DER-RELATED TRANSMISSION GROUND FAULT OVERVOLTAGE-PG&E CASE STUDY

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Abstract

Transmission Ground Fault Overvoltage (GFOV) due to Distributed Energy Resources (DERs) is a growing concern as DER generation to load ratios continue to grow. A GFOV can occur when a Single Line-to-Ground (SLG) fault happens on transmission systems upstream from Distributed Energy Resources (DER)-hosting distribution substation. The SLG fault can raise voltage on the un-faulted phases of the islanded portion of the transmission system while collapsing voltage on the faulted phase. The overvoltage is sustained until the DERs cease to energize substation transformers or the fault extinguishes in the islanded subsystem. During this time, the power frequency overvoltage may reach damaging magnitudes, thereby affecting utility equipment. These GFOV concerns have become a barrier for greater penetrations of DER in some locations and typically involve expensive substation protection upgrades. This white paper presents case study results and evaluates both unconventional and conventional mitigation options.

Keywords

Distributed energy resources
Distribution protection
Ground fault overvoltage
Grounding
Inverters
Power system protection
Surge arresters
Transient overvoltage

Case Study Summary

PG&E is concerned by the risk of transmission GFOV due to existing and anticipated DER installations in several substation scenarios. Of approximately 1000 distribution substation transformers, 250 substations have been identified with potential for backfeed and risk of transmission GFOV. Given this scale, it would be costly and time consuming to evaluate all the affected equipment and site-specific mitigations. To quantify the condition and prioritize the evaluations, this study devised models and performed simulations on two sample systems that are representative of the 250 substation scenarios. The primary objectives were to determine if or when high penetration of DER presents a GFOV issue and to assess mitigations options and equipment risk.

A particularly unique aspect of the studied PG&E feeders is the presence of large-scale irrigation motor loads, and the paper studies their impact on GFOV. The GFOV impacts are quantified in terms of phase-to-ground, neutral, and peak RMS voltages at each substation transformer. Surge Arrester (SA) applications and energy dissipation were also studied. Four GFOV protection and mitigation options have been examined: (i) Installing overvoltage protection at the substation (59P phase-to-ground relay); (ii) relying on the DER onboard trip protection (over/under-voltage, over/under-frequency, and islanding detection) to trip; (iii) relying on SAs to reduce the overvoltage to acceptable levels without exceeding the arrester energy handling capabilities; and (iv) employing arrester leakage current monitors on substation arresters to sense excessive leakage current and then trip the medium voltage (MV) feeders disconnecting DER.

The key findings of the study are as follows:

- With DER penetration levels of < 30% (defined as aggregate DER nameplate rating divided by load level), GFOV was not likely to damage SAs. Generation-to-load (G/L) ratios of 67% and greater on the 115kV system and greater than 50% on the 70kV system result in GFOV magnitudes and durations that cause SAs to conduct heavily and likely exceed their energy handling capacity, indicating a need for protection or mitigation.
- In the scenarios studied, the presence of large amounts of irrigation-based motor load contributes to greater GFOV risk. The GFOV characteristics are dependent upon the rating and type (asynchronous/synchronous) of motor. It was also found that in the case where DER was not present, the motor load by itself was shown to increase GFOV risk.
- DER reactive compensation, such as fixed power factor or volt-var, did not have a noticeable impact on GFOV.
- Substation high voltage (HV) protection (phase-to-ground relay 59P) with fast tripping of MV feeder breakers is an effective mitigation of GFOV. Simulations indicate that sensing OV and

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isolating the MV feeder behind the substation transformer is generally fast enough to maintain SA energy within energy handling capabilities and below Transient Overvoltage (TOV) withstand capabilities. The results are specific to the scenarios analyzed and DER with larger aggregate power outputs will lead to increased arrester energy that may hasten arrester failure.

- Although DER trip settings are well defined and tested (per IEEE 1547 or CA R21), voltage conditions sensed at the DER can vary significantly based upon measurement location. Trip settings are considered in the study but cannot be relied upon as a GFOV prevention measure in all cases.
- Arresters that are in heavy conduction due to a TOV event can provide some power frequency voltage suppression. However, this conduction was not sufficient to fully mitigate the GFOV. Assessing the arrester energy handling capability and TOV curves are critical to determine the arrester survivability from a GFOV event. To assess varying degrees of arrester energy sharing, the study analyzed cases with multiple arrester's energy sharing and a single arrester absorbing the entire energy.
- Arrester current sensing may be a viable GFOV detection option. However, it is not yet proven and would require some development in detection technique to avoid nuisance tripping of feeders.

Transmission Ground Fault OV Background

A Ground Fault Overvoltage (GFOV) can occur when a Single-Line to Ground (SLG) fault happens on a sub-transmission upstream from a Distributed Energy Resources (DER)-hosting distribution substation, as shown in Figure 1. Following the SLG fault, the main feeder breaker opens, thus isolating the sub-transmission system and distribution substation. If the high voltage winding of the substation transformer is not a ground source (e.g., grounded-wye winding on the transmission side and a delta secondary or tertiary winding), the isolated zone will not have a zero-sequence grounding path. In the conventional situation, without any generation sources connected to the feeder, this is inconsequential because the feeder is not energized when the breaker is open. However, when DERs are connected to the distribution system or systems served by the islanded transmission subsystem, there is the possibility that energization of the transmission subsystem could be maintained for a short time following opening of the transmission line breaker isolating the faulted transmission line and interconnected substation distribution transformer. During this time, the voltage can increase on the un-faulted phases of the islanded subsystem. This condition is referred to as GFOV. The overvoltage is sustained until the DERs cease to energize the islanded substation distribution transformers. This overvoltage may affect line-to-ground utility equipment such as Surge Arresters (SAs) and must be avoided.

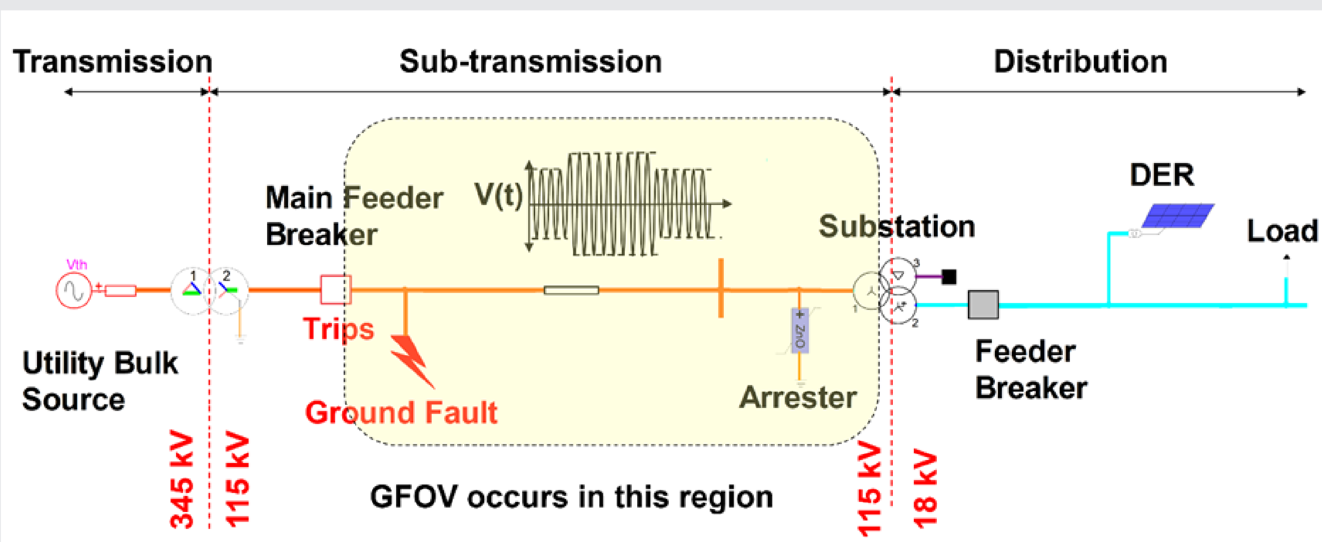

Figure 1. Transmission Ground Fault Overvoltage Scenario with DER (note DER transformer connection to MV assumed but not shown)

Similar scenarios of GFOV can also occur on a faulted distribution system (MV). In this case the connected DER may not have visibility to the ground fault either because it is not a grounded source (such as 3-phase PV inverters) and/or the DER transformer connection does not provide zero sequence continuity. The key difference in the distribution case of ground fault is that the GFO is visible to the DER plant. For a Yg-Yg DER connection the OV is indicated directly to LV terminals. If Yg-Δ at the plant, then this ground source is likely to mitigate GFO. Other transformer configurations will require protective relays on the MV (either 59n or 59p) to directly detect and provide a trip signal to the DER. So, compared to the substation case, there are remedies on distribution. These include supplemental grounding, substation 3VO protection, L-N connected loading, and/or direct transfer trip.[1] This distribution case of GFOV is not addressed in the study although some of the mitigations are common.

In the sub transmission case, DERs on the MV feeders continue to energize the distribution substation following disconnection of the bulk system source. Until the DERs cease to energize MV and trip, the HV to ground can increase on the un-faulted phases upstream of the substation. This overvoltage first affects line-to-ground connected utility equipment such as surge arresters and needs to be mitigated below the TOV withstand levels of all equipment, but it does not affect distribution loads.

GFOV in three-phase power systems occur due to a shift of the neutral point relative to phase voltages. In traditional synchronous generator-dominated power systems, with transmission-connect power plants, GFOV has been mitigated by the substation ground source. That is, the power system is effectively grounded[2] typically by a Δ connection on the transmission side of the substation transformer. This generation-side ground source provides zero-sequence continuity to the fault location. For example, in Figure 1 the bulk system-side delta transformer winding acts as a ground source providing effective grounding prior to the breaker opening. In case of distributed generation, this mitigation is lost when the breaker opens.

With the DER back feeding the MV there is still a source of substation voltage after loss of the bulk system. However, the DERs are isolated from the upstream ground fault making the condition undetectable from the MV side. That is, there is no zero-sequence continuity between the DER and the fault. This then supports line to line voltage on the sub-transmission's unfaulted phases relative to the grounded phase, and result in GFOV.

The ***duration*** of the overvoltage depends on how long the island lasts before the DER's trip. The ***magnitude*** of the overvoltage depends on generation relative to load. If load exceeds generation then voltage is depressed by the excessive load. If generation exceeds load, then the voltage will be increased by over generation. Both depend on the DER and its controls. DER Load Rejection Overvoltage (LROV)[3] response characteristics can contribute to the transmission phase to ground OV. Other influential factors include motor loads and imbalance.

It should be emphasized that LROV inherently involves a generation/load imbalance. Therefore, the island and LROV cannot be sustained for long. In practice, a DER-driven overvoltage is a combination of the above-mentioned two mechanisms. Given the difference in the mechanism of GFOV under DERs and synchronous generators, the classical methods to analyze GFOV exposure do not apply to DERs, and the classical GFOV mitigation options may not apply either.[4] With increasing level of DER integration, utilities need to identify GFOV concerns in their system and develop adequate mitigation options.

This paper evaluates the effectiveness of four alternative GFOV mitigation options, namely: (i) high voltage substation phase-to-ground relay 59P overvoltage protection with Medium Voltage (MV) feeder trip; (ii) DER onboard over/under-voltage (OUV) and over/under-frequency (OUF) protection; (iii) Relying on SAs to reduce the overvoltage to acceptable levels without exceeding the SA energy dissipation rating; and (iv) SA leakage current monitoring in selected high voltage SAs.

[1] *Protection from Unintended Islanding and Substation Primary Ground Fault Overvoltage Caused by DG Infeed, A Summary of Methods, Challenges, and Opportunities.* EPRI, Palo Alto, CA: 2017. 3002011001.

[2] IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems, IEEE Standard C62.92, 2011.

[3] G. Kou et al., "Load Rejection Overvoltage of Utility-Scale Distributed Solar Generation," *IEEE Trans. Power Del.*, vol. 35, no. 4, pp. 2113-2116, Aug. 2020, doi: 10.1109/TPWRD.2019.2951949.

[4] *Effective Grounding and Inverter-Based Generation: A "New" Look at an "Old" Subject*. EPRI, Palo Alto, CA: 2019. 3002015945.

This paper performs a GFOV study on the PG&E electric grid with the following two goals:

1. Determine if or when high penetration DER presents a GFOV problem; and
2. Determine how to prioritize the mitigation and equipment evaluation if needed.

PG&E has over 250 distribution transformers which provide a condition for GFOV. Due to the large number of transformers and equipment involved, it would be costly and time consuming to evaluate all the affected equipment or install mitigation. To quantify the condition and prioritize the evaluations, simulation case studies have been performed on two test systems denoted by Case 1 and Case 2.

GFOV Case Studies

In two selected cases the simulated GFOV event is caused by a close-in SLG fault near the main transmission source breaker and within the Zone-1 or instantaneous protective relay element of the main breaker, followed by opening of the breaker. This leads to the isolation of the network downstream the breaker, thus causing the formation of an unintentional island consisting of the sub-transmission system equipment, distribution substations, and the distribution feeders. DERs on the distribution feeders energize the island through the substation transformers and continue to feed the SLG fault.

This scenario creates a condition for GFOV on the high side of substation transformers, thus affecting the SAs and other phase-to-ground connected equipment at the 70 kV and 115 kV voltage levels in Case 1 and Case 2, respectively. The GFOV impacts manifest themselves in increased phase-to-ground voltage, neutral voltage, and SA energy dissipation at each substation transformer location. In severe cases, the SA energy dissipation may exceed arrester capability, thus potentially damaging the SAs.

Case 1: 70-kV System

The 70 kV sub-transmission case circuit diagram used in the GFOV simulations is shown in Figure 2. Six substations are separated by a main breaker from the bulk system to form the island.

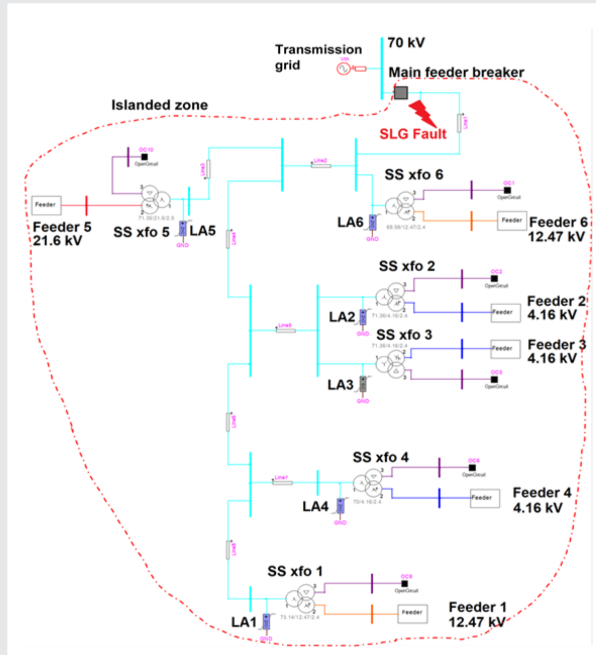

Figure 2. 70kV Circuit used in simulations

In the island six substation transformers connect "equivalent" feeders, one thru 6 and related DER. The equivalent feeders represent the aggregate characteristics of multiple primary distribution feeders served by the substation.

Table 1 provides feeder data including DERs and loads. The DERs consist mainly of residential solar photovoltaic (PV) resources. A large portion of the load consists of irrigation pumps which including small-scale residential as well as large-scale pumps of a large water agency. It has been assumed that the motors are continuously operated. The substation transformers have an ungrounded high side winding and are protected by SAs.

To study GFOV impacts, a simulation model of the test system has been developed within an Electromagnetic-Transient-type (EMT) software. EMT simulations enable adequate representation of DER control and protection schemes, the nonlinear behavior of SAs and transformers, protective relays, and motor loads representing irrigation pumps.

Table 1. Substation load and DER characteristics in 70kV case

Feeder ID	Load (kW)						DER (kW)
	1ph induction motor	3ph 50hp induction motor	3ph 900hp induction motor	3ph 2000hp synch motor	Other	Total	
Feeder 1	0	439	0	11,010	0	11,449	0
Feeder 2	0	219	0	5,505	0	5,725	0
Feeder 3	0	219	0	5,505	0	5,725	0
Feeder 4	0	658	1,579	0	0	2,237	0
Feeder 5	172	4,962	0	0	2,394	7,528	577
Feeder 6	7	2,589	0	0	313	2,909	432
Total	**179**	**9,087**	**1,579**	**22,020**	**2,707**	**35,572**	**1,009**

Modeling Considerations

The DERs have been represented using a generic EMT model of a three-phase PV unit including detailed model of control and onboard protection schemes. To study the impact of DER control on GFOV characteristics, two control modes have been considered, namely constant power factor (PF) and volt-var control per IEEE 1547-2018.[5] The DER model further includes onboard OUV/OUF protection per CA Rule 21 Tariff.[6] These protection functions have been activated in GFOV mitigation case studies. Other DER modeling details include inner current control, current limiter, and dc-link voltage regulation schemes.

A finding of the case study is that motor loads contribute to GFOV and hence need to be adequately represented. Small-scale residential irrigation pumps have been represented as 1 hp single phase induction motors (IMs), agricultural irrigation pumps have been represented as 50 hp three-phase IMs, and the larger pumps of the water authority have been represented by 900 hp three-phase IMs and 2000 hp three-phase synchronous motors (SMs). As Table 1 shows, the SMs constitute the largest portion of motor loads and hence have more influence on GFOV characteristics.

Several SAs exist in the islanded zone of the test system, as shown in Figure 2. Adequate modeling of these SAs is necessary to represent DER energy sharing by SAs during a GFOV. The SAs have a Maximum Continuous Operating Voltage (MCOV) of 48 kV. SA3 arresters are gapped silicon-carbide type which are not likely to conduct with GFOV level and hence have not been modeled. The rest of SAs are station class Metal-Oxide Varistor (MOV) type and have been represented by a nonlinear resistor.

The V-I characteristic of the SAs was not available; hence, a typical arrester V-I characteristic for a station class 48 MCOV arrester was used.[7] For the type of overvoltage seen during a GFOV, the operating region of an SA is in the range of tenths of an Amp to a few hundred Amps. The V-I curve has been represented in more granularity in this region to provide a smoother curve for simulation. In the simulation model, the same V-I characteristic is used for all MOV arresters assuming ideal arrester current sharing. In practice, MOV arresters do not share current well due to actual V-I curve dissimilarity combined with the severe nonlinearity of the characteristics.

Such arrester non-sharing will force most of the duty on the weak arrester, and hence the most severely affected arrester is likely to have even greater duty than shown by this simulation. Given that arrester manufacturers do not publish (or test for) energy capability for the type of long duration overvoltage seen during a GFOV event, an estimate of energy rating at 60 Hz is obtained using typical arrester switching surge energy capabilities. This estimate is 470 kJ for the SAs of the system based on manufacturer datasheet. The

[5] Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces, IEEE Std IEEE Standard for Interconnection 1547-2018, Apr. 2018.
[6] https://www.cpuc.ca.gov/Rule21.

[7] http://www.arresterworks.com/.

Temporary Overvoltage Capability (TOV) characteristic of the SAs is obtained from manufacturer datasheet.

The substation transformer model includes nonlinear magnetization characteristic which is necessary to represent potential transformer saturation under severe overvoltage conditions.

GFOV Simulation Results

A close-in phase-a-to-ground fault has been applied near the main feeder breaker at t=5 s, followed by opening of the breaker in 4 cycles (i.e., at t=5.067 s) and formation of an unintentional island consisting of the sub-transmission system and the 6 distribution feeders. The DERs on these feeders energize the island through the substation transformers and continue to feed the SLG fault, thus causing a GFOV condition. The onboard OUV/OUF protection of DERs have not been activated, and its assumed that the DERs continue to energize the island for 2s. This represents worst case scenario for DER tripping.

The GFOV scenario has been repeated at various DER integration levels corresponding to identify the DER level beyond which GFOV presents a problem. Generation-to-load (G/L)=0% scenario represents a case without any DER feeding the fault and is used to characterize the impact of motor loads on GFOV. The scenario with G/L=3% corresponds to the aggregated generation capacity of existing DER installations in the system. Higher DER integration levels correspond to future DER installations. In each scenario, the phase-to-ground voltage, neutral voltage, and SA energy dissipation at each substation transformer location have been obtained.

Figure 3 presents the results of the G/L=0% scenario, presenting the phase-to-ground voltage, neutral voltage, and SA energy dissipation at substation transformer 1. As Figure 3(a) shows, following the islanding event the high-side phase-A (the faulted phase) voltage drops to near zero, while the voltage increases on the un-faulted phases; Figure 3(b) shows a zoomed view of the voltage within the first few cycles after islanding. Furthermore, as Figure 3(c) shows the high-side neutral voltage also rises due to the voltage imbalance.

This overvoltage is caused by the motor loads; essentially, as the motors spin down, their remnant flux may turn them into generators keeping the island energized and feeding the fault. This causes an overvoltage by shifting transformer neutral. In the studies system, the 2000 hp SMs of a large water authority are the most influential.

Figure 3(e) shows the aggregate active and reactive power output of the 2000 hp SMs, showing the post-islanding operation of the SMs as generators. Figure 3(f) shows the speed of the motors showing that the larger motors spin down more slowly due to their larger mechanical inertia.

Figure 3(g) and (h) show the instantaneous current conducted by the three SAs at the transformer location and their energy consumption, respectively. The level of overvoltage is not sufficiently high to cause SAs to heavily conduct, and hence SA energy remains well below the estimated SA energy rating. In summary, this case study suggests that the studies system has a GFOV condition due to motor loads even with no DERs feeding the fault; the overvoltage is not large enough to cause a noticeable current conductance by the SAs. However, with increasing DER integration, the combination of this overvoltage and DER-driven overvoltage is expected to lead to more severe overvoltages.

Next, the DER level has been increased by adding more DERs on specified feeders, and the GFOV scenario has been repeated. Table 2 summarizes the simulation results of these scenarios, presenting the peak RMS phase-to-ground voltage, peak RMS neutral voltage, and SA energy dissipation at the substation transformer locations. As shown, the overvoltage level increases with increasing G/L ratio, causing the SAs to conduct more current and dissipate more energy. At G/L=67%, the energy dissipation of SAs exceeds the estimated arrester energy rating, suggesting that DER integration level beyond 67% is expected to cause a GFOV problem.

Figure 4 shows the results of this scenario. As shown, the peak RMS phase-to-ground voltage on the un-faulted phases reaches 1.94 pu, and the peak RMS neutral voltage reaches 1.11 pu. The overvoltage is a combination of DER-driven GFOV and motor load effect. The SAs conduct heavily, and the energy dissipation of at least one SA exceeds the estimated energy rating. This suggests that while SAs clamp the overvoltage, they are likely to be destroyed in the process as energy exceeds arrester capability. As expected, for other scenarios with G/L>67% the arrester energy exceeds estimated energy rating as highlighted in Table 2. Note that the results of this table assume ideal arrester current sharing. In practice due to MOV arrester non-sharing, arrester energy may be larger than that shown in the simulations.

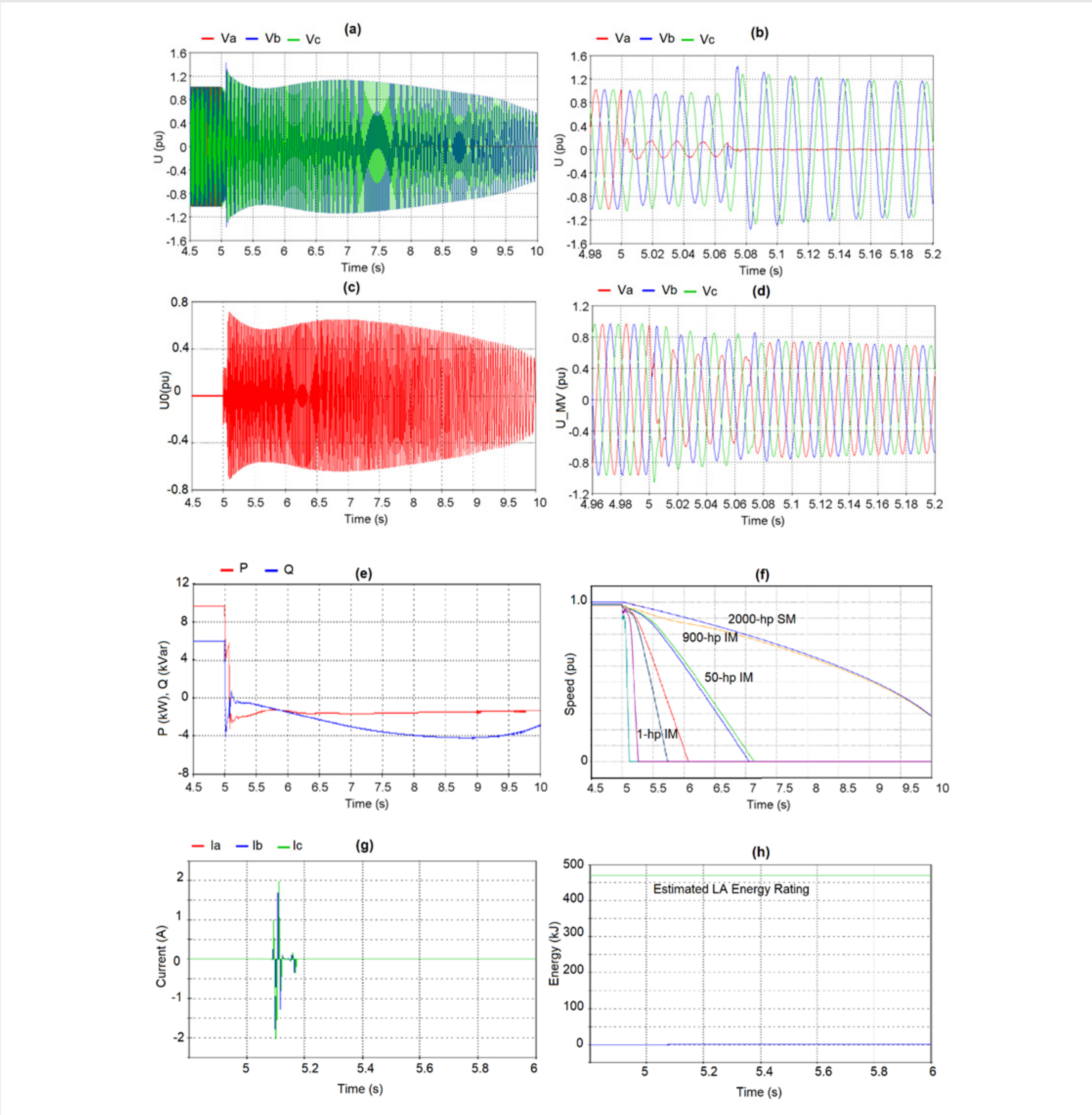

Figure 3. Simulation of a GFOV in the test system of Case 1 under G/L=0%: (a) the instantaneous phase voltage on the high side of substation transformer SS xfo 1; (b) Zoomed view of the first few cycles of the instantaneous phase voltage on the high side of substation transformer SS xfo 1; (c) the instantaneous value of neutral voltage on the high side of substation transformer SS xfo 1; (d) the instantaneous value of phase voltage on the MV side of substation transformer SS xfo 1; (e) the aggregate active and reactive power output of the 2000 hp SMs; (f) motors speed; (g) the instantaneous current conducted by the three SAs at the transformer location; and (h) arrester energy consumption.

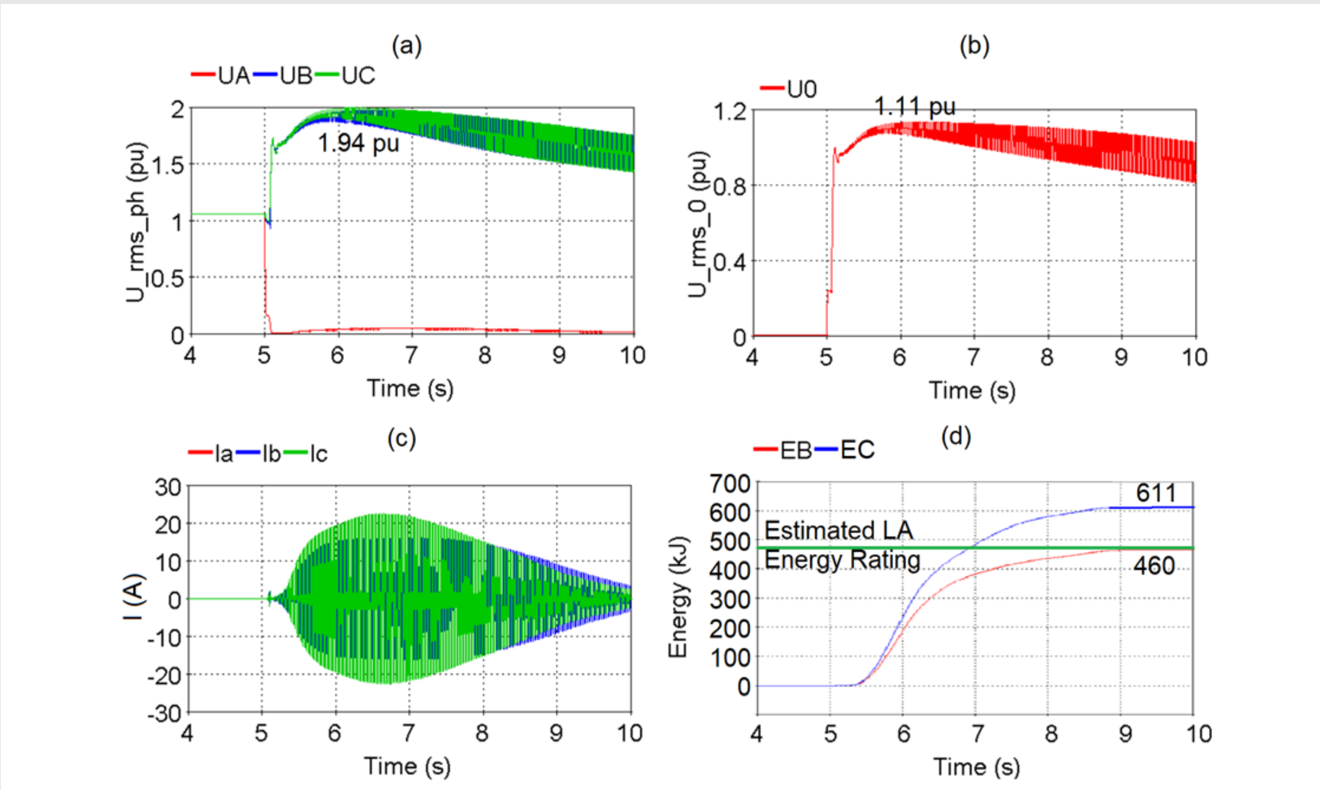

Figure 4. GFOV simulation results of the test system of Case 1 under G/L=67%: (a) the peak RMS phase-to-ground voltage on the high side of transformer SS xfo 1; (b) peak RMS neutral voltage; (c) the instantaneous current conducted by the three SAs at the transformer location; and (d) arrester energy consumption.

In summary, the key findings of the case are as follows:

- In the scenarios studied, the presence of large amounts of irrigation-based motor load contributes to greater GFOV risk. In the case where DER was not present, the motor load by itself was shown to increase GFOV risk. To further illustrate this effect, the motor loads of the test system of Figure 2 have been replaced by constant-impedance loads, and the GFOV scenario with G/L=67% has been repeated. Table 3 compares the GFOV results with motor load and with constant-impedance load. As shown, the peak RMS voltage and arrester energy consumption are lower with constant-impedance load. Essentially, with constant impedance load the GFOV problem occurs at a higher G/L. This illustrates that motor load contributes to GFOV.
- At the existing DER level (3%) of the test system, GFOV is mainly characterized by motors, and DERs have a negligible impact. At this penetration level, SAs are not expected to conduct sufficient current to modify the voltage. The large SMs of a large water authority are the most influential;
- GFOV risk increases with future addition of DERs. At G/L=67%, GFOV becomes a problem. For GFOVs occurring at this G/L level and beyond, SAs are expected to conduct heavily. While they clamp the overvoltage, they are likely to be destroyed in the process as energy exceeds arrester capability. As such, SAs as a mitigation of the overvoltage would be sacrificial element. In practice due to arrester non-sharing, the most severely impacted arrester may have greater duty than shown in the simulations.

- DER compensation (PF vs. volt-var per IEEE 1547-2018) does not have a noticeable impact on GFOV. The reason is that the open loop response time of volt-var setting under IEEE 1547-2018 Category B default setting of 5 s which makes volt-var too slow to be of any significance for GFOV; and
- The location of SLG fault may impact GFOV level. A simulation case study was conducted by placing the SLG fault on various system buses, and the results suggested that the largest GFOV is caused by a fault at the high side of substation transformer SS xfo 5.

Table 2. Summary of GFOV simulation results of Case 1 at various G/L ratios

Transformer	G/L=0%	G/L=3%	G/L=21%	G/L=50%	G/L=67%	G/L=100%	G/L=150%	G/L=200%
Peak RMS Voltage (pu)								
SS xfo 1	1.37	1.37	1.50	1.65	1.94	1.98	2.07	2.10
SS xfo 2	1.37	1.37	1.50	1.65	1.94	1.98	2.07	2.10
SS xfo 3	1.37	1.37	1.50	1.65	1.94	1.98	2.07	2.10
SS xfo 4	1.37	1.37	1.50	1.65	1.94	1.97	2.07	2.10
SS xfo 5	1.37	1.37	1.48	1.65	1.94	1.95	2.05	2.02
SS xfo 6	1.37	1.37	1.49	1.65	1.94	1.98	2.07	2.1
Peak RMS V0 (pu)								
SS xfo 1	0.78	0.78	0.86	0.95	1.11	1.11	1.15	1.16
SS xfo 2	0.78	0.78	0.86	0.95	1.11	1.11	1.15	1.16
SS xfo 3	0.78	0.78	0.86	0.95	1.11	1.11	1.15	1.16
SS xfo 4	0.78	0.78	0.86	0.95	1.11	1.11	1.15	1.16
SS xfo 5	0.78	0.78	0.86	0.95	1.11	1.11	1.15	1.16
SS xfo 6	0.78	0.78	0.86	0.96	1.12	1.12	1.16	1.17

SA Energy (kJ)

Arrester	Phase		Phase		Phase		Phase		Phase		Phase		Phase		Phase	
	B	C	B	C	B	C	B	C	B	C	B	C	B	C	B	C
SA1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1	1	460	611	~1000	~1000	>1000	>1000	>10^4	>10^4
SA2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1.5	1.5	457	608	~1000	~1000	>1000	>1000	>10^4	>10^4
SA4	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1	1	370	509	~1000	~1000	>1000	>1000	>10^4	>10^4
SA5	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1.5	1.5	447	594	~1000	~1000	>1000	>1000	>10^4	>10^4
SA6	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1.5	1.5	452	610	~1000	~1000	>1000	>1000	>10^4	>10^4

Table 3. GFOV results under G/L=67% with motor load and with constant impedance load

Peak RMS Voltage (pu)				
Transformer	**G/L=67% with motor loads**		**G/L=67% with constant-impedance load**	
SS xfo 1	1.94		1.35	
SS xfo 2	1.94		1.35	
SS xfo 3	1.94		1.35	
SS xfo 4	1.94		1.35	
SS xfo 5	1.94		1.35	
SS xfo 6	1.94		1.35	
Arrester energy (kJ)				
Arrester	**Phase**		**Phase**	
	B	**C**	**B**	**C**
SA1	460	611	<0.1	<0.1
SA2	457	608	<0.1	<0.1
SA4	370	509	<0.1	<0.1
SA5	447	594	<0.1	<0.1
SA6	452	610	<0.1	<0.1

Mitigation Options

The above case studies have illustrated that DER integration above 67% in Case 1 presents a GFOV problem and necessitates installation of mitigation options. The most effective mitigation option is protection grade tripping from bulk power system with DTT back to DERs; Nevertheless, this option may be costly due to the required communication. This section studies the effectiveness of alternatives to protection grade tripping from bulk power sources, namely detection/trip or surviving overvoltage the overvoltage condition. Substation overvoltage detection and feeder tripping is assumed to be at each individual substation with no communication between stations. Options for surviving OV include DER detection/trip and/or adding parallel arresters without downstream DER/feeder tripping. The study includes both mechanisms of GFOV under DERs, namely rejection of power to the un-faulted phase and LROV. All options include consideration of the DER onboard protection per Rule 21.

- *Option 1: High voltage substation 59P protection*

  Given that a GFOV impact is increased voltage amplitude on the high side of substation transformer, a potential mitigation option is to install 59P phase to ground overvoltage relay with MV feeder trip (no DTT communication to individual DERs). To evaluate this option, a 59P relay has been added at the 6 substation transformer locations. The pickup voltage threshold is set at 1.4 pu, and the total clearing time is assumed to be 5 cycles. The GFOV simulation scenarios at various G/L ratios have been repeated, and the phase-to-ground voltage, neutral voltage, and SA energy dissipation at each substation transformer location have been obtained.

  Figure 5 shows the results captured at the SS xfo 1 location under G/L=67%, suggesting the effectiveness of the 59P protection in mitigating GFOV. Following the islanding at t=5.067 s, the RMS phase-to-ground voltage on phases B and C increases above 1.4 pu, and the 59P element asserts in about 6 cycles at t=5.171 s and trips Feeder 1. The 59P relays at other transformer locations also assert, thereby tripping other feeders. Consequently, the voltage quickly drops to zero. The SAs conduct transiently, and the 59P operation is fast enough to maintain their energy within rating. As Figure 5(e) shows, the TOV seen by the SAs is 1.3 times MCOV for 0.086 s, which is within the TOV withstand capability. It should be mentioned that LROV may continue in the isolated feeders depending on generation-to-load mismatch, thus triggering DER protection. In the simulated case, the DER OUV protection asserted after isolation of Feeder 1 at t=5.356 s. The simulation results further suggested the effectiveness of 59P protection in mitigating GFOV at G/L={100,150,200}% levels.

- *Option 2: DER onboard OUV/OUF protection*

  This option relies on DER plant-level protection to trip the DER on overvoltage. To test this option, the DERs have been equipped with DER OUV/OUF protection set based on Rule 21/IEEE 1547-2018. The 59P protection of Option 1 has been disabled to exclusively study the response of DER protection.

  Conducted simulation suggest that DER protection is not a reliable GFOV mitigation option. The OUV protection may not see an overvoltage since the substation transformer blocks zero-sequence GFOV, and the DER terminal voltage only sees marginal effect by high side ground fault. Further, tripping for generation-to-load mismatch may not operate fast enough due to inertia of SMs which leads to delayed frequency decline. Consequently,

high side SAs will likely be stressed beyond capability assuming low-side island persists for up to 2 s (island could persist longer than 2 seconds due to persisting effect of motors). If load and generation are significantly mismatched, DER tripping by OUV/OUF is expected eventually; if load and generation are matched, tripping may be delayed beyond protection limits.

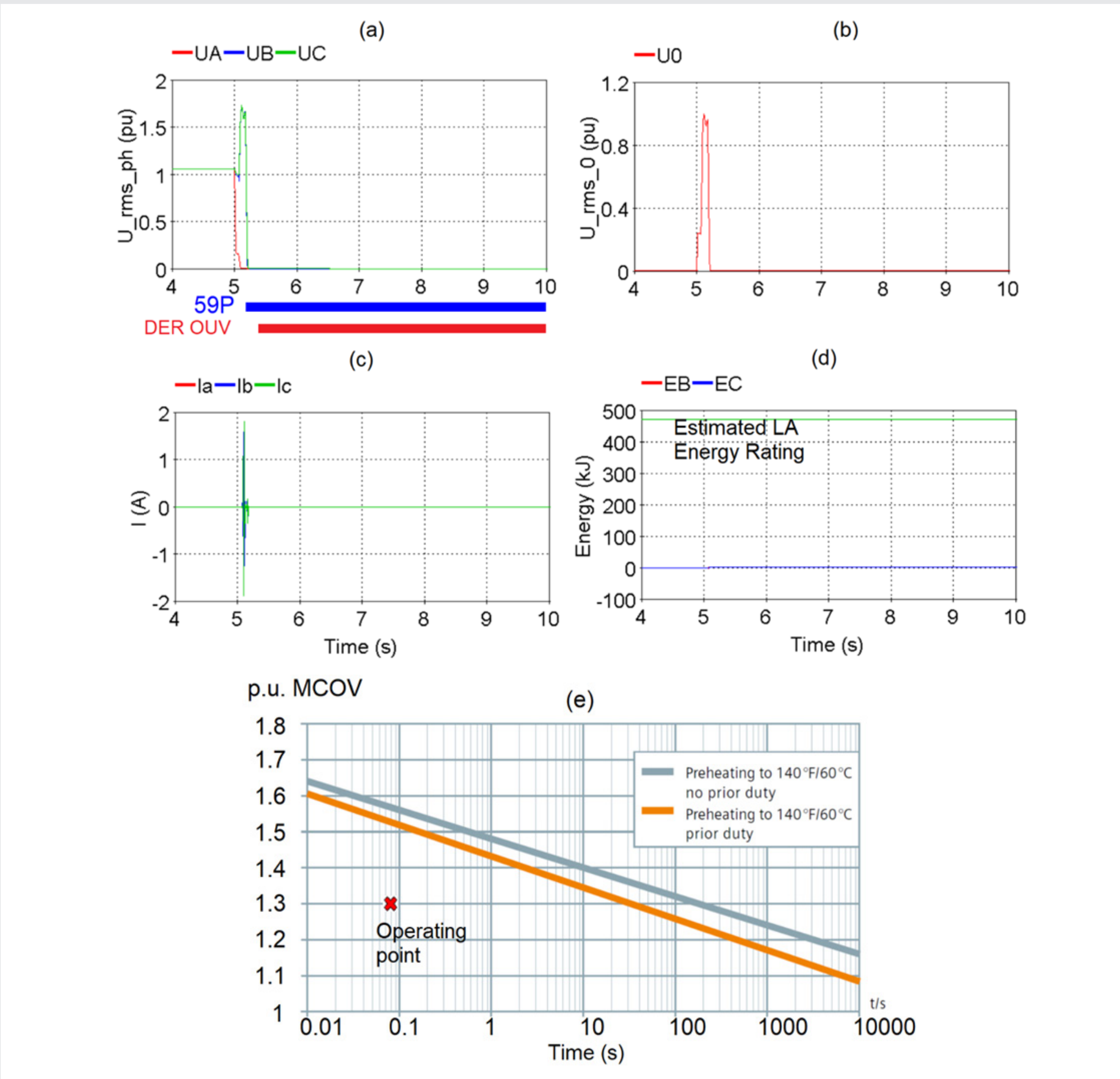

Figure 5. GFOV simulation results of the test system of Case 1 under G/L=67% with 59P protection: (a) the peak RMS phase-to-ground voltage on the high side of transformer SS xfo 1; (b) peak RMS neutral voltage; (c) the instantaneous current conducted by the three SAs at the transformer location; (d) arrester energy consumption; and (e) arrester TOV capability characteristic.

- *Option 3: Doubling the SA at each transformer location*

  This option studies whether doubling the SA at each transformer location can reduce the overvoltage to acceptable levels while maintain SA energy within rating. The main motivation for considering this option is the lower cost. Conducted simulations suggest that this option is not effective. The primary reason is the non-sharing of MOV arresters. The non-sharing depends on various factors such as arrester manufacturer, production batch, and service experience. In practice, having perfectly matched arresters may be challenging as it requires working directly with original equipment manufacturer. Further, the failure of one arrester necessitates repeating the process. Even with ideal arrester sharing, the energy may still be high with double arresters. Another consideration is that the relation between number of arresters and energy is nonlinear and determining the number of required arresters is not straightforward.

- *Option 4: Arrester sensing*

  The operating principle of this option is that arrester current signature can be used as an indication of GFOV. The implementation entails continuously monitoring arrester current via a current transformer (CT) and performing time-current analytics to identify a GFOV condition and trip the feeder breaker, as needed. This option provides an alternative to adding high-side Power Transformers (PTs) for phase to ground or 3V0 sensing. The best setting and detection methods for specific application will need to be examined through simulation analysis and field experience. This EPRI report provides further details.[8]

  This option was not specifically implemented and tested in the simulations; however, the results suggest the potential effectiveness of this approach. Conducted simulations show that the time until arrester energy handling capability is exceeded is at least 30 cycles which is sufficient for the required measurement and analytics of the arrester sensing option. An advantage of this approach is that implementation does not require substation shut down. Another potential advantage is the lower cost compared to adding high voltage PTs. A disadvantage is that arresters are not as reliable as PTs for detection. Further, detection at one transformer location still requires tripping at other locations, thus potentially necessitating communication.

Case 2: 115-kV System

Another GFOV case study has been conducted on the test system of Figure 6which represents a 115 kV grid. The sub-transmission system is connected to an upstream transmission grid through a main feeder breaker and energizes 4 distribution feeders denoted by Feeder 1 to Feeder 4 through 4 substation transformers represented by SS xfo 1 to SS xfo 4, respectively.

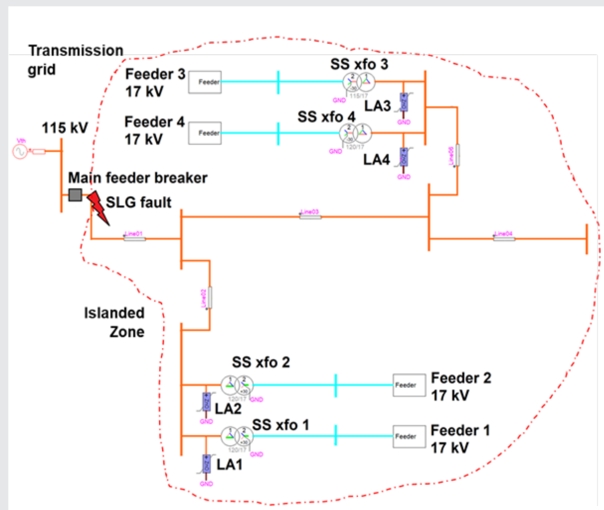

Figure 6. The 115-kV test system (Case 2)

Table 4 presents the feeder data including DERs and loads on each feeder. The existing level of DER in this case is 30%. The load includes irrigation pumps which have been represented by single phase 1 hp IMs and 3-phase 50 hp IMs. The substation transformers have an ungrounded high side winding and are protected by SAs (one SA per phase). These SAs are represented by SA1-SA4. The arresters are metal oxide type with an MCOV of 76kV.

[8] *Protection from Unintended Islanding and Substation Primary GFOV Caused by DG Infeed*, EPRI, Palo Alto, CA: 2017. 3002011008.

Table 4. Feeder data of 115kV system (Case 2)

Feeder ID	Load (kW)				DER (kW)
	1ph induction motor	3ph 50hp induction motor	Other	Total	
Feeder 1	49	3,394	19,838	23,281	7,997
Feeder 2	413	4,332	14,639	19,384	6,011
Feeder 3	267	2,575	1,646	4,488	1,404
Feeder 4	1,312	21,135	3,795	26,242	6,636
Total	**2,041**	**31,436**	**39,918**	**73,395**	**22,048**

Conducted GFOV simulations on this test system suggest the same overall conclusions as those of Case 1. The simulations were conducted for G/L={0,30,50,67,100,150,200}%. At G/L=0% (no DER), the test system showed a GFOV condition due to motor loads, causing a peak phase to ground voltage of about 1.2 pu on the high side of substation transformers. At this level, the arresters did not conduct sufficient current to modify the voltage, and their energy remained well within their rating. The overvoltage level increased with increasing level of DERs. At the existing DER level of 30%, the peak phase to ground voltage was about 1.68 pu. At this level, the arresters did not conduct sufficient current to modify the voltage, and their energy remained well within their rating. The GFOV problem manifested itself at G/L=50% with arrester energy exceeding the rating. A reason is the difference in motor tyhpe and rating compared to Case 1; In Case 1, a large share of motors are 2000 hp synchronous motors whereas in Case 2, a majority of motor are residential/agricultural 50 hp induction motors.

In terms of mitigation options, the 59P protection option was effective in all studied G/L levels. The DER onboard protection and double arrester options showed the same limitations as in Case 1. The results further suggested that the time delay of arrester thermal runaway is sufficient for the sensing and analytics required by the arrester sensing mitigation option.

Conclusions

This paper has presented a case study on transmission GFOV concerns due to DERs and evaluated potential mitigation options. To reiterate, the key findings are as follows:

- With DER penetration levels of < 30% (defined as aggregate DER nameplate rating divided by minimum daytime load level), GFOV was not likely to damage SAs. Generation-to-load (G/L) ratios of 67% and greater on the 70kV system and greater than 50% on the 115kV system result in GFOV magnitudes and durations that cause SAs to conduct heavily and likely exceed their energy handling capacity, indicating a need for protection or mitigation.
- The presence of large amounts of motor load creates a GFOV concern without any DER back feeding the fault.
- Properly set substation transformer phase overvoltage protection (59P) is an effective mitigation of GFOV. Simulations suggest that:
  - 59P isolates the MV feeder behind the transformer fast enough to keep arresters' energy within the rated capability;
  - Overvoltage remains within arresters TOV withstand capability.
- DERs that meet Rule 21 or IEEE 1547-2018 may not detect the overvoltage condition because of zero-sequence isolation and cannot be relied upon to trip during transmission ground faults.

Future Areas of Study

The study uncovered several findings that deserve additional scrutiny:

- DER power output and load level have a direct impact on the arrester survivability and sensitivities could be performed to quantify the correlation.
- DER island detection schemes could play a role in hastening a DER trip. DER island detection schemes could be modeled in the DER to determine impacts.
- Significant amounts of motor loads, without the presence of DER, contribute greatly to GFOV. Sensitivity analysis could be performed to define % motor load thresholds that are of concern.

Note

For further information about EPRI, call the EPRI Customer Assistance Cen- ter at 800.313.3774 or e-mail askepri@epri.com.

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DER Integration

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