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Impact of Distributed Energy Resources on Temporary Overvoltages

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SUMMARY

The proliferation of distributed energy resources (DER) in distribution systems has created a new potential concern for temporary overvoltages (TOV). Two ways that DERs in the distribution system can cause TOVs include: load rejection overvoltages (LRO) and ground fault overvoltages (GFO). A GFO occurs when a single-phase fault occurs in a non-effectively grounded system resulting in a neutral shift where full line-to-line voltage is applied line-to-neutral. These events have a potential to stress equipment insulation and surge arresters. Load rejection overvoltages (LRO) occur when a distribution feeder containing a significant amount of DER and some equal or smaller amount of load becomes disconnected from the grid, resulting in a high generation to load ratio. This paper focuses on the impact of a large DER plant interconnected along a distribution feeder in a client's system and its impact on the client's sub-transmission equipment. The system under study considered the use of a Delta (Δ) primary – Wye, impedance grounded (Yg) secondary transformer to tie the distribution systems to the sub-transmission system. The paper describes the Electromagnetic Transients (EMT) model development, results of the ground fault overvoltage analysis, study conclusions, and potential mitigation options. This analysis demonstrated that there is a potential of unintentional islanding operation for balanced load to generation scenario and sustained temporary overvoltages are observed on the sub-transmission system for a normally cleared single-phase fault.

KEYWORDS

Distributed Energy Resources (DER), Temporary Overvoltages (TOV), Ground Fault Overvoltages (GFO), Electromagnetic Transients (EMT) Analysis

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I. INTRODUCTION

Distributed energy resources (DER) are being installed in electric utilities' distribution systems at an increasing rate. This is concerning because these systems were designed and historically operated assuming unidirectional power flow from the transmission system down. However, with higher penetrations of DER, there are impacts for both the transmission and distribution system. The distribution system may experience current and voltage overloads, reduced power quality (e.g., flicker), mis-operation/overuse of voltage regulating devices (e.g., load tap changers and capacitor banks), mis-operation of protection schemes fuses/relays, etc. At the bulk energy system (BES) level, primary concerns with regards to DER are related to increases in operation costs because of regulation, ramping generation, scheduling generation, and unit commitment [1].

The overall goal of this paper is to quantify the overvoltages, surge arrester energy duties, and potential operational issues associated with GFO events at a sub-transmission substation following the addition of a new 5 MVA rotating generator along one of the distribution feeders fed from this substation. To quantify these impacts, an EMT analysis was performed using the software PSCAD/EMTDC version 4.6. A simplified model of the client's sub-transmission and distribution system around the study area was created to study GFO events and assess the worst-case TOV scenarios.

When examining TOVs, both the magnitude and duration of the overvoltage must be considered and evaluated with regards to the relevant equipment's TOV withstand capability. It is assumed that for phase-to-ground TOVs lasting for a few seconds or less, surge arresters will have a limited capability [2]. Figure 1 illustrates typical TOV withstand voltage versus time characteristics used for different class surge arresters [3]. For the purposes of this analysis, the "Station Class Arresters with Prior Duty" capability curve is used for evaluation because it is more conservative with regard to the assumed TOV capability of the surge arresters.

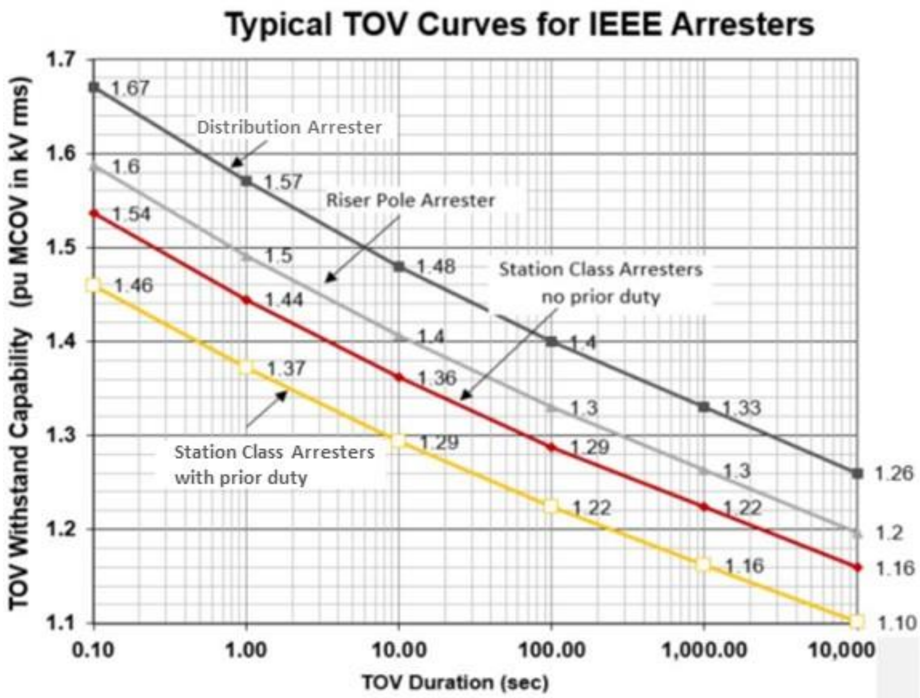

Figure 1. Plot of the typical per-unit TOV withstand voltage-time curves.

The rest of the paper is organized as follows: Section II describes the approach, input parameters, and validation of the electromagnetic transients (EMT) model developed, Section III analyses the impact of the proposed new generator on TOVs during single phase-to-ground faults. Conclusions from this study are provided in Section IV.

II. MODEL DEVELOPMENT

For the performance of the GFO analysis, a simplified EMT model of the system of interest was developed in PSCAD/EMTDC version 4.6. Figure 2 provides an illustration of the system under study. The developed EMT model included an eleven-mile sub-transmission feeder under study with a Delta primary – Wye, impedance grounded secondary transformer connected to two distribution feeders of interest. The sub-transmission system beyond the study area was represented as short-circuit equivalents tuned to the 60-Hz short-circuit contribution of the system outside of the immediate study area. For the purposes of this analysis where the goal was to quantify maximum TOVs during GFO events, detailed modelling of the entire distribution feeder wasn't necessary. Reduced models of the two feeders, including the load and feeder impedances between the substation and the DER under study was created using data obtained from a distribution load flow model. The generator-based DER under study was represented based on the machine's dynamic characteristics including its governor and excitation system.

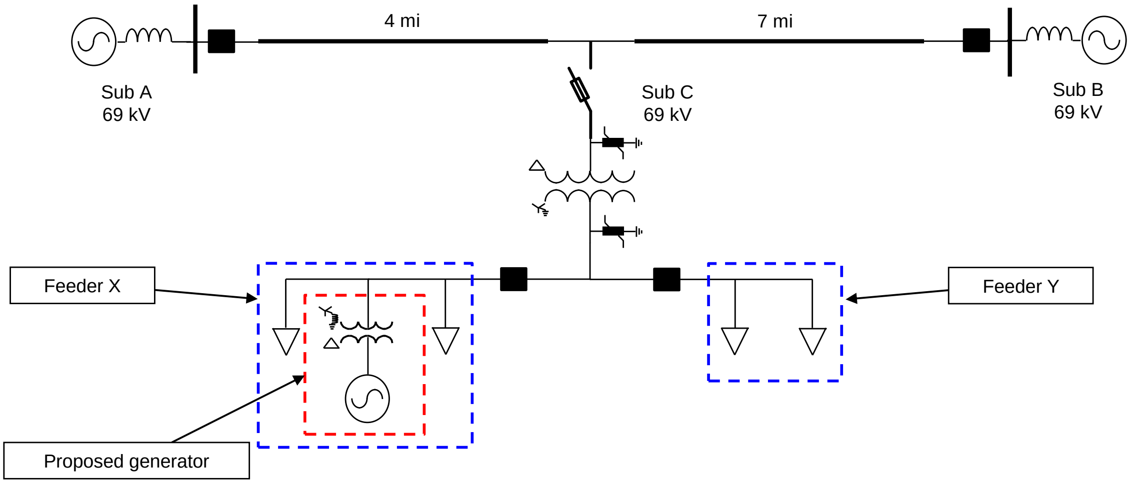

Figure 2. One-line diagram of the study area model used for this analysis.

The simplified distribution feeder models (Feeder X and Feeder Y) were developed based on the daytime minimum load scenario. All of the existing solar PV generation in the two feeders is turned on by adjusting this case to achieve the highest export scenario. The feeders under study included small (<100 kW) mostly single-phase behind the meter solar installations. Because of the small size of these solar installations, they were not explicitly represented in the EMT model and instead modeled as net load (i.e., load minus solar). The final loading was close to zero for feeder X and about 1 MW for feeder Y for the daytime minimum load scenario.

Figure 3 provides an illustration of the 5 MVA rotating generator (4.5 MW at 0.9 power factor) considered in this analysis.

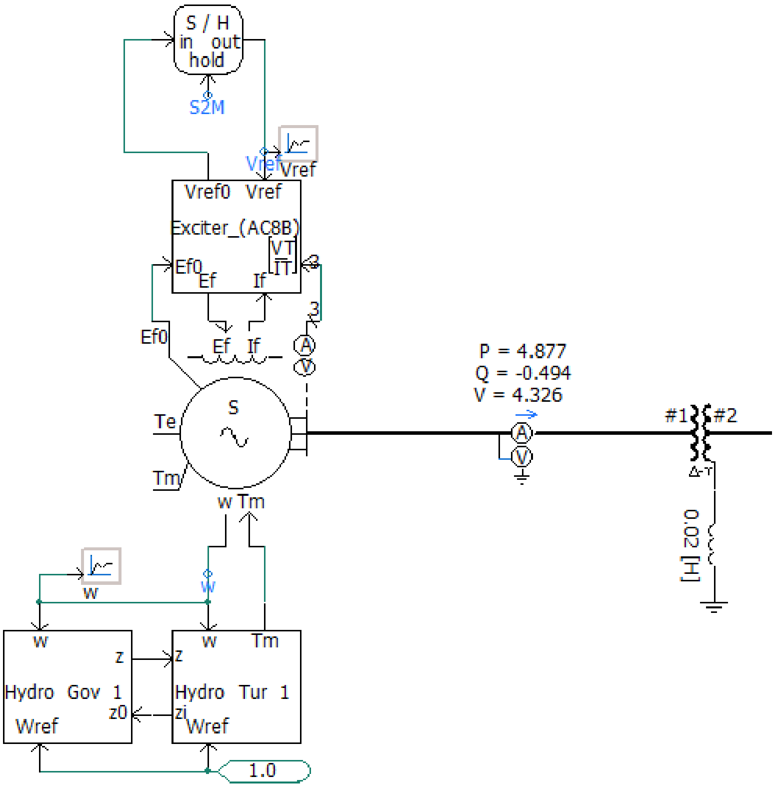

Figure 3. Generator Model in PSCAD.

The synchronous machine parameters and the generator protection settings (27, 59, 81/O, 81/U) were obtained and implemented from the data provided by the interconnecting customer (IC). Since only the type of the exciter was provided, the IEEE equivalent excitation system was used in PSCAD (AC8B) with the typical values provided in IEEE Std. 421.5-2016 [4]. For the governor and the turbine, typical values for hydro generators are used from the PSCAD library. The generator step-up transformer parameters were obtained from the one-line diagram provided by the client.

III. GROUND FAULT OVERVOLTAGE (GFO) ANALYSIS

This section describes the effect of the new generator on GFOs. The magnitude and duration of the GFO event is a function of the following, some of which were not evaluated in this paper:

- DER penetration level (i.e., the export level)
- The balance of reactive power in the islanded power system
- The trip settings of the DER
- The type of load in the islanded power system (spinning machine load will resist changes in system frequency)
- The DER control system
- The ratio of types of DER (i.e., inverter-based and synchronous machine based)

Using the Electromagnetic Transients (EMT) model described in the previous section, a study was performed where a single-phase to ground fault was applied at the sub-transmission side terminals of the Sub C transformer and cleared via the sub-transmission circuit breakers at Sub A and Sub B. This analysis was performed under maximum export (Case 1) and balanced load and generation (Case 2) conditions to represent the worst-case temporary overvoltage (TOV) scenarios. The analysis neglected the impact of a transfer trip scheme and assumed that the generator would trip according to its own voltage and frequency protections. The following two cases were examined:

(1) Single line-to-ground fault and clearance at the sub-transmission side while the generator is at full power output (4.5 MW) and exporting power to the grid at 0.99 power factor leading (absorbing)

(2) Single line-to-ground fault and clearance at the sub-transmission side while the generator is at reduced power output (around 3.9 MW) and matching the total load (3.85 MW) at feeder X and Y with less than 150 kW imported from the sub-transmission system

    a. For this case, the load is increased (half of daytime heavy load with solar on) compared to the minimum daytime load and is assumed to be constant during the simulation

Figure 4 provides an illustration of the system under study highlighting the key system model components and GFO event under study.

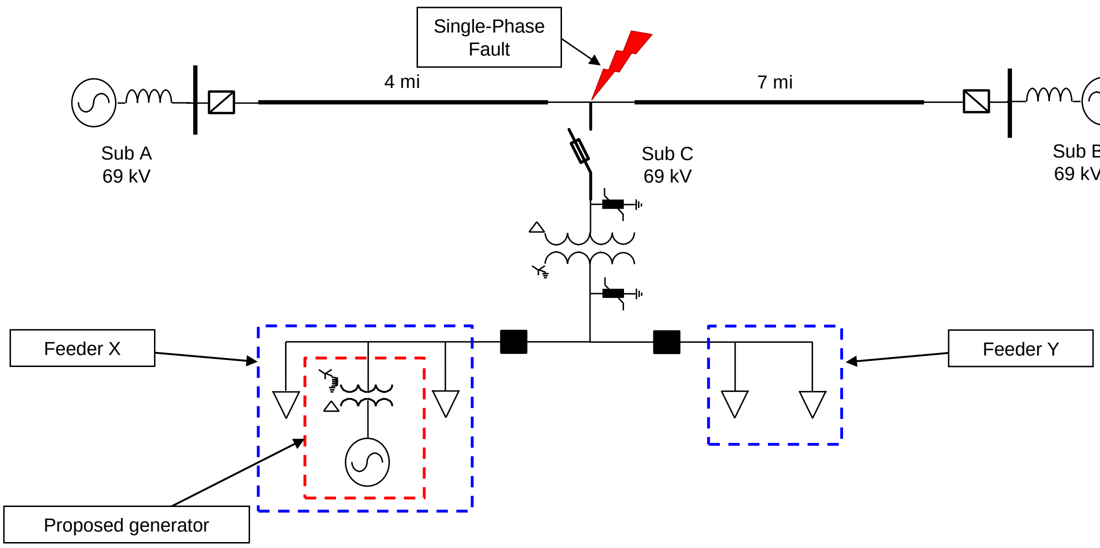

Figure 4. One-line diagram of the study area model used for the GFO analysis.

For each examined case, the following sequence of events was utilized:

(1) System operating in steady-state with the generator at Feeder X at full (or reduced for Case 2) power output.

(2) At time, t = 2 seconds, a single-phase fault (phase A) is applied at the sub-transmission side terminals of the Sub C transformer.

(3) Six (6) cycles later at time, t = 2.1 seconds, the sub-transmission line end breakers at Sub A and Sub B open to clear the fault.

(4) The maximum overvoltage, duration of overvoltage, and surge arrester energy duties are recorded.

Table 1 provides a summary of the results for the two cases studied. Both cases experience full line-to-line voltage being applied to line-to-neutral of unfaulted phases on the high side (Δ connected sub-transmission bus) when the sub-transmission system is fed by the large DER from the low side (Yg connected distribution bus) after the fault is cleared by the sub-transmission line end breakers at Sub A and Sub B, and an island is formed.

Table 1
Summary of Results from the Ground Fault Overvoltage (GFO) Analysis

Case No.	Case Description	Peak Fault Current (kA)	Sub C High-Side		Feeder X		Feeder Y	
			Maximum Transient Overvoltage (p.u.)	Time over 1.1 p.u. (ms)	Maximum Transient Overvoltage (p.u.)	Time over 1.1 p.u. (ms)	Maximum Transient Overvoltage (p.u.)	Time over 1.1 p.u. (ms)
1	Single line-to-ground fault and clearance at full export	9.65	1.95	225	1.25	100	1.25	100
2	Single line-to-ground fault and clearance at balanced load and generation	9.65	1.85	20000+	1.05	0	1.05	0

The following is a summary of key results from the GFO analysis considering maximum export (Case No. 1):

- The generator tripped due to over frequency 7 cycles after primary protection cleared the sub-transmission lines.
  - During this time period, a sustained TOV of approximately 1.9 p.u. (107.0 $kV_{PG,Peak}$ or 75.7 $kV_{PG,RMS}$) was observed. This equates to a TOV of 1.33 p.u. on the surge arrester MCOV base.
  - Utilizing typical surge arrester TOV curves considering prior duty (Figure 1), it is estimated that the 57 kV MCOV surge arrester can handle a TOV of this magnitude for 3.5 seconds.
- With the proposed relay settings for the generator under study no temporary overvoltages of concern were identified at the 13.2 kV feeders for a GFO event under maximum export conditions.
- Refer to Figures 5 and 6 for an illustration of the instantaneous line-to-ground voltage at 13.2 kV DER point of interconnection (POI) and the high side terminal of the load transformer, respectively.
- Figure 7 provides an illustration of the real and reactive power output of the DER under study during the GFO event.

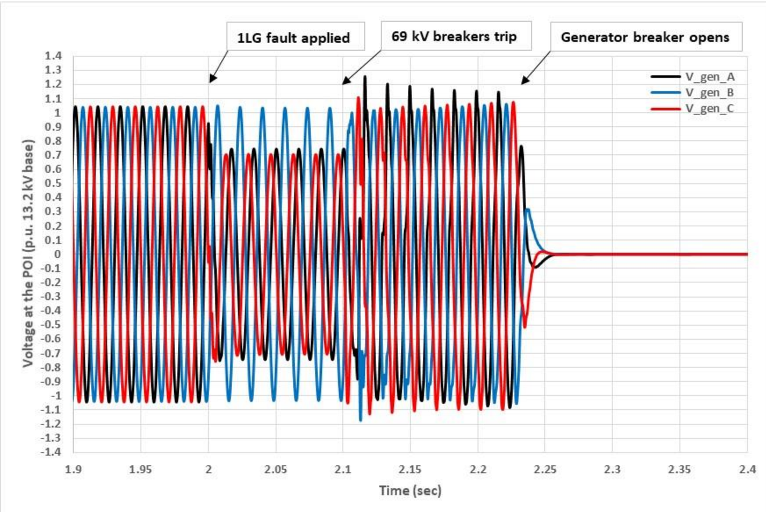

Figure 5. Voltage at the generator point of interconnection (POI).

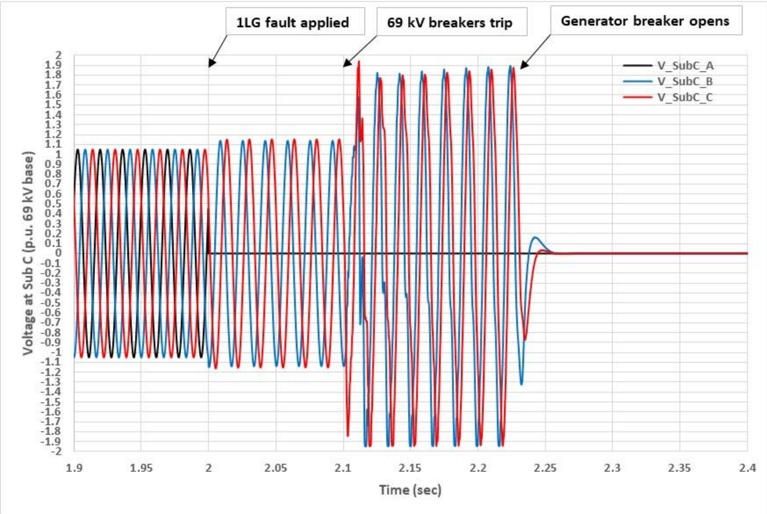

Figure 6. Voltage at the Sub C high side.

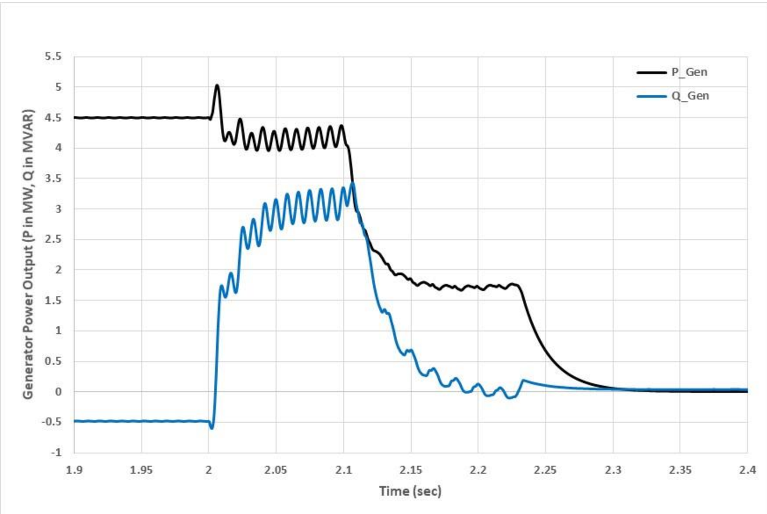

Figure 7. Generator Power Output (positive means injection).

The following is a summary of key results from the GFO analysis considering balanced load and generation (Case No. 2):

- In the examined case, the generator did not trip after primary protection cleared the sub-transmission lines and formed an unintentional island lasting over 20 seconds.
  - During this time period, a sustained TOV of approximately 1.8 p.u. (101.4 $kV_{PG,Peak}$ or 71.7 $kV_{PG,RMS}$) was observed at the unfaulted phases of the sub-transmission system. This equates to a TOV of 1.26 p.u. on the surge arrester MCOV base.
  - Utilizing typical surge arrester TOV curves considering prior duty (Figure 1), it is estimated that the 57 kV MCOV surge arrester can handle a TOV of this magnitude for 30 seconds.
  - If the load stays close to generator output during this period (i.e., within less than 150 kW export/import to/from sub-transmission and closely balanced reactive power i.e., generator in voltage regulation mode), there is a risk of exceeding TOV capability of the surge arrester on the high side of the transformer.
- No temporary overvoltages of concern were identified at the 13.2 kV feeders for a GFO event under balanced load and generation conditions. The peak voltage observed at Feeder X and

Feeder Y were 1.05 p.u. (11.32 $kV_{PG,Peak}$) under maximum export scenario.

- Refer to Figures 8 and 9 for an illustration of the instantaneous line-to-ground voltage at 13.2 kV DER POI and high side of the load transformer, respectively.
- Figure 10 provides an illustration of the real and reactive power output of the DER under study during the GFO event.

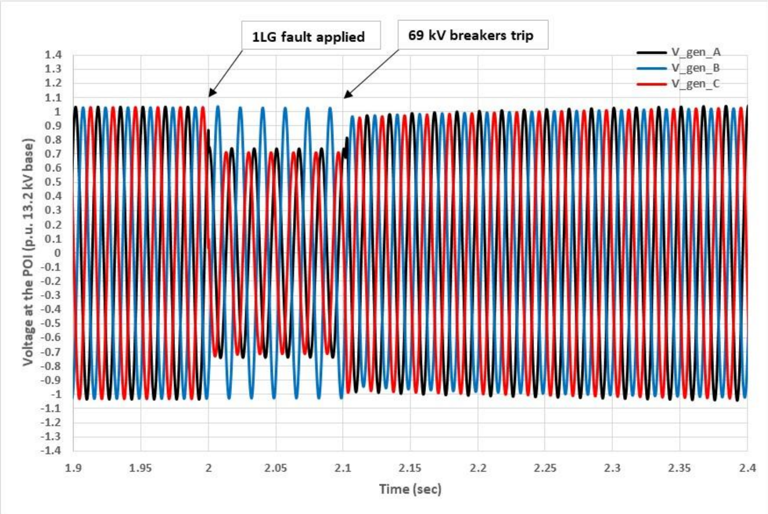

Figure 8. Voltage at the generator POI (Zoom-In).

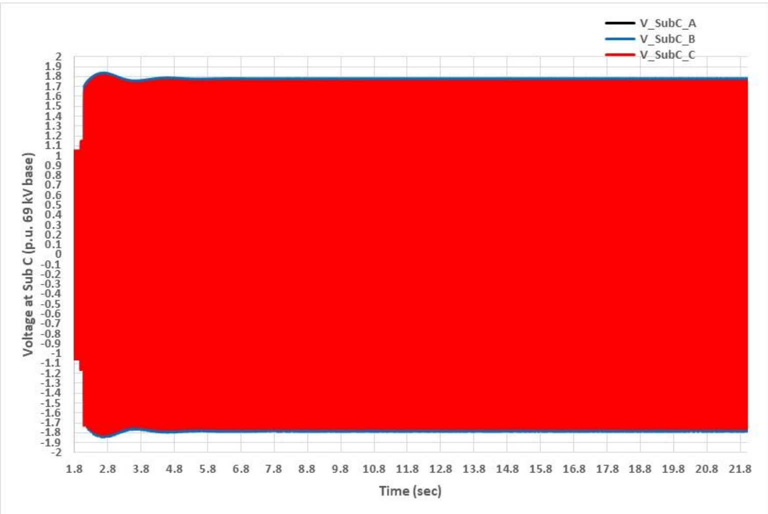

Figure 9. Voltage at the Sub C high side.

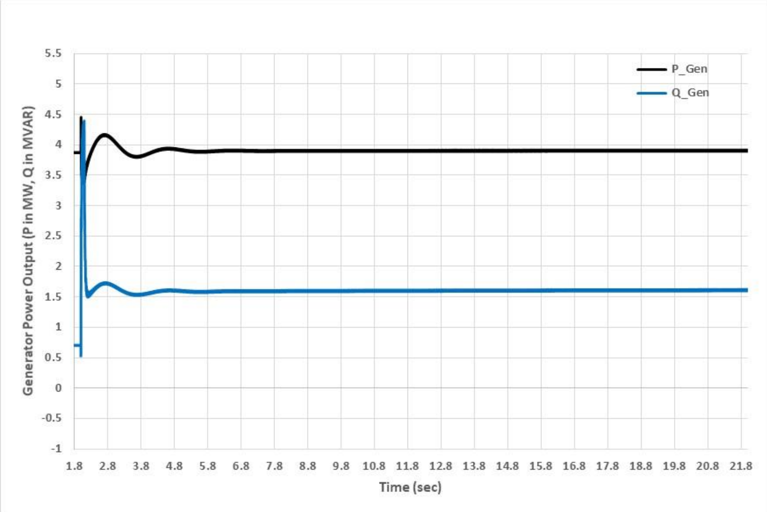

Figure 10. Generator Power Output (positive means injection).

IV. CONCLUSIONS

This study examined the impact of a large DER on GFO for the worst-case TOV scenarios. For the maximum export scenario, voltages close to 2 p.u. were observed at the high side of the load transformer. For the matched load and generation (both real and reactive power) scenario lasting longer than 30 seconds, there is a risk of forming an unintentional island and exceeding the TOV capability of the surge arrester on the high side of the transformer. To prevent this situation, the authors recommend considering one of the methods listed below:

- Time coordinated transfer trip to the large DER breaker or the Feeder X breaker once a fault is detected at Sub A or Sub B
- Negative-sequence current detection at Sub C and transfer trip to the Feeder X breaker or the large DER breaker
- Zero-Sequence Voltage detection (3V0 detection) at Sub C and transfer trip to the Feeder X breaker or the large DER breaker

For future work, the authors are planning to study the impact of different levels of inverter-based DER penetration, different power factor settings, and different DER protection settings on GFO.

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