3	CLOSED Location 4	SWITCHING Location 4	Result
100%	1.42 pu	1.199 pu	1.25 pu	1.53 pu	1.20 pu	1.44 pu	Shutdown?
50%	1.42 pu	1.199 pu	1.25 pu	1.54 pu	1.19 pu	1.44 pu	Shutdown?
25%	1.42 pu	1.199 pu	1.25 pu	1.54 pu	1.18 pu	1.41 pu	Islanding
13%	1.42 pu	1.199 pu	1.25 pu	1.53 pu	1.18 pu	1.40 pu	Islanding

The 22 MCOV Arrestor Clamps the Voltage to below 1.53 pu on the Collector. PSCAD shows at all power levels Islanding is possible without a VDH/GSMI

High Voltage RideThrough PSCAD Simulation with a Typical Breaker. GSU Transformer is in saturation Its Tap is set at 5% Buck.

I.G.U. Plant Power Setting	I.G.U. Trip Set	Interconnect Voltage. Location 1	**Collector 24MCOV**		Low Side IGU		
			CLOSED Locations 2 & 3	SWITCHING Locations 2 & 3	CLOSED Location 4	SWITCHING Location 4	Result
100%	1.42 pu	1.199 pu	1.27 pu	1.76 pu	1.21 pu	1.63 pu	Insulation Damage
50%	1.42 pu	1.199 pu	1.26 pu	1.69 pu	1.20 pu	1.53 pu	ShutDown
25%	1.42 pu	1.199 pu	1.26 pu	1.64 pu	1.19 pu	1.50 pu	Shutdown?
13%	1.42 pu	1.999 pu	1.26 pu	1.60 pu	1.19 pu	1.47 pu	ShutDown?

The 24 MCOV Arrestor clamps the Voltage to 1.76 pu on the Collector. Islanding may not happen however we are not certain as the V-I curve lowers as the Arrestor gets hotter.

High Voltage RideThrough PSCAD Simulation with a Typical Breaker. GSU Transformer is in saturation Its Tap is set at 5% Buck.

I.G.U. Plant Power Setting	I.G.U. Trip Set	Interconnect Voltage. Location 1	**Arrestor with Reduced V-I Characteristic**		Low Side IGU		
			CLOSED Locations 2 & 3	SWITCHING Locations 2 & 3	CLOSED Location 4	SWITCHING Location 4	Result
100%	1.42 pu	1.199 pu	1.27 pu	1.57 pu	1.21 pu	1.45 pu	Shutdown?
50%	1.42 pu	1.199 pu	1.26 pu	1.44 pu	1.20 pu	1.35 pu	Islanding
25%	1.42 pu	1.199 pu	1.26 pu	1.4 pu	1.19 pu	1.31 pu	Islanding
13%	1.42 pu	1.999 pu	1.26 pu	1.238 pu	1.19 pu	1.27 pu	Islanding

V-I curve lowers (e.g. more current at a lower voltage) due to overheating or shorted components.

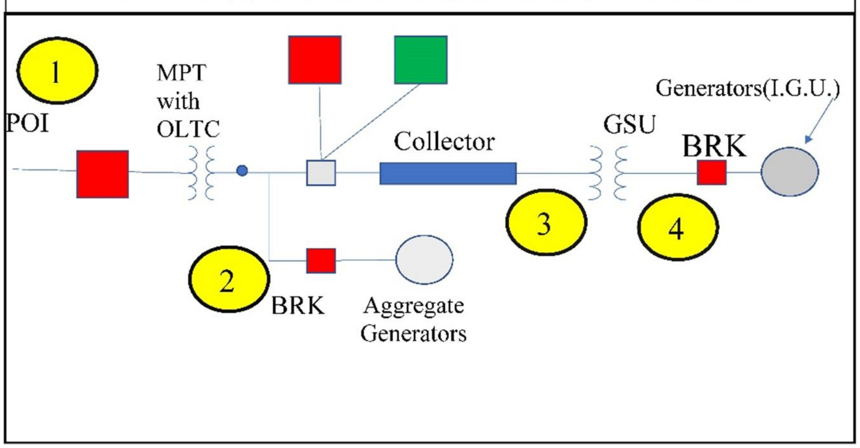

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Table 7. *High Voltage Ridethrough Simulation with a VDH/GSMI.*

High Voltage RideThrough PSCAD Simulation with a VDH/GSMI. I.G.U (GSU) Transformer is in saturation its Tap is set at 5% Buck.

I.G.U. Plant Power Setting	I.G.U. Trip Set	Interconnect Voltage. Location 1	Collector 22MCOV		Low Side IGU		
			CLOSED Locations 2 & 3	SWITCHING Locations 2 & 3	CLOSED Location 4	SWITCHING Location 4	Result
100%	1.42 pu	1.199 pu	1.25 pu	1.49 pu	1.20 pu	1.40 pu	Shutdown
50%	1.42 pu	1.199 pu	1.25 pu	1.43 pu	1.19 pu	1.34 pu	Shutdown
25%	1.42 pu	1.199 pu	1.25 pu	1.44 pu	1.18 pu	1.34 pu	Shutdown
13%	1.42 pu	1.199 pu	1.25 pu	1.40 pu	1.18 pu	1.30 pu	Shutdown

The 22 MCOV Arrestor clamps with the help of the VDH/GSMI, the voltage to below 1.49 pu on the Collector. VDH/GSMI prevents Islanding.

High Voltage RideThrough PSCAD Simulation with a VDH/GSMI. I.G.U (GSU) Transformer is in saturation its Tap is set at 5% Buck.

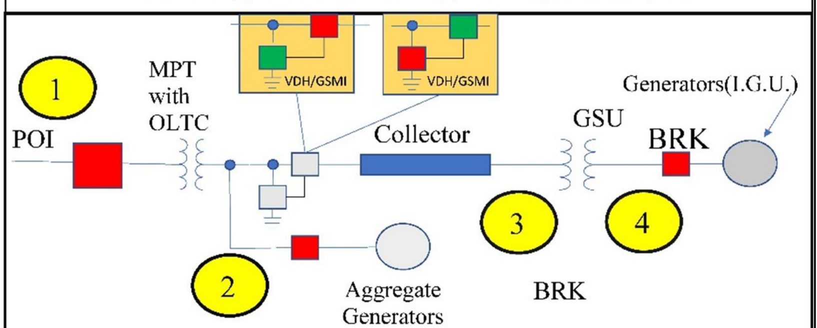
I.G.U. Plant Power Setting	I.G.U. Trip Set	Interconnect Voltage. Location 1	Collector 24MCOV		Low Side IGU		
			CLOSED Locations 2 & 3	SWITCHING Locations 2 & 3	CLOSED Location 4	SWITCHING Location 4	Result
100%	1.42 pu	1.199 pu	1.27 pu	1.54 pu	1.21 pu	1.46 pu	Shutdown
50%	1.42 pu	1.199 pu	1.26 pu	1.49 pu	1.20 pu	1.39 pu	Shutdown
25%	1.42 pu	1.199 pu	1.26 pu	1.52 pu	1.19 pu	1.41 pu	Shutdown
13%	1.42 pu	1.999 pu	1.26 pu	1.49 pu	1.19 pu	1.39 pu	Shutdown

The 24 MCOV Arrestor clamps with the help of the VDH/GSMI, the voltage to below 1.54 pu on the Collector. VDH/GSMI prevents Islanding.

High Voltage RideThrough PSCAD Simulation with a Typical Breaker. (I.G.U.) GSU Transformer is in saturation its Tap is set at 5% Buck.

I.G.U. Plant Power Setting	I.G.U. Trip Set	Interconnect Voltage. Location 1	Arrestor with Reduced V-I Characteristic		Low Side IGU		
			CLOSED Locations 2 & 3	SWITCHING Locations 2 & 3	CLOSED Location 4	SWITCHING Location 4	Result
100%	1.42 pu	1.199 pu	1.27 pu	1.42 pu	1.21 pu	1.31 pu	Shutdown
50%	1.42 pu	1.199 pu	1.26 pu	1.36 pu	1.20 pu	1.28 pu	Shutdown
25%	1.42 pu	1.199 pu	1.26 pu	1.36 pu	1.19 pu	1.27 pu	Shutdown
13%	1.42 pu	1.999 pu	1.26 pu	1.33 pu	1.19 pu	1.22 pu	Shutdown

V-I curve lowers (e.g. more current at a lower voltage) due to heating or shorted components.



6 SUMMARY

The PSCAD simulation (along with the calculations in these sections) show that, for Ridethrough, the voltage at the mains of the inverter or low side of its transformer may exceed 1.4 pu. This will require the high voltage trip point on each inverter to be set to exceed this value to provide Ridethrough capability. The PSCAD simulations show that islanding is likely at various power levels with the set point required to be so high a typical breaker will not resolve this problem. However, the PSCAD simulations show the VDH/GSMI will resolve this problem and help inverter manufactures and solar plant designers provide a BES with required ride-through functionality.

6.1 Projected Voltage Rise Across the Collector

The following is provided as an example of how one can project the voltage rise from the high side of the MPT to the low side of the GSU and see if theory matches the simulations.

6.2 Problem Statement

The initial active power, reactive power, and voltage at the POI is 0.95, 100 MW, 33 MVAr (voltage lagging current) and sourcing capacitive VARs to the BES from the wind power plant. NERC PRC-024-2 requires the WPP to operate up to 1.199 pu during a disturbance on the BES (See Figure 3). The OLTC on the main plant transformer is boosting the voltage 5% (i.e., decreasing the turns ratio by 5%). If the voltage were to rise to 1.199 pu within a few cycles, what is the voltage at the closest inverter-based resource to the substation within the wind plant with only the homerun collection circuit in between? What is the voltage of the far turbines within the wind plant when considering all the cables? If the collection circuit is equivalent, would certain constraints at each individual IBR be masked? (See Figure 18).

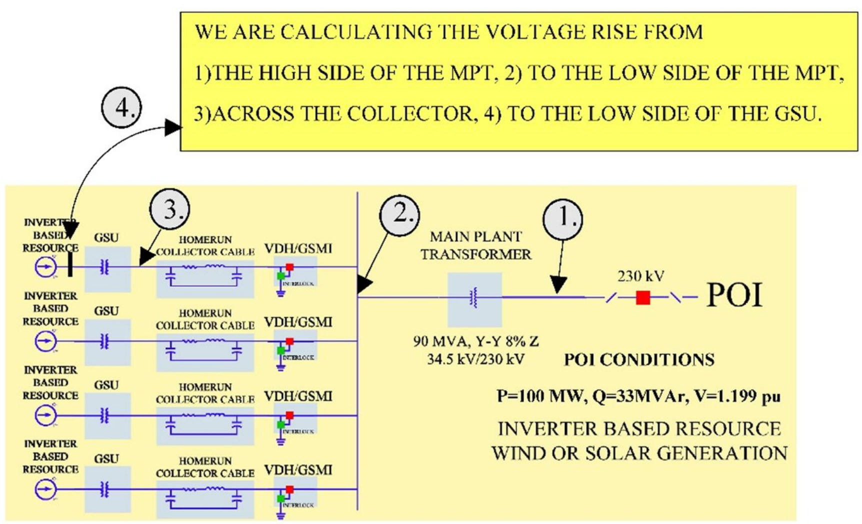


Figure 18. Single Line for Calculations.

6.3 Given Constants and Equations

In order to support the PSCSD simulation results, phasor equations are used to project the voltage rise across the collection system. An example is presented along with equations to calculate the voltage rise.

MPT: 90 MVA, 8% Z, X/R=30, 1 pu, 230 kV/34.5V, OLTC Boost 5% (Reduced Turns Ratio).

HOMERUN CABLE: Note: Values are for a 1000 MCM per km from PSCAD constants program.

R[pu.]: 0.0014280, X[pu.]: 0.015045, B[pu]: 0.0019760. Per unit values based on 100 MVA Base at 34.5 kV.

GSU: 2.5 MVA, 6% Z., X/R=10.1 pu, 34.5kV/690V, TAP 5% boost (Reduced Turns Ratio).

We are going to Start our calculations with P, Q, and V from the High Side or "Receiving Side of the MPT to find the Low Side or "Sending Side P, and Q, and V[5]:

$I\_{Single\_Phase} = (P_{Single\ Phase} + j\,Q_{Single\ Phase})^* / V_{Line\ to\ Ground},\ [V\angle 0\ \text{Deg}]$. **(6)**

$\Delta V = I_{\_Single\_Phase} \cdot Z = I_{\_Single\_Phase} \cdot (\quad + \quad)$ *(7)*

$V_{(Low\ Side)} = [V_{(High\ Side)} + (\Delta V)] / Turns\ Ratio$ *(8)*

$Turns\ Ratio = N \cdot OLTC\_POS$ *(9)*

$N = \underline{Rated\ High\_Side\_Voltage} / \underline{Rated\ Low\_Side\_Voltage}$ **(10)**

$I_{(Low\ Side)} = Turns\ Ratio \cdot I_{(High\ Side)}$ *(11)*

$(P+jQ)^* = I_{(Low\ Side)} \cdot V_{(Low\ Side)}$ **(12)**

*We finish with P, Q, and V on the Sending Side, where t**he following equations:***

$Z = [\%Z \cdot (V_{Line\ to\ Ground})^2] / [MPT\_RATED\_MVA/3]$ *(13)*

$X = Sin \cdot (Arc\ Tangent\ (X/R\ Ratio)\ [Transformer]$ *(14)*

$R = Cos \cdot (Arc\ Tangent\ (X/R\ Ratio)\ [Transformer]$ *(15)*

$Q_{Cap\_Single\_Phase} = \cdot (V_{POI\_Line\text{-}to\text{-}Ground}{}^2 \cdot / X_{cap})$ *(16)*

Concerning Cables, we apportion the power for a given feeder and we use ABCD transmission parameters for calculating P, Q, and V[6]. . For an individual generation unit use the Transformer equation above to find the P, Q, and V "Sending" at the low side mains of the IBR.

---

[5] MPT Main Plant Transformer

[6] $V_S=AV_R+BI_R$, $I_S=CV_R+DI_R$, $A=ZY/2+1$, $B=Z$, $C=Y(ZY/4+1)$, $D=ZY/2+1$.

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The fact that we know what we want from the POI with respect to NERC PRC-024-2 (i.e., 1.199 pu V at 0.95 power factor), and when we know the parameters within each transmission element, using the equations, we can move back into the collection system and find the required current and voltage. Then we find the required active power (P), reactive power (Q), and voltage (V). We will then take the Sending Values of voltage and current just computed and convert them to P, Q, and V and change them to "new" Receiving Values and divide by the number of feeders for the next set of calculations for the collection system. For this next set, we are re-naming the Sending-Values of voltage and current (amps) just calculated at the common node of the low side of the MPT and the collection-system homerun cables to Receiving Values. Consequently, the other side of the homerun cable is named the Sending Value of voltage and current (Amps) for this next set of calculations.

6.4 The Calculated Case

A load shed out on the grid causes the voltage to pop up to 1.199 pu at the POI and PRC-024-2 requires the plant to remain on line. The OLTC does not change tap position and it is boosting the voltage by 5%. What is the calculated voltage at the low side of the GSU with 6% impedance located at an individual generator with 9

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km of 1000 MCM homerun collection cable between the MPT and GSU of the individual generator? From the equation above, the voltage rise is calculated and given in Table 8. The positions are given in Figure 19.

Table 8. *Calculated Voltage Rise Across the Collector.*

Position	1	2	3	4
P	100	100.2 MW	25.172 MW	1.93 MW
Q	33	39.03 MVAr	6.4 MVAr	0.542
V	0.95 pu to 1.20 pu very fast	1.29 pu	1.293 pu	1.38+2=1.4 pu voltage imbalance

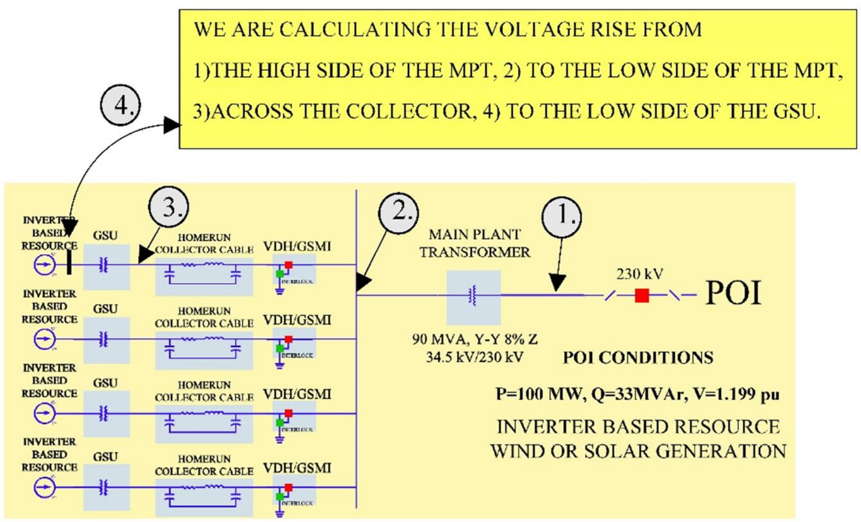

Figure 19. Calculated Voltage Rises.

6.5 Voltage Imbalance

Add a 1 to 2 percent rise for phase imbalance and we get near 1.4 pu at the low side of the GSU for the individual generating unit. The calculations above are for positive sequence symmetrical conditions. With regard to asymmetric conditions

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during a disturbance, the voltage will be much higher than the Lightning Arresters are conducting, and significantly distort the waveform and change the voltage and current crest factors.

Comparing the calculations to the PSCAD simulations, we find we are close. Case 1 would be a good example to compare to the calculations. We see the PSCAD simulations show a voltage between 1.3 and 1.4 pu. We also see the calculated voltage rise is between 1.3 and 1.4 pu.

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7 CONCLUSION

The calculations presented in the previous section are for reference and may not match the PSCAD simulations in all cases. They are just a simple way to express a voltage rise across the feeder collection circuit. Table 9 below is tabulated from several projections concerning PSCAD simulations where the VDH/GSMI 1) opens and clears, then 2) closes and grounds the feeder collection circuit. The table shows that the high voltage conditions on the collection circuit and the VDH/GSMI are resolved. With the VDH/GSMI ground acting so quickly (within 12 ms), the voltage spikes are kept to a minimum.

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Table 9. VDH/GSMI Improves Performance.

High Voltage RideThrough PSCAD Simulation with a VDH/GSMI. **I.G.U** (GSU) Transformer is in saturation its Tap is set at 5% Buck.

I.G.U. Plant Power Setting	I.G.U. Trip Set	Interconnect Voltage. Location 1	**Collector 22MCOV**		Low Side IGU		
			CLOSED Locations 2 & 3	SWITCHING Locations 2 & 3	CLOSED Location 4	SWITCHING Location 4	Result
100%	1.42 pu	1.199 pu	1.25 pu	1.49 pu	1.20 pu	1.40 pu	Shutdown
50%	1.42 pu	1.199 pu	1.25 pu	1.43 pu	1.19 pu	1.34 pu	Shutdown
25%	1.42 pu	1.199 pu	1.25 pu	1.44 pu	1.18 pu	1.34 pu	Shutdown
13%	1.42 pu	1.199 pu	1.25 pu	1.40 pu	1.18 pu	1.30 pu	Shutdown

The 22 MCOV Arrestor clamps with the help of the VDH/GSMI, the voltage to below 1.49 pu on the Collector. VDH/GSMI prevents Islanding.

High Voltage RideThrough PSCAD Simulation with a VDH/GSMI. I.G.U (GSU) Transformer is in saturation its Tap is set at 5% Buck.

I.G.U. Plant Power Setting	I.G.U. Trip Set	Interconnect Voltage. Location 1	**Collector 24MCOV**		Low Side IGU		
			CLOSED Locations 2 & 3	SWITCHING Locations 2 & 3	CLOSED Location 4	SWITCHING Location 4	Result
100%	1.42 pu	1.199 pu	1.27 pu	1.54 pu	1.21 pu	1.46 pu	Shutdown
50%	1.42 pu	1.199 pu	1.26 pu	1.49 pu	1.20 pu	1.39 pu	Shutdown
25%	1.42 pu	1.199 pu	1.26 pu	1.52 pu	1.19 pu	1.41 pu	Shutdown
13%	1.42 pu	1.999 pu	1.26 pu	1.49 pu	1.19 pu	1.39 pu	Shutdown

The 24 MCOV Arrestor clamps with the help of the VDH/GSMI, the voltage to below 1.54 pu on the Collector. VDH/GSMI prevents Islanding.

High Voltage RideThrough PSCAD Simulation with a Typical Breaker. (I.G.U.) GSU Transformer is in saturation its Tap is set at 5% Buck.

I.G.U. Plant Power Setting	I.G.U. Trip Set	Interconnect Voltage. Location 1	**Damaged Arrestor**		Low Side IGU		
			CLOSED Locations 2 & 3	SWITCHING Locations 2 & 3	CLOSED Location 4	SWITCHING Location 4	Result
100%	1.42 pu	1.199 pu	1.27 pu	1.42 pu	1.21 pu	1.31 pu	Shutdown
50%	1.42 pu	1.199 pu	1.26 pu	1.36 pu	1.20 pu	1.28 pu	Shutdown
25%	1.42 pu	1.199 pu	1.26 pu	1.36 pu	1.19 pu	1.27 pu	Shutdown
13%	1.42 pu	1.999 pu	1.26 pu	1.33 pu	1.19 pu	1.22 pu	Shutdown

The Damaged Arrestor Clamps the Voltage on the Collector and causes Islanding and provides questionable Ride-through.

Table 9 (Same as Table 7) is the same data above shows the voltage rise across the collector when the voltage at the POI is at 1.199 pu. The calculations show that the GSU and the MPT are the primary causes of the voltage rise. Even though it

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does not cause a significant voltage rise, each homerun collection cable ends up as a significant source of capacitive reactive power and inductive reactive power. Consequently, the collector cable impacts the needed reactive power from each individual generator unit. This in turn impacts the voltage on the low side of the GSU (see Table 10). Table 10 is the same as Table 1 in the executive summary.

Table 10. Voltage Rise Table.

P,Q,V TABLE **(13 Gen. Units/Feeders, 4 Feeders). Homerun cable for each feeder included in calculations.**				
	POI **Location (1)** ①	**34.5 kV Sub** **Location (2)** **OLTC BOOST 5%** **(52 units)** ②	**34.5kV High_Side GSU** **Location (3) (13 Units)** **(partial equivalence)** ③	**690 V Low_Side GSU** **Location (4) (1 unit)** **All tap to boost 5%** **(partial equivalence)** ④
P	100 MW	100.05 MW	25.05 MW	1.93 MW
Q	33 MVAr	39.15 MVAr	7.1 MVAr	0.61 MVAr
V	V=1.199	1.286 pu	1.304 pu	1.38 pu+2% Phase Imbalance

If we were to reduce the amount of equivalencing we would “see” even more the magnitude of the constraints. Consequently, equivalencing is found to mask certain constraints and the PSCAD simulations and the calculations are for reference. Detailed modeling should be performed. The calculation herein assumes a 60 Hz sinusoid, with the Lightning Arresters conducting the voltage. The simulations and calculations show the relay at each IBR or individual

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generating unit has trouble differentiating between islanding and Ridethrough conditions; the VDH/GSMI solves this problem. Table 5 and Table 10 show that the voltage is rising near 1.4 pu. With either a 22 or 24 MCOV Lightning Arrester in an affected feeder collection circuit, the PSCAD simulations show a VDH/GSMI is required to provide Ridethrough and anti-islanding functionality in order to provide the BES the functionality required by PRC-024-2 and the plant with the proper insulation coordination.

Depending on generating conditions, where one generator may be at lower production than the others, its voltage may stay low enough during islanding that the high voltage threshold of 1.4 pu is not exceeded, and it will remain on-line and islanding. Concerning Ridethrough, if the high voltage trip relay setting at an individual generating unit is set lower than 1.4 pu and there is a requirement for Ridethrough above 1.4 pu, the individual generator will not ride through.

The report asked the questions: "Will Lightning Arresters interfere with the inverter's "high voltage shutdown threshold" at each individual generating unit(IGU) concerning PRC-024-02 for the transient case where the point of interconnections voltage swings from 0.95pu to near 1.199pu? Should generator owners be concerned? If there is a problem does the VDH/GSMI resolve it?

This report concludes through PSCAD simulations the Lightning Arresters as well as local transformer saturation will interfere with the IGU Inverter's "local" capability of detecting when to ride-through or shutdown. This in turn will cause islanding. Therefore, plant owners and operators should be concerned because of the resulting delays and uncertainties from remote signaling; where such delays are in excess of 100ms-200ms. PSCAD simulations also show that the VDH/GSMI resolves this problem by providing a "faster" and "clearer" signal "locally" to each inverter (at each individual generating unit) to either Ridethrough or shut down (See Figure 17).

The VDH/GSMI provides a solution for both islanding and high voltage Ridethrough detection issues because it will ground out the feeder, therefore providing a clear signal to the relay to shut down the individual generating unit during both islanding or Ridethrough at the POI.

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