PacWave Grid Integration Study: Transient and Dynamic Conditions

Final Report

Terry Lettenmaier,[1] Vahan Gevorgian,[2] and Michael Antonishen[3]

1 Williwaw Engineering
2 National Renewable Energy Laboratory
3 David Evans and Associates, Inc.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5D00-78226
March 2022

PacWave Grid Integration Study: Transient and Dynamic Conditions
Final Report

Terry Lettenmaier,[1] Vahan Gevorgian,[2] and Michael Antonishen[3]

1 Williwaw Engineering
2 National Renewable Energy Laboratory
3 David Evans and Associates, Inc.

Suggested Citation
Lettenmaier, Terry, Vahan Gevorgian, and Michael Antonishen. 2022. *PacWave Grid Integration Study: Transient and Dynamic Conditions—Final Report*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5D00-78226. https://www.nrel.gov/docs/fy22osti/78226.pdf.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5D00-78226
March 2022

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Water Power Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

NREL prints on paper that contains recycled content.

Acknowledgments

This work was funded by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Water Power Technologies Office under Award Number: DE-EE-0007899.0000 to Oregon State University for the PacWave South project. We would like to thank Bob Thresher at NREL for his continuous support for this work. Central Lincoln People's Utility District (CLPUD) has provided significant support for this work, and we would especially like to thank Steve Alexanderson and Shamus Gamache, who provided detailed information about CLPUD's system and also recommendations for the PacWave design.

List of Acronyms

BPA	Bonneville Power Administration
CLPUD	Central Lincoln People's Utility District
GFOV	ground fault overvoltage
LROV	load rejection overvoltage
MCOV	maximum continuous operating voltage
NERC	North American Electric Reliability Corporation
NREL	National Renewable Energy Laboratory
PSCAD	Power System Computer-Aided Design
SLG	Single Line to Ground
TOV	temporary overvoltage
UCMF	utility connection and monitoring facility
WEC	wave energy converter

Executive Summary

This report describes the results of Power System Computer-Aided Design (PSCAD) simulations that were performed in 2020 and 2021 to assess the impacts of PacWave South generation on the Central Lincoln People's Utility District (CLPUD)'s 12.47- kV distribution and 69- kV subtransmission systems. The simulations assessed the following dynamic and transient conditions:

1. Reactive compensation: Because of the capacitance of the PacWave subsea cables, the CLPUD distribution voltages will increase substantially when PacWave cables are connected unless reactive compensation is added. In addition, there is potential for fluctuating power output from PacWave that could cause fluctuations in CLPUD's distribution voltage. Simulations assessed the reactive compensation that is necessary to mitigate distribution voltage violations and to avoid undesirable operation of tap changers at the CLPUD substations.
2. Temporary overvoltage (TOV): Simulations assessed the impacts of load rejection overvoltage (LROV) and ground fault overvoltage (GFOV) events on the CLPUD distribution and subtransmission systems.

PSCAD Model

The National Renewable Energy Laboratory (NREL) developed a PSCAD model that included worst-case PacWave generation and relevant portions of CLPUD's 12.47-kV distribution and 69-kV subtransmission system, including electrical lines, circuit breakers, transformers, surge arresters, and distribution loads. Three different wave energy converter generation scenarios were considered at PacWave South: (1) four 2.5-MW generators with 30-kV connection voltages, (2) two 5-MW generators with 30-kV connection voltages, and (3) one 700-kW generator with 12.47-kV connection voltage. The model included subsea cables that connect the wave energy converters to a utility connection and monitoring facility (UCMF) on shore, where transformers and circuit breakers are located for the connection to a CLPUD 12.47-kV distribution feeder that runs north-south along U.S. Highway 101. This distribution feeder connects to CLPUD's 69-kV subtransmission system through either of two alternate distribution substations. The 69-kV subtransmission connects to a Bonneville Power Administration 230-kV transmission line via BPA's substation at Toledo, which is approximately 25 km from the PacWave UCMF. To simulate reactive compensation, the model included both fixed shunt reactors and a static synchronous compensator (STATCOM) at the UCMF. To simulate TOV, surge arresters were modeled at both the UCMF and in relevant locations on the CLPUD system.

Results

The results show that without any reactive compensation at the PacWave UCMF, CLPUD distribution voltages will exceed 1.05 p.u. with worst-case PacWave generation. This is not acceptable, and some form of reactive compensation is necessary. When compensation with either shunt reactors alone or a combination of shunt reactors and STATCOM is added at the UCMF, CLPUD substation voltage swings do not exceed 2%, and voltage swings do not exceed approximately 2%–3% throughout the CLPUD distribution feeder for the typical CLPUD Seal Rock substation connection or 3%–4% for the alternate CLPUD Lundy substation connection. In addition, CLPUD distribution voltages remain in the window from 0.95 p.u. to 1.05 p.u.as

recommended by ANSI C84.1. When the STATCOM is included, voltage swings at the PacWave point of interconnection are reduced compared to compensation with shunt reactors alone, but voltage swings at the substations are not reduced. These results show that the use of shunt reactors alone for compensation is probably sufficient, and the benefits of adding a STATCOM at the UCMF will probably not justify the installation and maintenance costs.

The TOV simulation results show that when PacWave generation exceeds the 700 kW minimum load on CLPUD's 12.47 kV feeder that PacWave connects to, some CLPUD and UCMF surge arrester voltages can exceed arrester TOV ratings during both LROV and GFOV events. Because specific information about generators connecting to PacWave was not available for this work, a worst-case PacWave generation model was used where all generators were modeled as ac current sources with no voltage limit. Actual generators connecting at PacWave will likely be inverter connected and the inverter outputs will be voltage limited, which may reduce the magnitude of arrester overvoltages during TOV events. Also, UCMF anti-islanding detection was modeled with a 200 ms overvoltage delay per NERC PRC-024 and faster anti-islanding detection could be used to reduce the duration of arrester overvoltages. When PacWave is planning for specific WEC deployments that will result in total PacWave generation that exceeds 700 kW, further TOV modeling should be completed that includes both generator and inverter details for the WECS connecting to PacWave and also anti-islanding protection to determine if either CLPUD or PacWave surge arresters will be affected.

Table of Contents

List of Figures

List of Tables

Introduction

This report describes the results of Power System Computer-Aided Design (PSCAD) simulations that were performed in 2020 and 2021 to assess the impacts of PacWave generation on the Central Lincoln People's Utility District (CLPUD) 12.47-kV distribution and 69-kV subtransmission systems. PacWave South (PacWave) is a wave energy test facility planned by Oregon State University. PacWave shore facilities will be located south of Seal Rock on the Oregon coast. PacWave is expected to be operational in 2024 and will connect up to 10 MW of generation to CLPUD's Seal Rock distribution feeder. The PSCAD modeling described in this report was done by Vahan Gevorgian at the National Renewable Energy Laboratory (NREL). Simulations assessed the following dynamic and transient conditions:

1. **Reactive compensation**: Because of the capacitance of the PacWave subsea cables, the CLPUD distribution voltages will increase substantially when PacWave cables are connected unless reactive compensation is added. In addition, there is potential for fluctuating power output from PacWave that could cause fluctuations in CLPUD's distribution voltage. Simulations assessed the reactive compensation that is necessary to mitigate distribution voltage violations and to avoid undesirable operation of tap changers at the CLPUD substations.
2. **Temporary overvoltage (TOV)**: Simulations assessed the impacts of load rejection overvoltage (LROV) and ground fault overvoltage (GFOV) events on the CLPUD distribution and subtransmission systems.
    A. **LROV**: A LROV event is one where a circuit breaker opens upstream of generation, without first stopping the generation. During the time between the breaker opening and the generation shutting down because of anti-islanding protection, there could be generation in a partially islanded power system, sometimes with no ground source, depending on the location of the circuit breaker opened.
    B. **GFOV**: A GFOV event is one where an unbalanced fault (ground fault) causes a circuit breaker upstream of the generation to trip. During the time between the first breaker tripping and the generation shutting down because of anti-islanding protection, there could be generation in a partially islanded and faulted power system, sometimes with no ground source, depending on the location of the ground fault and breaker trip.

    To assess the impacts of LROV and GFOV, NREL performed simulations with a PSCAD model that included worst-case PacWave generation and relevant portions of CLPUD's 12.47-kV distribution and 69-kV subtransmission systems, including circuit breakers and surge arresters.

This report follows earlier work done in 2018 and 2019 by NREL and Williwaw Engineering. The results of that work are shown in Appendix C.

1 PSCAD Model

Figure 1-1 shows an overview of PacWave's grid interconnection via the CLPUD 12.47-kV distribution and 69-kV subtransmission systems; the solid red lines were included in NREL's PSCAD model. Terrestrial and subsea cables will connect four PacWave offshore test berths to a PacWave utility connection and monitoring facility (UCMF) facility on land. The four PacWave subsea cables will be between 16 km and 21 km long and will be operated at up to 30 kV nominal to reduce cable voltage drop. At the UCMF, connections will be made to a CLPUD 12.47-kV distribution feeder that runs north-south along U.S. Highway 101. This feeder primarily connects residential services in the area. During normal operation, the distribution feeder is connected to the Seal Rock substation to the north (circuit SS162 F12), but there is an alternate Lundy substation connection to the south that can be used when the Seal Rock substation is shut down because of maintenance or failures. Both the Seal Rock and Lundy substations connect to CLPUD's 69-kV subtransmission system, which connects to a Bonneville Power Administration (BPA) 230-kV transmission line via transformers at BPA's Toledo substation, approximately 25 km to the northeast. To simplify the PSCAD model, the 69-kV line connecting the Lundy substation directly to Toledo (shown by the dashed red lines in Figure 1-1) was not included in the model because it is normally not connected.

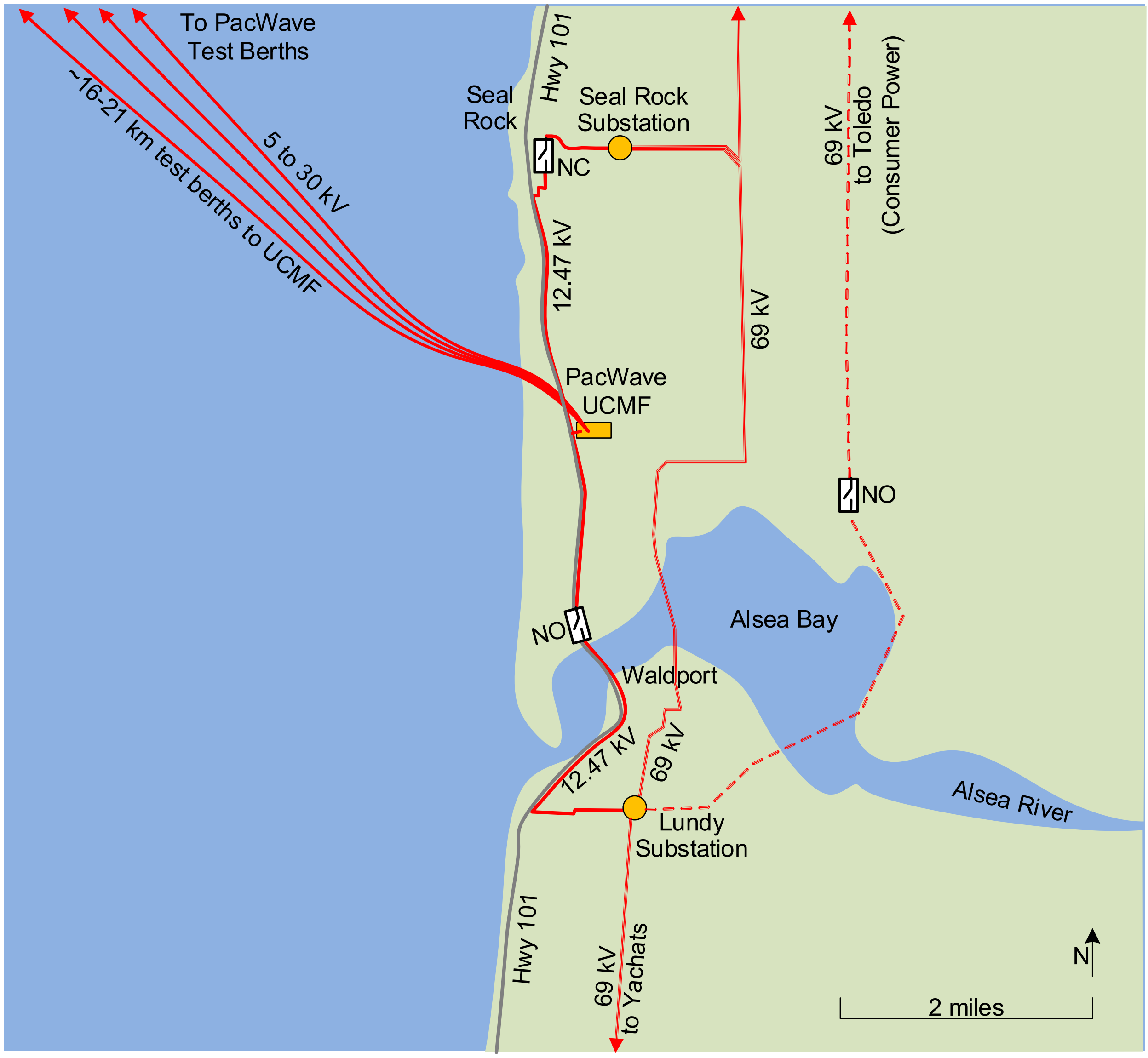


Figure 1-1. Overview of PacWave grid interconnection via CLPUD distribution. The dashed 69-kV lines were not included in the PSCAD model.

See Appendix A for a complete PSCAD diagram of NREL's model. This model is described in detail in the following sections. All subsea, underground, and overhead cables were modeled as pi-sections by using lumped R, L, and C elements, with values specified for each portion of the CLPUD and PacWave cabling.

1.1 PacWave

For this work, PacWave was modeled using the three different generation scenarios shown in Table 1-1, which are expected to have the worst-case impacts on the CLPUD system. See Section 1.1.1 through Section 1.1.3 for descriptions of each generation scenario. The PacWave test facility will be used for short-term testing of different prototype wave energy converter (WEC) designs at each test berth. Each WEC can be connected with different subsea cable

voltages (maximum 30 kV) by changing out transformers on land. Although many different combinations of generator and interconnect designs will be possible at PacWave, the total generation will not exceed 10 MW, and the generation from any test berth will not exceed 5 MW.

Table 1-1. Generation Scenarios Modeled in PSCAD

Generation Scenario	Connection Voltage	Notes
Four 2.5-MW generators	30 kV	See Section 1.1.1. Used for modeling both reactive compensation and TOV. This is the worst-case situation for reactive compensation because all four subsea cables are energized at the highest possible subsea cable voltage (30 kV), and it is the worst case for TOV because total generation is the maximum 10 MW that will be allowed at PacWave.
Two 5-MW generators	30 kV	See Section 1.1.2. Used only for reactive compensation simulations. This scenario was included for comparison to results of earlier 2018–2019 modeling (see Appendix C).
One 700-kW generator	12.47 kV	See Section 1.1.3. Used only for TOV simulations. This scenario was included to show results for PacWave generation approximately equal to the minimum load on the CLPUD feeder.

The following aspects of the PacWave design will be fixed and were modeled the same for each generation scenario:

1. **Subsea and terrestrial cable parameters and lengths**: See Section 1.1.5 for details.
2. **Circuit breakers at UCMF**: One main circuit breaker and four feeder circuit breakers (one per test berth) at the UCMF were modeled. Each circuit breaker was modeled with the relay settings described in Section 1.1.6.
3. **Surge arresters**: One 24.4-kV maximum continuous operating voltage (MCOV) arrester was included at the UCMF termination of each terrestrial cable, and one 10.2-kV MCOV arrester was included at the UCMF main 12.47-kV bus. Surge suppressor modeling details are described in Section 1.5.
4. **Reactive compensation**: The same fixed shunt reactors and STATCOM options were modeled for each generation scenario. See Section 1.1.7 for details.
5. **WEC model**: The same simple model of inverter-connected, 690-V WEC generators connected to the subsea cable with a transformer were used. See Section 1.1.4 for details.

1.1.1 PacWave Model with Four 2.5-MW Generators

The PacWave model with four 2.5-MW generators shown in Figure 1-2 was used for PSCAD simulations of both reactive compensation and TOV. This generation scenario is the worst case for reactive compensation because all four PacWave subsea cables are energized at 30 kV, which will be the maximum allowed. The same scenario was also used for the TOV simulations, where any combination of maximum 10 MW of generation will be the worst case. It is very unlikely that PacWave will operate with four 2.5-MW generators connected at 30 kV because total generation will be limited to 10 MW, and lower power generators can connect at lower cable voltages without excessive cable voltage drop. (UCMF transformers are expected to be changed out for different WEC deployments.) For reactive compensation simulations, all generators were modeled with the ocean wave period power fluctuations described in Section 1.1.4 with perfect correlation among all four generator outputs.

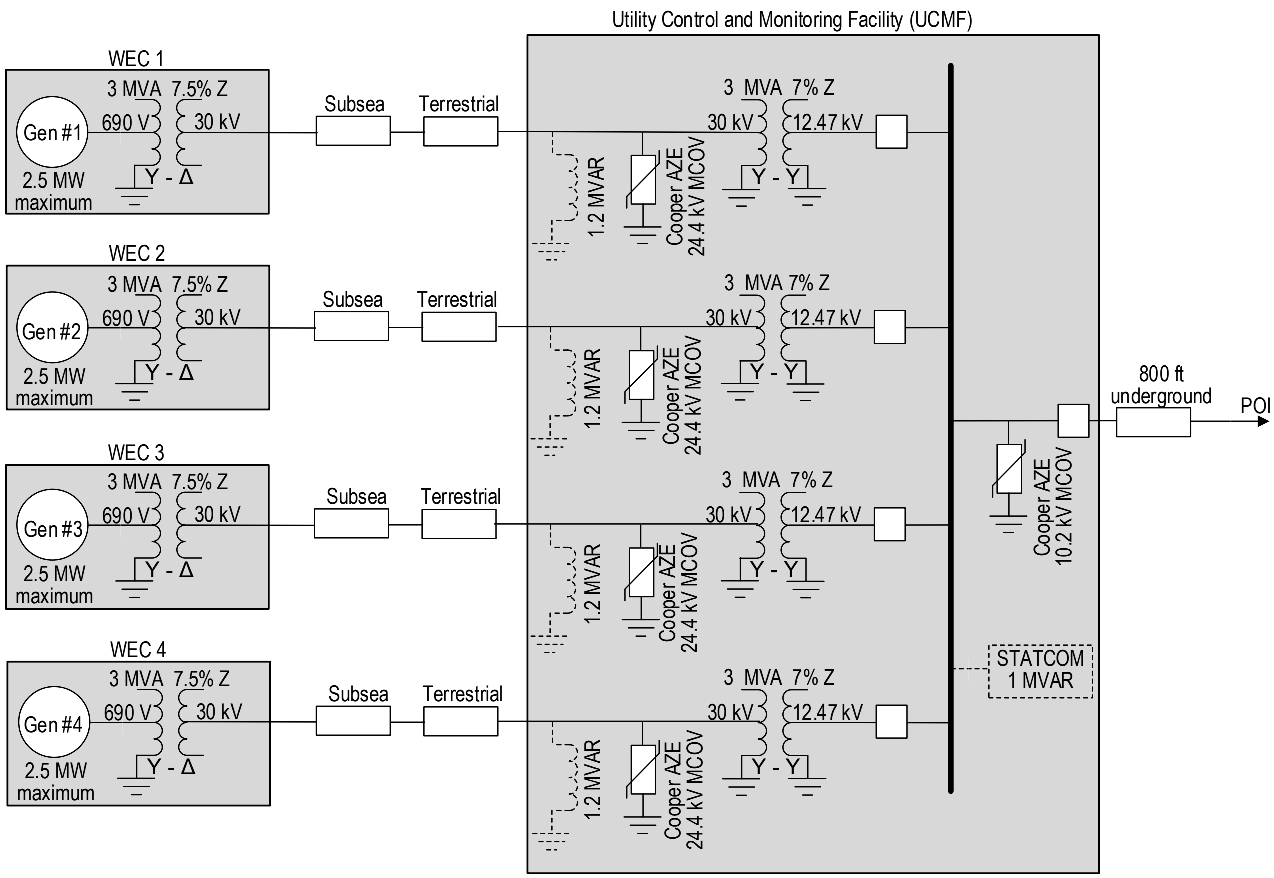


Figure 1-2. PacWave with four 2.5-MW generators connected at 30 kV

1.1.2 PacWave Model with Two 5-MW Generators

The PacWave model with two 5-MW generators shown in Figure 1-3 was used only for the reactive compensation simulations for consistency with previous NREL modeling work done in 2018–2019 (see Appendix C). The two longest PacWave subsea cables alone are energized at 30 kV.

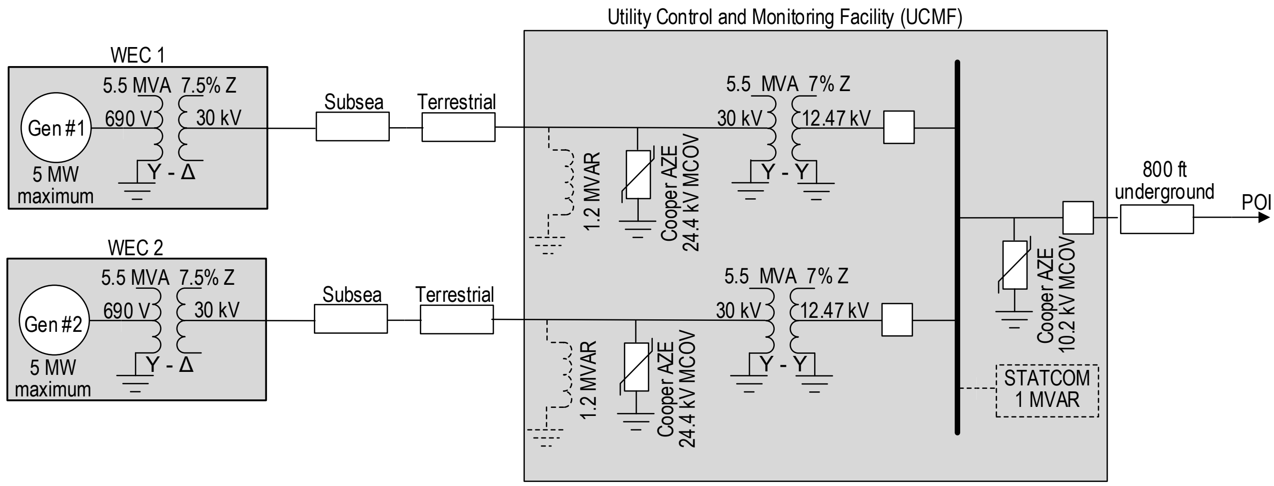


Figure 1-3. PacWave with two 5-MW generators connected at 30 kV

1.1.3 PacWave Model with One 700-kW Generator

The PacWave model with one 700-kW generator shown in Figure 1-4 was used only for the TOV simulations. One subsea cable is energized at 12.47 kV with a direct connection to the CLPUD distribution system. This scenario models total PacWave generation approximately equal to the 700-kW minimum load on the Seal Rock distribution feeder that PacWave will connect to. It is expected that generators in this size range may be connected directly at 12.47 kV because this is an appropriate cable voltage for this power level, and elimination of the transformer at the PacWave UCMF will reduce cost. The removal of the grounded wye transformer connection at the UCMF removes the impedance from the circuit and removes a ground source on the CLPUD system.

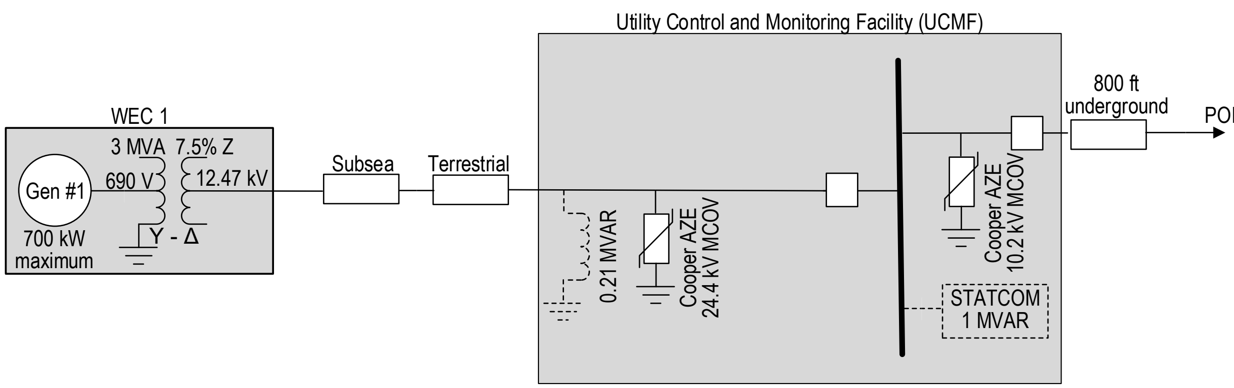


Figure 1-4. PacWave with one 700-kW generator connected at 12.47 kV

1.1.4 PacWave Wave Energy Converter Generator Model

The dynamic model of WEC generators are represented by d-q current sources with independent active and reactive power control loops and a current limiter. The model can simulate the WEC generators in both voltage control and power factor control modes. For this work, we used the power factor control mode with a unity power factor setting for all simulations. Both active and reactive power control loops were tuned to have response times similar to other inverter-based

resources of similar capacities, such as multimegawatt wind turbine generators with full-size power converters.

For reactive compensation simulations, the output power of each generator followed the sinusoidal ocean wave period profile shown in Figure 1-5. Perfect correlation of all PacWave generator outputs was assumed, which is highly unlikely and is considered a worst-case scenario. For the TOV simulations, each generator was modeled as a unity power current source providing constant, maximum power output. During fault conditions, current was limited to 10 % above the rated generator current (the generator current giving 1-MW, 2.5-MW, or 5-MW output at 1-p.u. voltage).

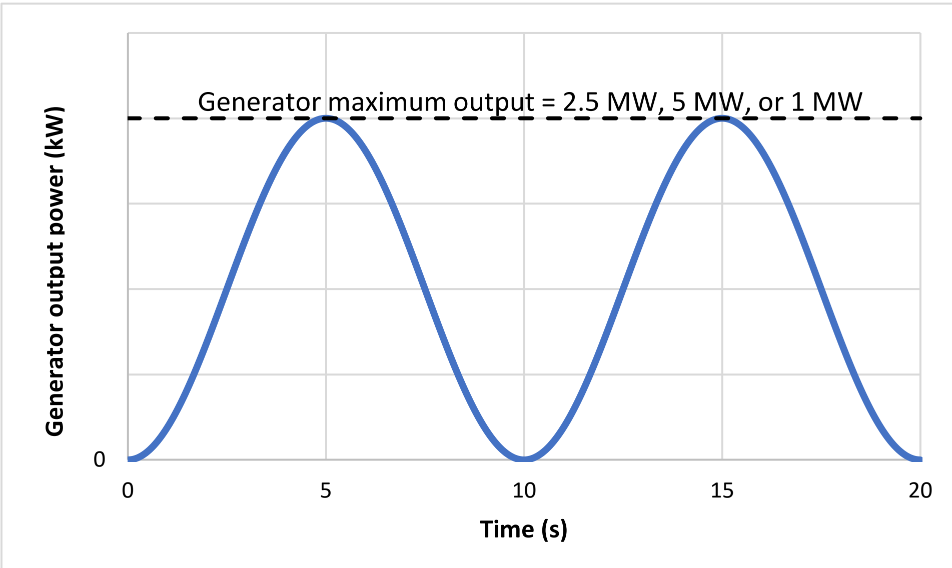


Figure 1-5. PacWave generator output for reactive compensation modeling

1.1.5 PacWave subsea and terrestrial cable parameters

See Table 1-2 and Table 1-3 for the parameters and lengths used to model the PacWave subsea and terrestrial cables in PSCAD. This information is derived from information provided by 3U technologies in late 2019. The subsea cable parameters are for a 50-mm^2 Oceaneering cable. Because PacWave has not yet selected the cable suppliers, final installed lengths and parameters for the PacWave cables might be different.

Table 1-2. PacWave Cable Impedances Used for PSCAD Model

Cable[a]	R1	R0	X1	X0	Xc	Xc0
Subsea	0.5015	0.865238	0.19	0.394172	0.020405	0.020405
Terrestrial	0.055874	0.111748	0.045169	0.090337	0.02625	0.02625

[a] All units are in Ω/km for R and X and in Mohm*km for X_c.

Table 1-3. PacWave Cable Lengths Used for PSCAD Model

Cable	Length
Subsea 1	20.8 km
Subsea 2	19.4 km
Subsea 3	17.4 km
Subsea 4	16.2 km
Terrestrial (all)	0.70 km

1.1.6 PacWave Utility Connection and Monitoring Facility Circuit Breaker Relay Settings

The PSCAD model included the anti-islanding trip settings shown in Table 1-4 and Table 1-5 for all five circuit breakers at the PacWave UCMF. These trip settings are per North American Electric Reliability Corporation (NERC) Standard PRC-024-2 – Generator Frequency and Voltage Protective Relay Settings.[1] Oregon State University will program the circuit breaker relays at the UCMF with these trip settings or settings that are more conservative.

Table 1-4. Voltage Trip Settings per NERC PRC-024 Used for PSCAD Model

Element	Voltage Pickup (Per Unit)	Time Delay (Cycles/S)	Phasing
59-1	1.19	(60/1.0)	Any 1 phase
59-2	1.265	(12/0.20)	Any 1 phase
27-1	0.87	(186/3.1)	Three-phase only
27-2	0.6	(21/0.35)	Three-phase only

Table 1-5. Frequency Trip Settings per NERC PRC-024 Used for PSCAD Model

Element	Frequency Pickup (Hz)	Time Delay (Cycles/S)
81-1	60.6	(11,100/185)
81-2	61.7	(1,800/30)
81-3	59.4	(11,100/185)
81-4	57.8	(540/9.0)

[1] See https://www.nerc.com/pa/Stand/Reliability%20Standards/PRC-024-2.pdf.

1.1.7 Reactive Compensation Modeling

The following reactive compensation components were assessed with the PSCAD modeling:

- **Shunt reactors**: Fixed shunt reactors at the subsea cable side of each transformer at the PacWave UCMF. These were sized at 1.2 MVAR/30 kV (250 ohms) total (400 kVAR per phase) to compensate for the capacitive reactance of the subsea cables. The capacitive reactance of the four subsea cables ranges from 850 kVAR to 1.1 MVAR, depending on specific cable lengths.
- **STATCOM**: A 1-MW STATCOM connected to the main bus of the UCMF that was controlled with Q-V droop. See descriptions of NREL 2018–2019 modeling in Appendix C for details.

The connections of the shunt reactors and STATCOM in the PSCAD model of the PacWave UCMF are shown in Figure 1-2 through Figure 1-4.

The reactive compensation assessment simulations were performed first. Simulations were done with no compensation, shunt reactors alone, and with both shunt reactors and STATCOM. The results showed that the shunt reactors alone will provide sufficient compensation, and these are the least-cost solution. All TOV modeling was then done with the shunt reactors alone.

1.2 CLPUD 12.47-kV Distribution

The PSCAD model of CLPUD's distribution feeders developed by NREL in 2018–2019 was used for all 2020-2021 modeling. Full details are included in Appendix C. This model is shown in Figure 1-6. The PacWave UCMF will connect to the CLPUD SS162 F12 feeder that runs north-south along U.S. Highway 101. This feeder is normally connected to the SS162 Seal Rock substation, but it has an alternate connection to the SS163 Lundy substation via feeder SS163 F12. A normally closed switch south of the Seal Rock substation and a normally open switch at the south end of the SS162 F12 feeder (near the north end of the Alsea Bridge) could be used to switch to the alternate connection. These switches are opened and closed manually, and both are simultaneously closed only for very short times during switching operations.

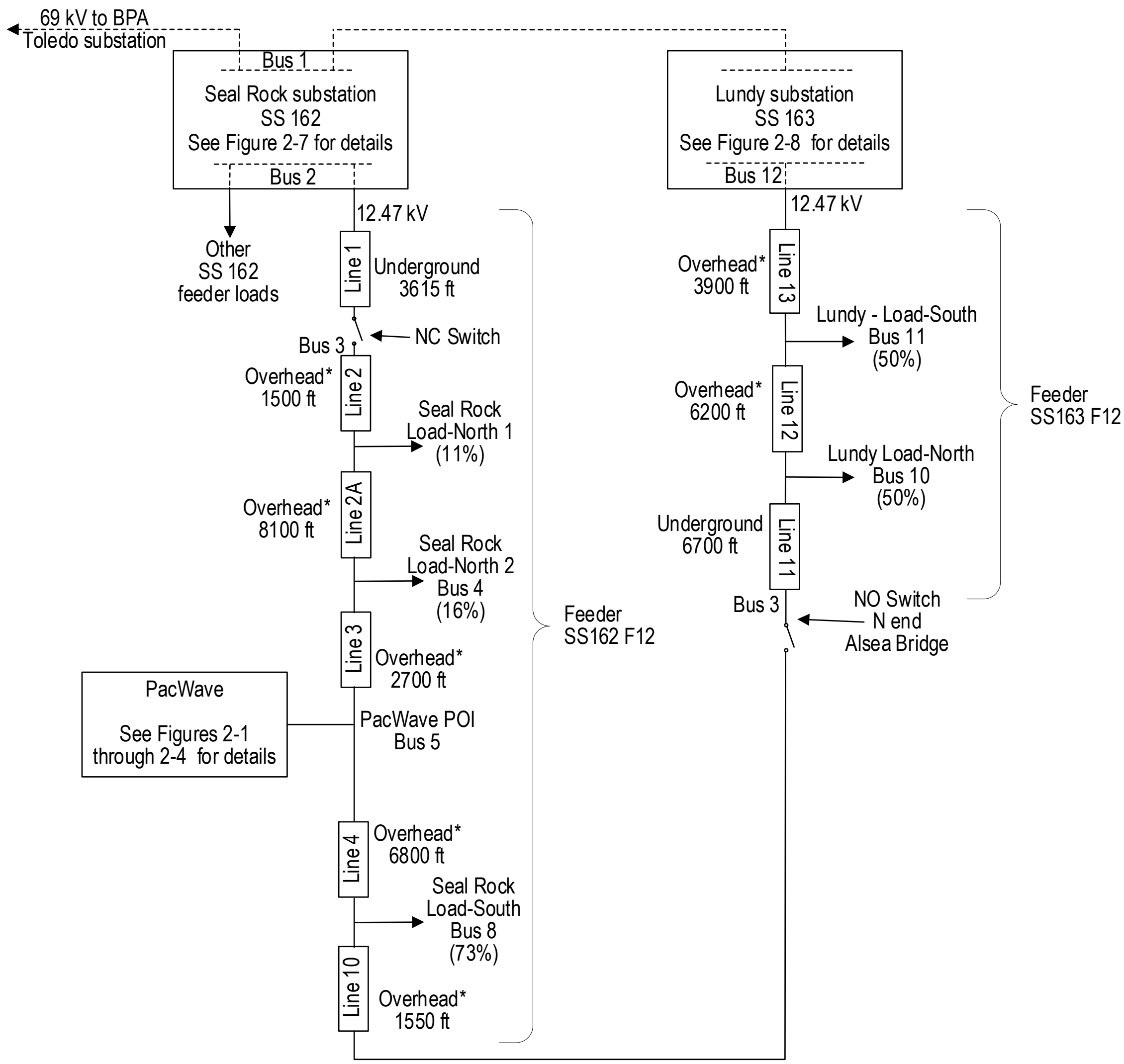


Figure 1-6. PSCAD model of CLPUD 12.47-kV distribution feeders connecting PacWave

1.2.1 CLPUD Distribution Feeder Loads

The estimated loads shown in Table 1-6 were used for the PSCAD modeling. Minimum loading was the worst-case condition for both reactive compensation and temporary overvoltages, and it was used for the simulations unless otherwise noted. The minimum loads were estimated from July 2018 substation data provided by CLPUD. The lowest loads during the year occurred in July because the loads on these feeders are primarily residential and little air conditioning is used on the Oregon coast. Simulation runs were also performed at maximum feeder loading for reactive compensation to verify that the voltages at end of distribution feeders were not too low. The maximum loads were estimated from December 2018 substation data. All feeder loads were modeled with unity power factor. CLPUD provided power factor data for Seal Rock substation loads showing that the power factor exceeded 99.8% during both July 2018 and December 2018, and CLPUD stated that the Lundy and Yachats substation power factor normally exceeds 99%. An aggregate load model was used for the feeders connecting PacWave with the total feeder loads segregated per the percentages shown in Figure 1-6. This aggregate load model was developed for earlier work done in 2018–2019; see Appendix C for details.

To simplify reactive compensation modeling, the Yachats substation and loads were not included in the model, and only the Lundy SS162 F12 feeder loads were included in the model.

Table 1-6. CLPUD Distribution Feeder Minimum Loads Used for PSCAD Modeling

Distribution Feeder	Minimum Load	Maximum Load
Seal Rock total all feeders	3,000 kW	NA
Seal Rock SS162 F12	700 kW	5,000 kW
Seal Rock other feeders	2,300 kW	NA
Lundy total all feeders	2,000 kW	NA
Lundy SS163 F12	450 kW	2,500 kW
Lundy other feeders	1,550 kW	NA
Yachats total all feeders	1,500 kW	NA

1.3 CLPUD Seal Rock, Lundy, and Yachats Substations

The PSCAD model used for the CLPUD Seal Rock substation is shown in Figure 1-7. The substation transformer has a de-energized tap changer on the high-voltage side that is set to 65.2 kV and an on-load tap changer on the low-voltage side. To simplify the model, the on-load tap changer was fixed at the center tap position (17th of 33 taps). In actual operation, the CLPUD on-load tap changer control will regulate the low-voltage substation buses within the voltage band from 1.017 p.u. to 1.042 p.u. (123.5 ±1.5 V on a 120-V basis).

For the Seal Rock substation, circuit breakers were included on both the high- and low-voltage sides of the transformer, and other feeder loads not connecting to PacWave were modeled as a single lumped load at the substation bus. CLPUD has surge arresters installed on both sides of the substation transformer, but those arresters were not included in the PSCAD model for the Seal Rock substation (they were modeled as open circuits). The Cooper arrester on the 12.47 kV side of the substation has a design that includes a proprietary insulating ceramic ring assembly, which gives it infinite TOV capability. This makes it difficult to model in PSCAD. The surge arresters on the 69 kV side of the Seal Rock substation are significantly higher voltage arresters than used at the Lundy and Yachats substation. In both cases it was simpler and more conservative to model these arresters as open circuits, and minimal energy absorption was expected in these arrestors during TOV evens because these arresters have higher breakover voltages than other arresters in the system.

The PSCAD models for the Lundy and Yachats substations are shown in Figure 1-8 and Figure 1-9. The design details provided by CLPUD for these two substations are similar to the Seal Rock substation. The PSCAD model of the Lundy and Yachats substations was simplified by leaving out the circuit breakers because no modeling was done that required those circuit breakers to be opened. CLPUD uses lower voltage surge arresters on the 69 kV side of the transformers at both the Lundy and Yachats substations, and those arresters were included in the PSCAD model because, due to their lower breakover voltages, they are more likely to absorb energy during TOV events than the arresters at the Seal Rock substation.

The saturation of transformers was not included in the PSCAD model.

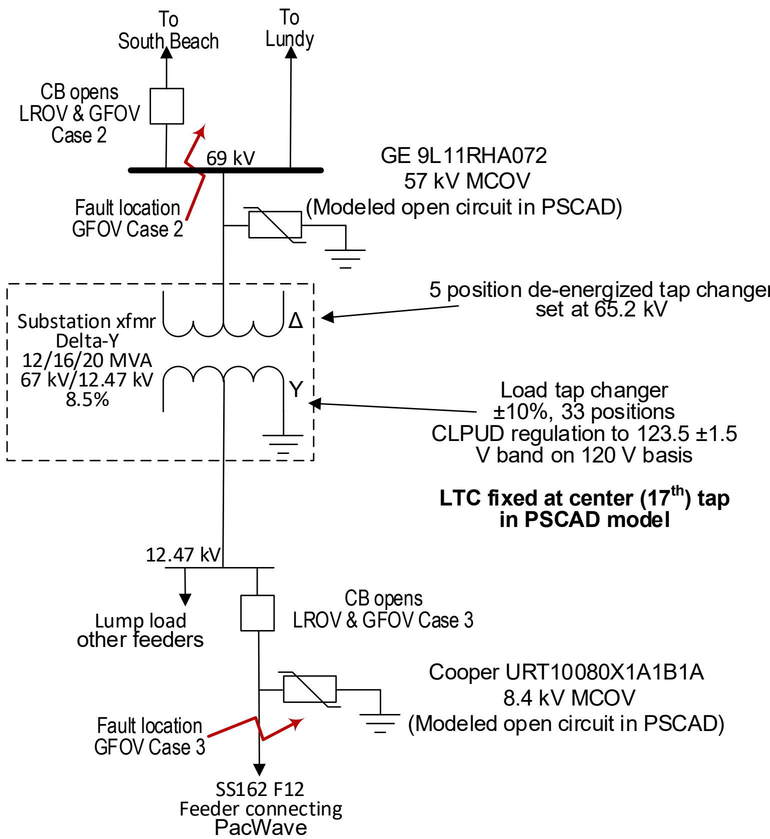


Figure 1-7. Seal Rock substation PSCAD model

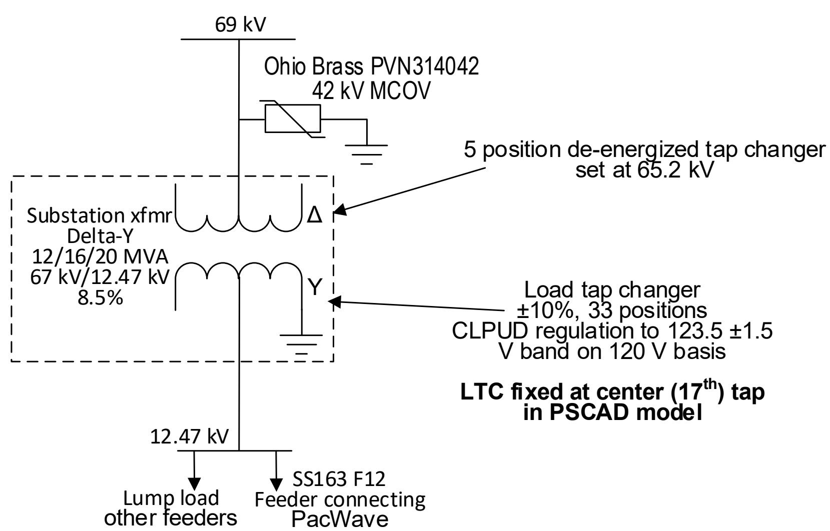


Figure 1-8. Lundy substation PSCAD model

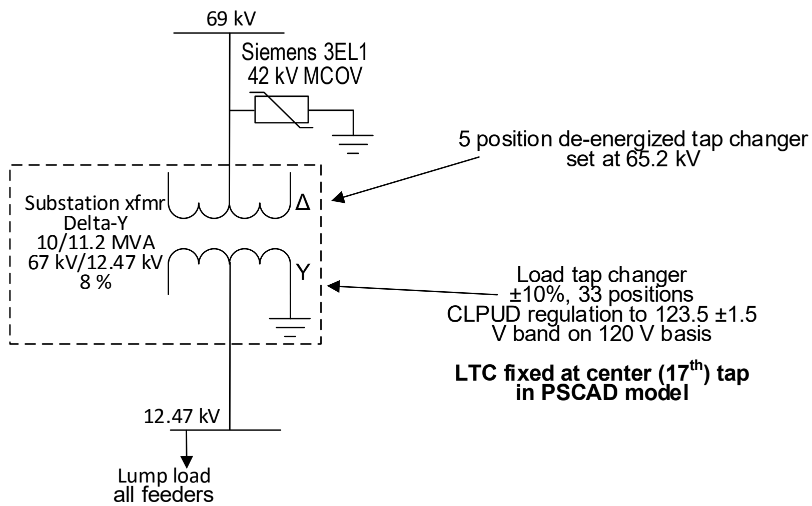


Figure 1-9. Yachats substation PSCAD model

1.4 CLPUD 69-kV Subtransmission

See Figure 1-10 for a diagram showing how the CLPUD 69-kV subtransmission was modeled in PSCAD. The normal CLPUD 69-kV subtransmission path between BPA's Toledo substation and the Seal Rock and Lundy substations is via the CLPUD Lower Olalla, Toledo, and South Beach substations. These lines were modeled in PSCAD using overhead line lengths and information provided by CLPUD. BPA provided fault data for the 69-kV bus at its Toledo substation. Note that alternate, normally open 69-kV connections that are primarily used for maintenance or during failures are not included in this model. Also, transformer saturation was not included in the PSCAD model.

The Yachats substation was not included in the model used for reactive compensation.

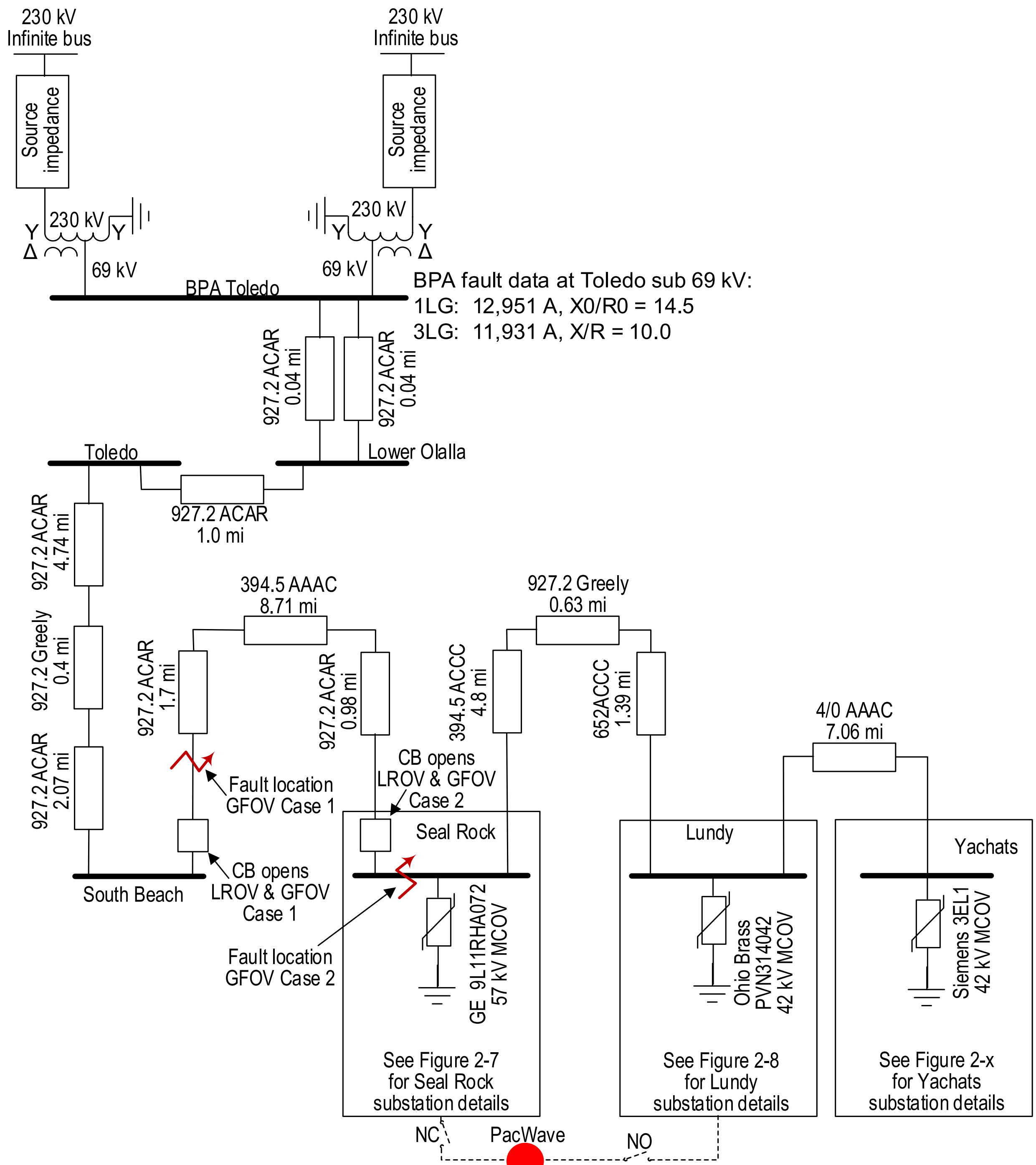


Figure 1-10. CLPUD 69-kV subtransmission connection of PacWave to BPA 230-kV transmission

1.5 Surge Arrester Modeling

The surge arrestors that are presently installed at the CLPUD substations near PacWave and are planned for installation at the PacWave UCMF are listed in Table 1-7. The locations of the CLPUD substation arresters are shown in Figure 1-7 through Figure 1-9 and the locations of the UCMF arresters are shown in Figure 1-2 through Figure 1-4. In addition, CLPUD uses 8.4 kV MCOV elbow arresters together with equivalent parking stand arresters at several pad-mounted transformers along their 12.47-kV distribution feeder. To simplify modeling, some surge arresters were not included in the PSCAD model and were effectively modeled as open circuits, as shown in the right column of Table 1-7. This was done to simplify the model for arresters that were not expected to absorb significant energy during the TOV events being simulated. Leaving these arresters out of the model gave more conservative results. PSCAD simulation voltages at these arrester locations were still checked against manufacturer published TOV capability as was done for all arresters, with results provided in Section 2.2. In the case of the CLPUD parking stand arresters, specific arrester locations along the distribution line were not known so voltages at the PacWave point of interconnection were used to check against arrester TOV capability.

Table 1-7. Surge Arresters at CLPUD Substations and PacWave UCMF

Arrester	Manufacturer	Part Number	Arrestor Voltage Rating	MCOV	In PSCAD Model?
Seal Rock substation (69 kV side)	GE	9L11RHA072	72 kV	57 kV	No
Lundy substation (69 kV side)	Ohio Brass	PVN314042	54 kV	42 kV	Yes
Yachats substation (69 kV side)	Siemens	3EL1 Series	54 kV	42 kV	Yes
Seal Rock substation (12.47 kV side)	Cooper	URT10080X1A1B1A	10 kV	8.4 kV	No
UCMF 12.47 kV	Cooper	Type AZE	12 kV	10.2 kV	Yes
UCMF 30 kV	Cooper	Type AZE	30 kV	24.4 kV	Yes
CLPUD elbow arresters	Cooper	3238018C10M	10 kV	8.4 kV	No

Arresters were modeled in PSCAD with the current-voltage characteristics that are shown in Figure 1-11, based on information provided by arrester manufacturers.

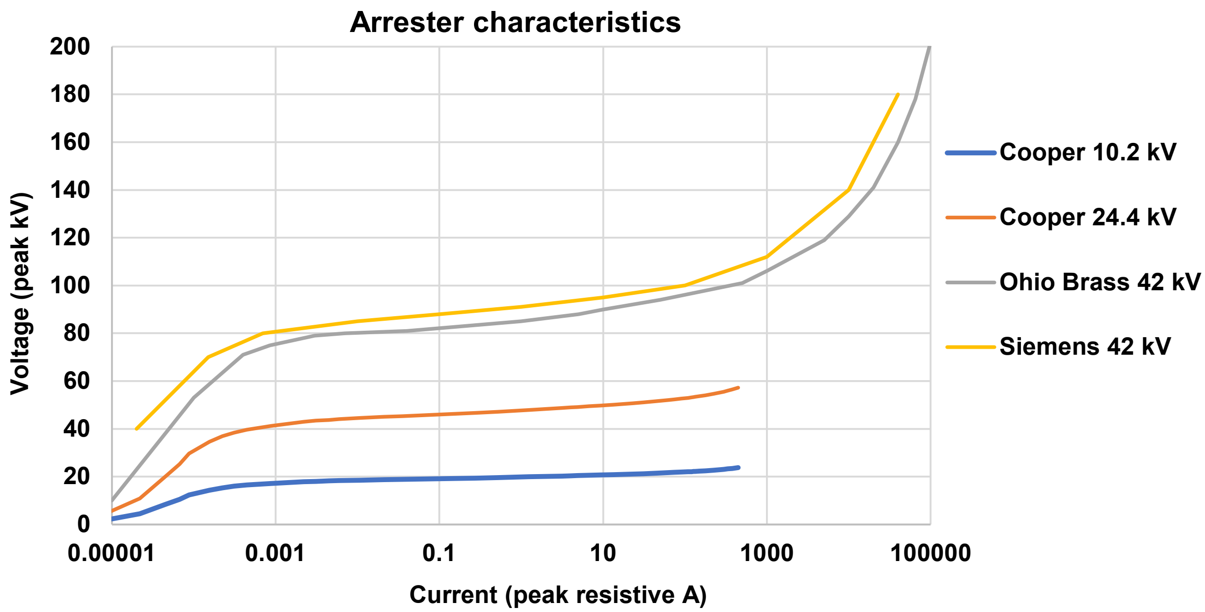


Figure 1-11. Arrester current-voltage curves used in PSCAD

The TOV capability of each CLPUD and PacWave UCMF arrester is shown in Figure 1-12 for operation with no prior duty. These TOV curves are based on published data from arrester manufacturers, and were used to assess potential arrester TOV damage in the results. All of the arresters other than the Cooper URT arresters use metal oxide varistor (MOV) technology. The Cooper URT arresters use a design that has an insulating ceramic ring together with MOV disks. This gives that arrester the flat TOV capability with respect to time that is different than the MOV arresters.

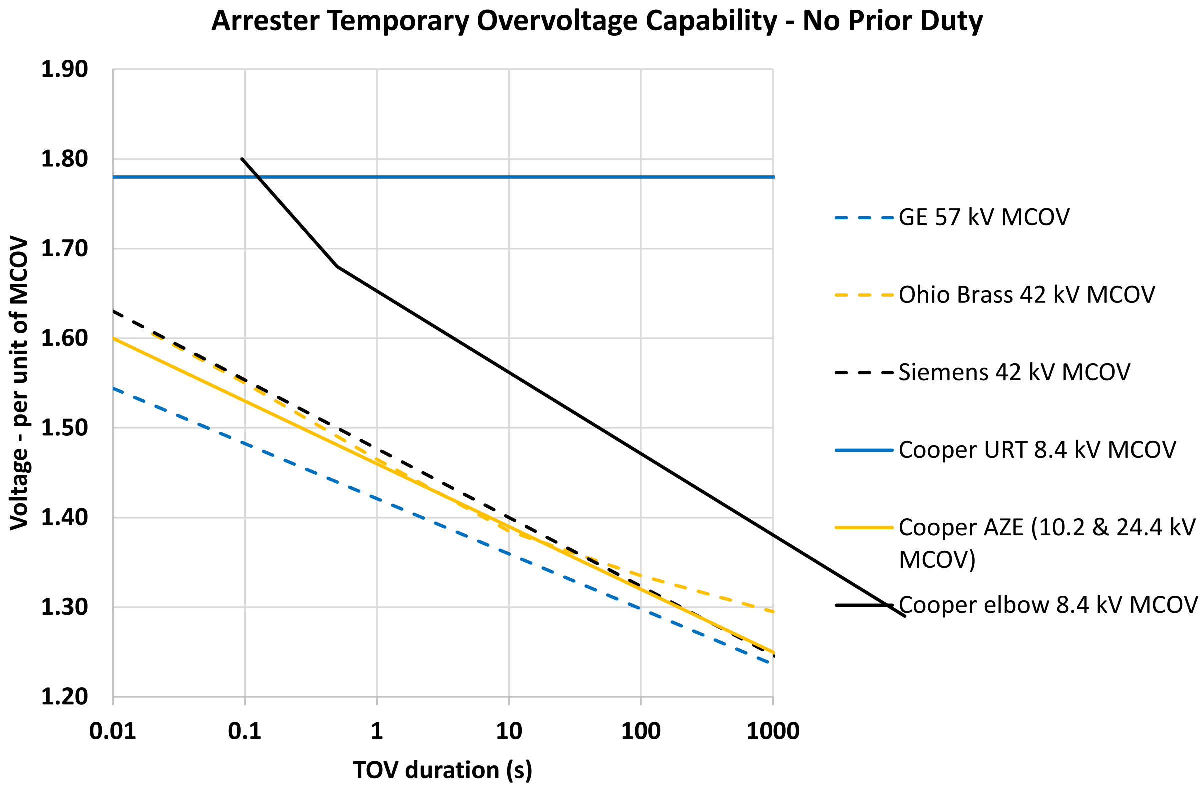


Figure 1-12. Arrestor TOV Capability

2 Results

2.1 Reactive Compensation Results

Results for the PSCAD reactive compensation simulations are shown in the time plots in the following subsections. Results are shown first for the normally used Seal Rock substation connection, then for the Lundy substation, which is used only when the Seal Rock connection is not available.

The NREL PSCAD model does not include regulation of the substation on-load tap changers. In the model, tap changers are fixed at the center position. In actual operation, CLPUD tap changer control will normally maintain Bus 2 (Seal Rock low voltage) and Bus 12 (Lundy low voltage) in

the regulation band from 1.017 p.u. to 1.042 p.u. (123.5 ±1.5 V on a 120-V basis). This will shift other voltages shown in the plots relative to the substation 69-kV bus (Bus 1).

To avoid adverse effects on the CLPUD substation operation and CLPUD distribution customers:

1. Voltage swings at CLPUD low-voltage buses (Bus 2 and Bus 12 for Seal Rock and Lundy) should not exceed 2% so that swings are always less than the CLPUD 2.5% wide on-load tap changer regulation band. This will give CLPUD confidence that PacWave operations will not cause increased use of these devices, which could result in accelerated maintenance and loss of life. The CLPUD on-load tap changer controls do have a 45-second delay, but longer time period voltage swings are possible from PacWave than are shown in these results.
2. CLPUD distribution customers should not experience voltage swings greater than ±5% of nominal per guidelines per ANSI C84.1. This applies to all voltages shown on the CLPUD 12.47-kV distribution system.
3. Higher WEC generator voltages are acceptable because this will not affect the CLPUD system, and the WECs can be designed to accommodate this, if necessary.

The results described in the following subsections generally show that:

1. With no reactive compensation, distribution voltages are significantly higher than the substation bus voltages, so they will exceed 1.05 p.u. with the worst case PacWave generation. This is not acceptable, and some form of reactive compensation is necessary.
2. When compensation with either shunt reactors alone or the combination of shunt reactors and STATCOM is added, substation voltage swings do not exceed 2%, voltage swings do not exceed approximately 2%–3% throughout the distribution feeder for the Seal Rock connection or 3%–4% for the Lundy connection, and distribution voltages remain in the window from 0.95 p.u. to 1.05 p.u. recommended by ANSI C84.1 When the STATCOM is included, voltage swings at the PacWave point of interconnection are reduced compared to compensation with shunt reactors alone, but voltage swings at the substations are not reduced.

2.1.1 PacWave Connection to Seal Rock Feeder with Four 2.5-MW Wave Energy Converters

Figure 2-13 through Figure 2-15 show results for the Seal Rock connection of PacWave with four WECs generating 0 MW to 2.5 MW connected (the PacWave generation scenario shown in Figure 1-2), with and without reactive compensation.

Figure 2-13 shows baseline results with no reactive compensation at PacWave. In this case, the CLPUD distribution voltages will significantly exceed 1.05 p.u. This is not acceptable, so some form of reactive compensation will be necessary.

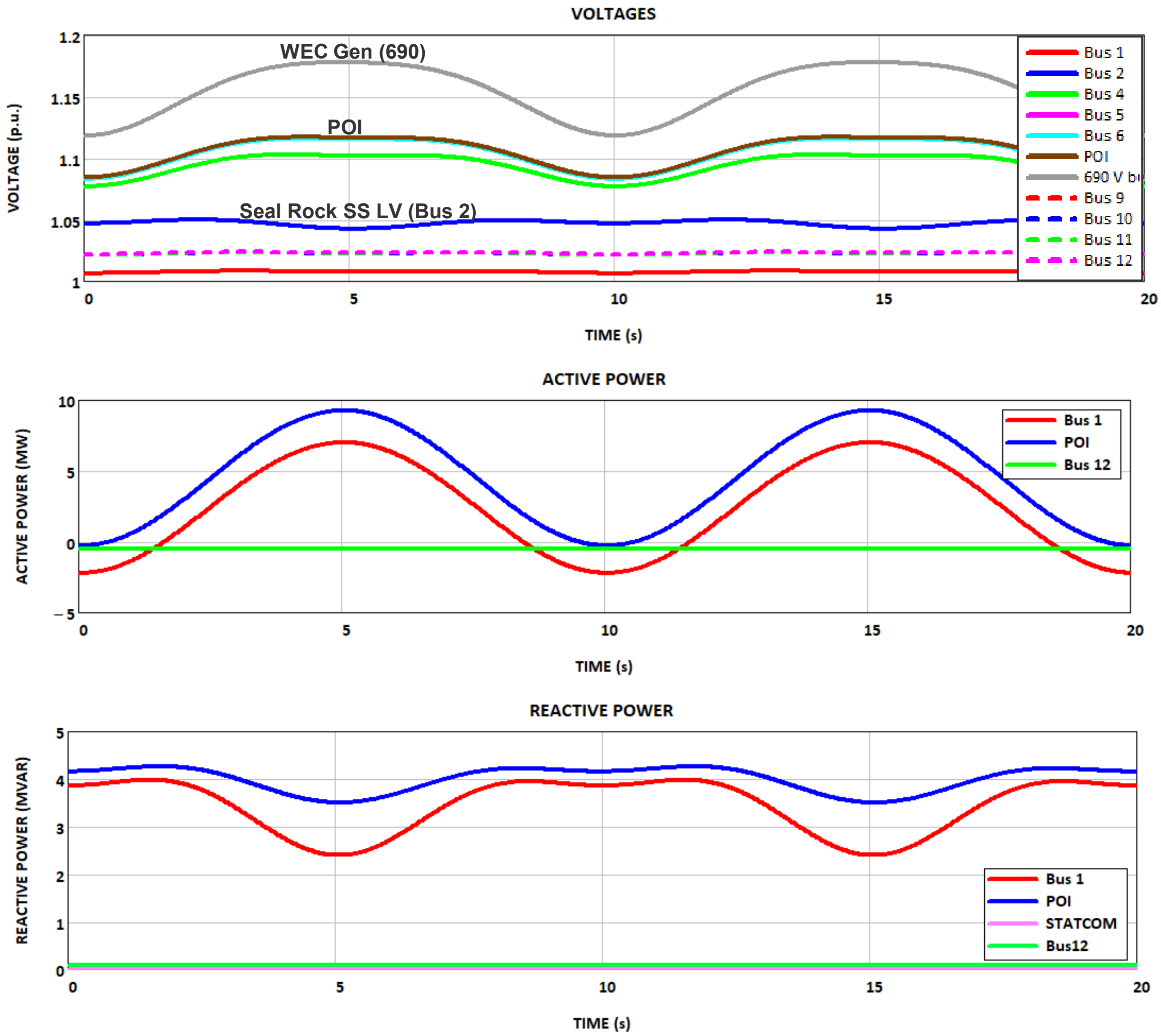


Figure 2-13. Seal Rock connection—no reactive compensation at PacWave UCMF

Figure 2-14 shows results with four 1.2-MVAR shunt reactors added at PacWave (one per subsea circuit to cancel out capacitive cable charging). If CLPUD on-load tap changer regulation is considered, Bus 2 (Seal Rock substation) will shift up into the regulation window from 1.017 p.u. to 1.042 p.u., with all other voltages except Bus 1 (Seal Rock substation high-voltage bus) shifting up by approximately the same amount. Bus 2 (Seal Rock substation) swings less than 2%, so the fluctuations resulting from the PacWave generation should not cause excessive switching of the tap changer. The other distribution voltages are never significantly higher than the substation Bus 2 voltage, so they will never exceed 1.05 p.u. during normal CLPUD operation. No distribution voltages swing more than 2%, so CLPUD customer voltage ranges should remain within the recommended ANSI 84.1 ranges.

WEC generator voltage can increase as much as 2% greater than the substation voltage, so it can exceed 1.05 p.u. This will not affect CLPUD, but it will need to be considered in the WEC electrical designs.

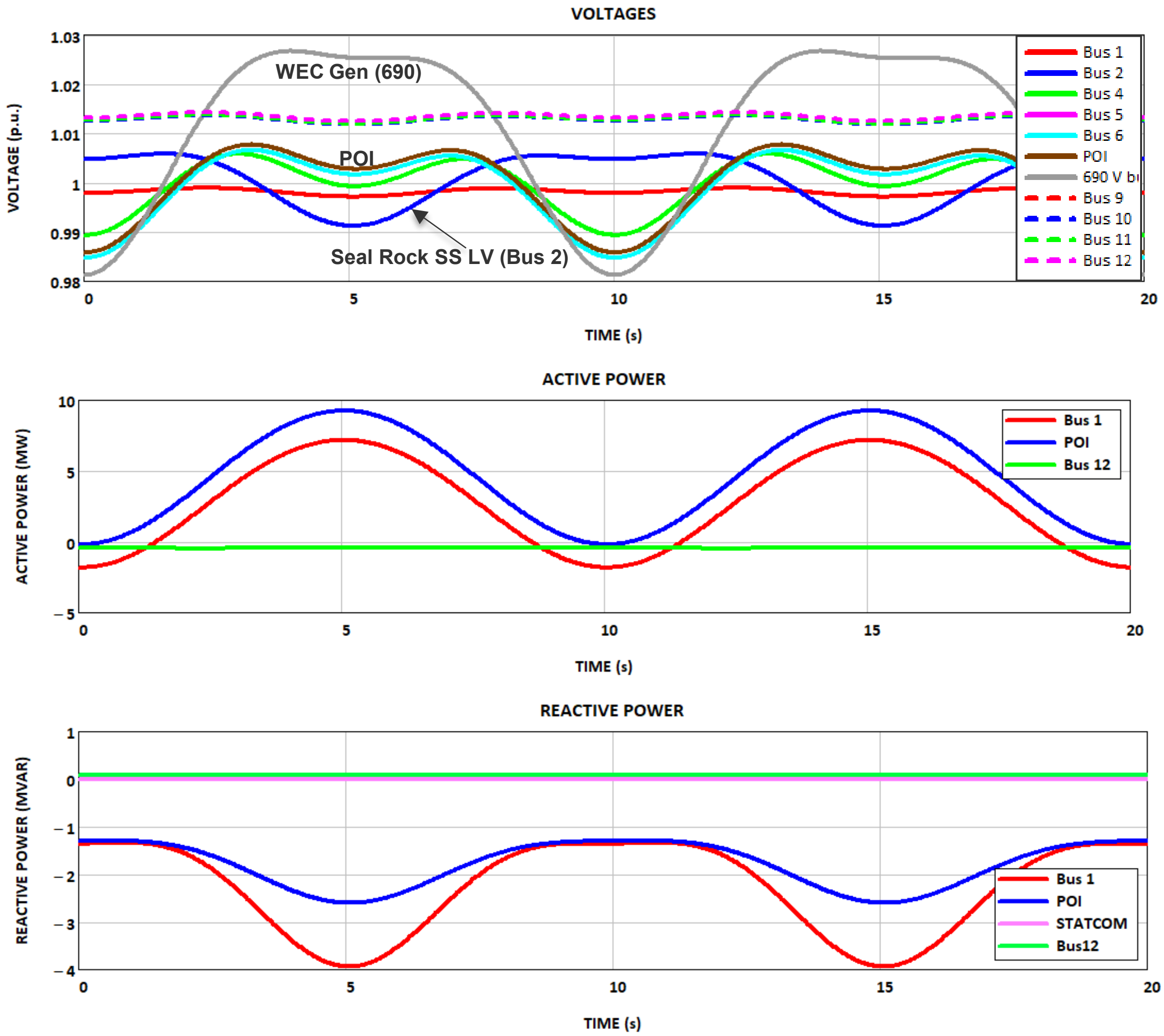


Figure 2-14. Seal Rock connection—compensation with 1.2-MVAR shunt reactors

Figure 2-15 shows results with a 1-MVAR STATCOM added at PacWave in addition to the 1.2-MVAR shunt reactors. The STATCOM is controlled with Q-V droop. The results are similar to the results for shunt reactors alone (Figure 2-14), except that the voltage swings at the PacWave point of interconnection are reduced. The voltage swing at the substation (Bus 2) increases some, but it still does not exceed 2%.

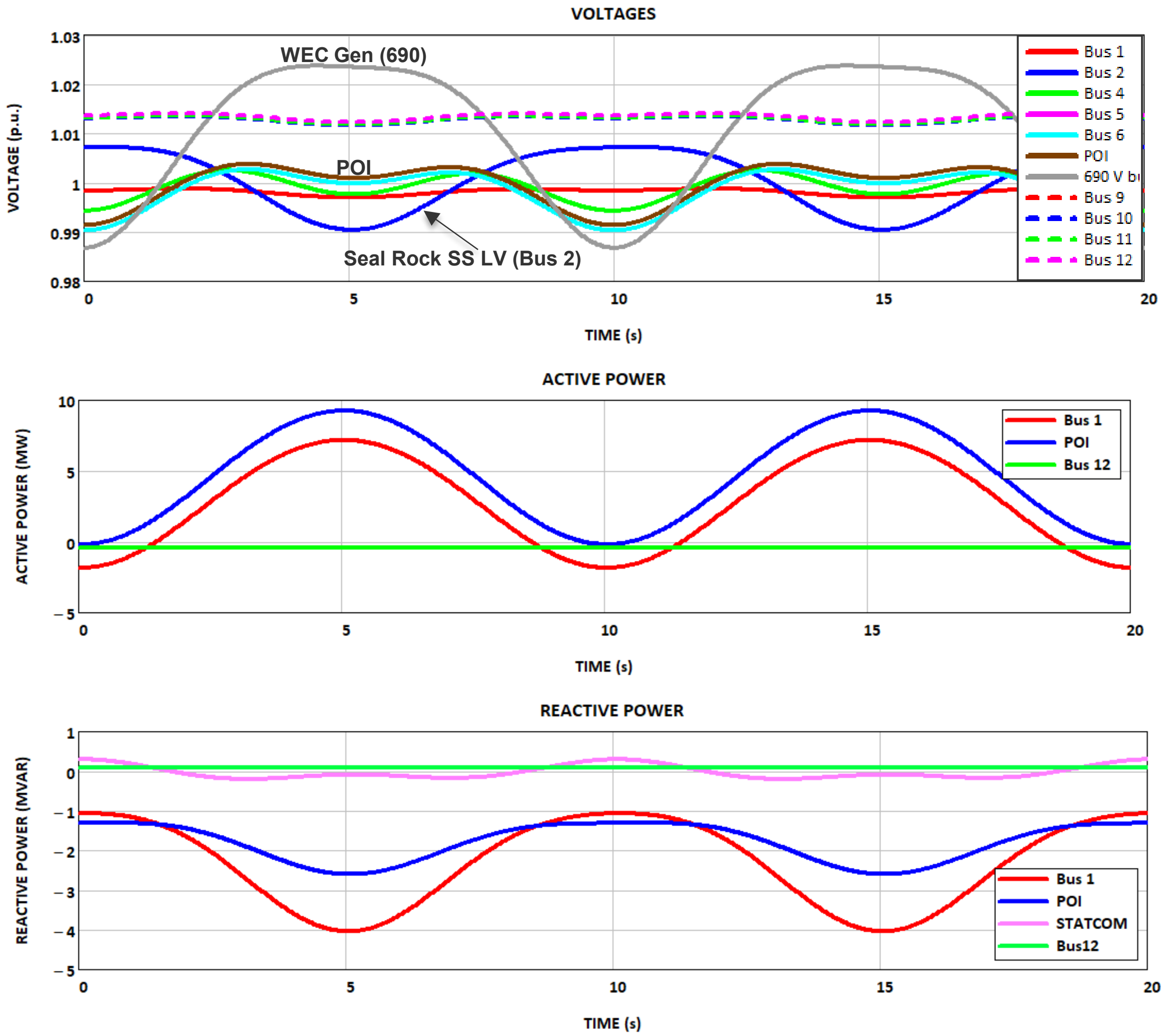


Figure 2-15. Seal Rock connection—compensation with both 1-MVAR STATCOM and 1.2-MVAR shunt reactors

Figure 2-16 shows results with maximum loads on the distribution feeder with four 1.2-MVAR shunt reactors (same configuration as Figure 2-14, with the exception of loads). If CLPUD on-load tap changer regulation is considered, Bus 2 (Seal Rock substation) will shift up into the regulation window from 1.017 p.u. to 1.042 p.u., with all other voltages except for Bus 1 (Seal Rock substation high-voltage bus) shifting up by approximately the same amount. Considering this, these results show all feeder voltages will exceed 0.95 p.u. that at maximum load. Bus 2 (Seal Rock substation) swings less than 1%, so the fluctuations caused by the PacWave generation should not cause excessive switching of the tap changer. Distribution voltages swing by approximately 3%.

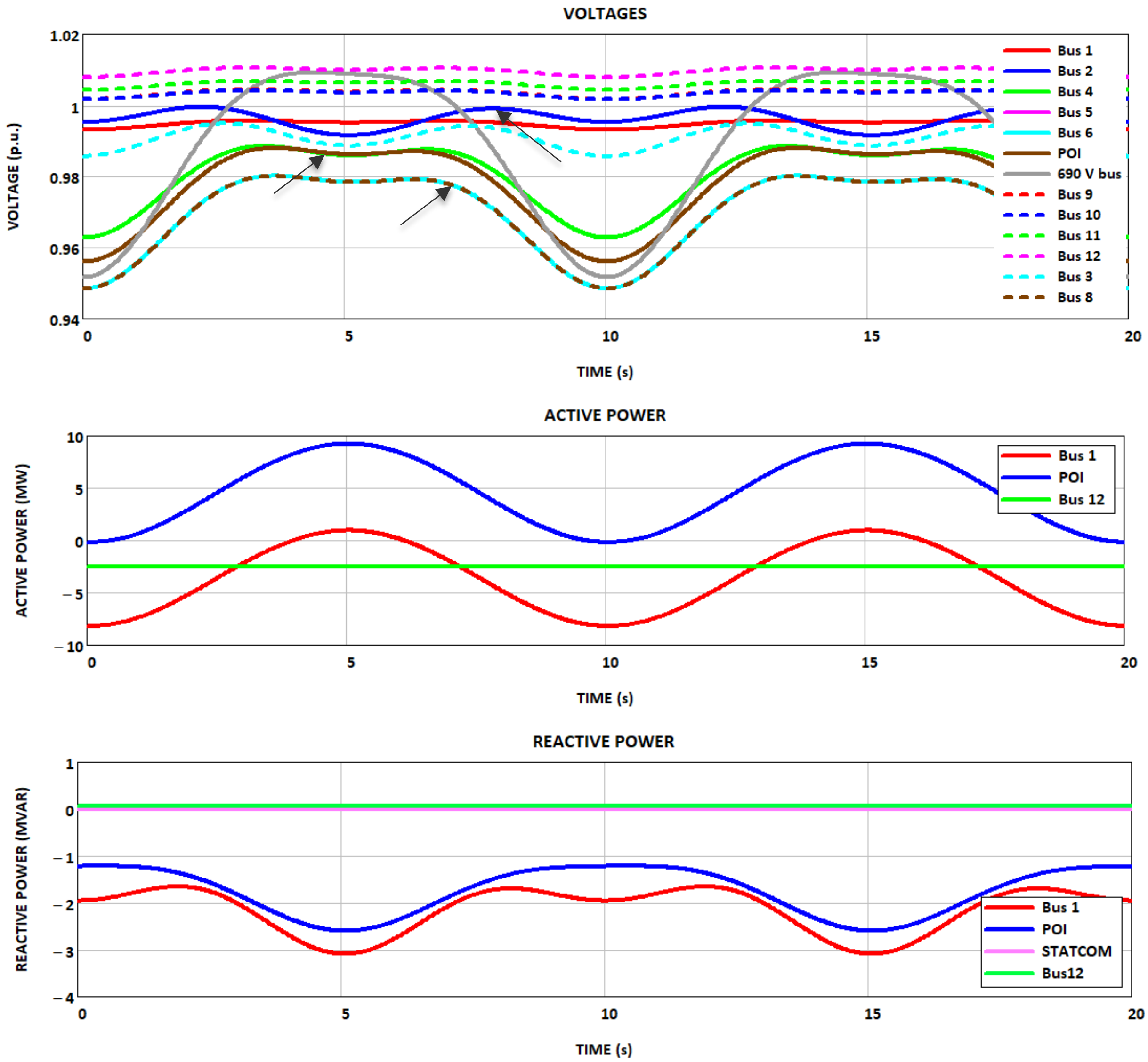


Figure 2-16. Seal Rock connection—compensation with 1.2-MVAR shunt reactors, maximum feeder loads

2.1.2 PacWave Connection with Two 5-MW Wave Energy Converters

See Figure 2-17 for results with two 5-MW WECs connected at 30 kV at PacWave (the generation scenario described in Section 1.1.2) with the PacWave connection to the Seal Rock feeder. Results are shown for only the 1.2-MVAR shunt reactor compensation. Substation voltage swings are less than 2%, and other distribution voltage swings are only a little more than 2%. The maximum PacWave point of interconnection voltage is approximately 1% greater than the maximum substation voltage, however, with similar voltages north and south of PacWave on the distribution feeder. This will cause distribution voltages to be 1.05 p.u. or slightly higher, but only when the maximum substation voltage (Bus 2) is on the upper end of the on-load tap changer regulation range (1.017 p.u. to 1.042 p.u.). The maximum WEC generation voltage is also quite high—approximately 5% greater than the maximum substation voltage. Although this will not affect CLPUD, it will need to be considered in the WEC electrical designs.

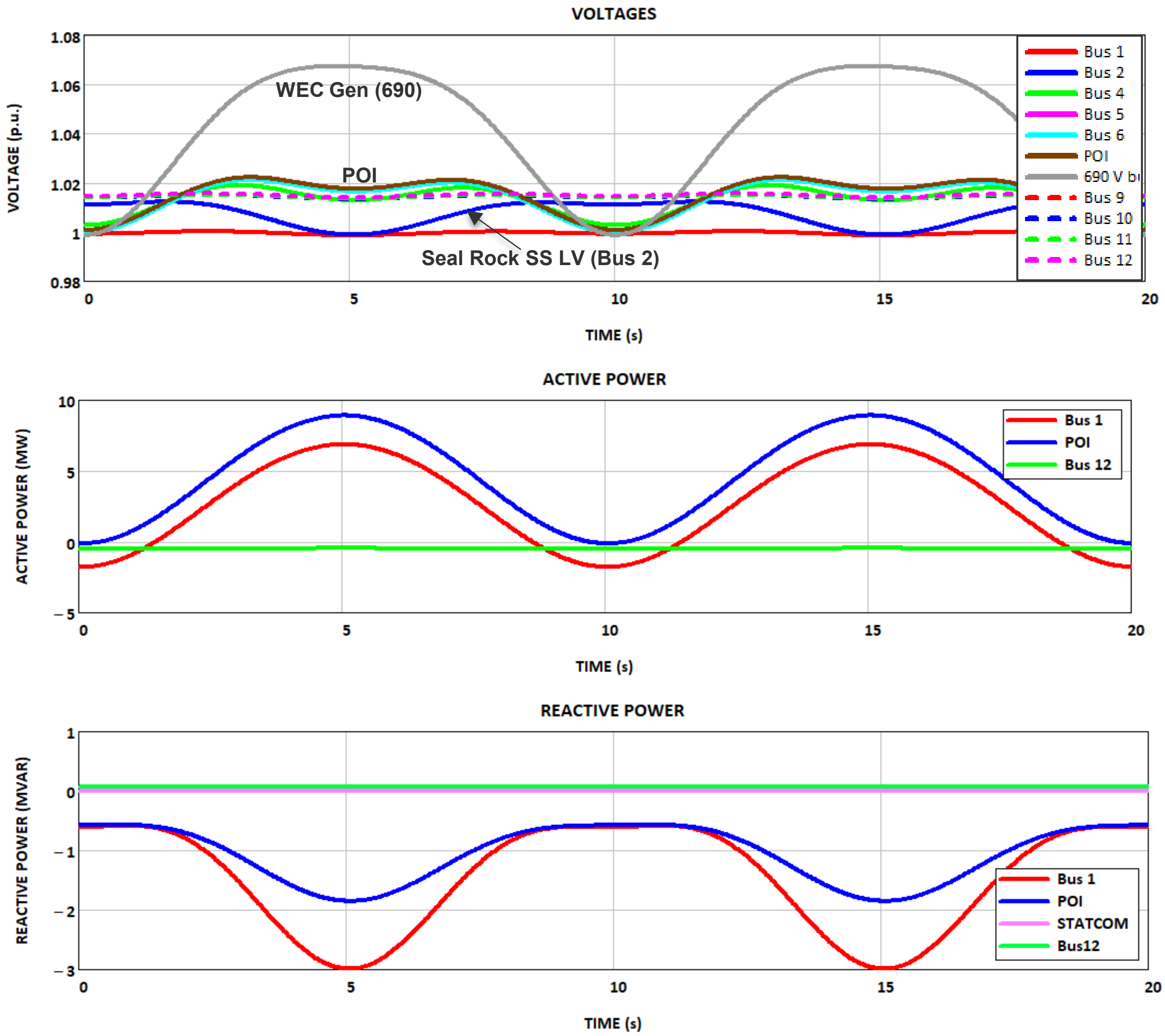


Figure 2-17. Seal Rock—two 5-MW PacWave generators and compensation with 1.2-MVAR shunt reactors

See Figure 2-18 for results with two 5-MW WECs connected at 30 kV at PacWave, with the PacWave connection to the Lundy feeder and 1.2-MVAR shunt reactors for reactive compensation. Results are similar to those shown in Figure 2-5 for the Seal Rock connection, except the PacWave point of interconnection swings by approximately 3% and sometimes exceeds the maximum substation voltage by as much as 1.2%. This could cause distribution voltages to be approximately 1.055 p.u. when the maximum substation voltage (Bus 2) is at the upper end of the on-load tap changer regulation range (1.017 p.u. to 1.042 p.u.). This is a result of the longer line lengths for the Lundy connection.

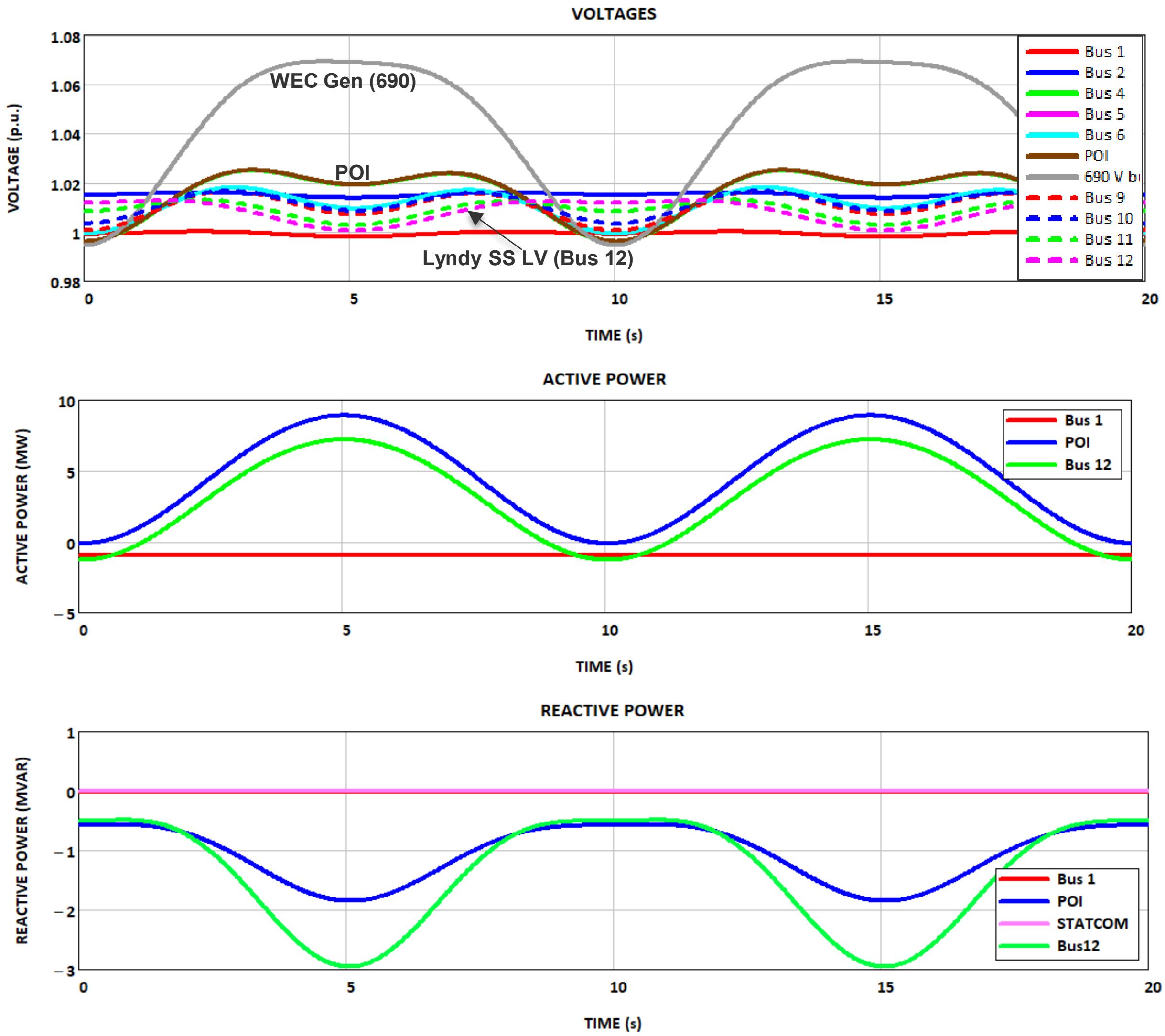


Figure 2-18. Lundy—two 5-MW PacWave generators and compensation with 1.2-MVAR shunt reactors

2.1.3 PacWave Connection to Lundy Feeder with Four 2.5-MW Wave Energy Converters

See Figure 2-19 for results with reactive compensation with shunt reactors alone when PacWave is connected to the Lundy substation. The voltage swing at the substation (Bus 12) is much less than 2%, and the feeder voltages (including the PacWave point of interconnection) never exceed the maximum voltage seen at the substation. The voltage swing at the PacWave point of interconnection is approximately 3%—higher than what is seen with the Seal Rock connection. This is a result of the longer line lengths for the Lundy connection.

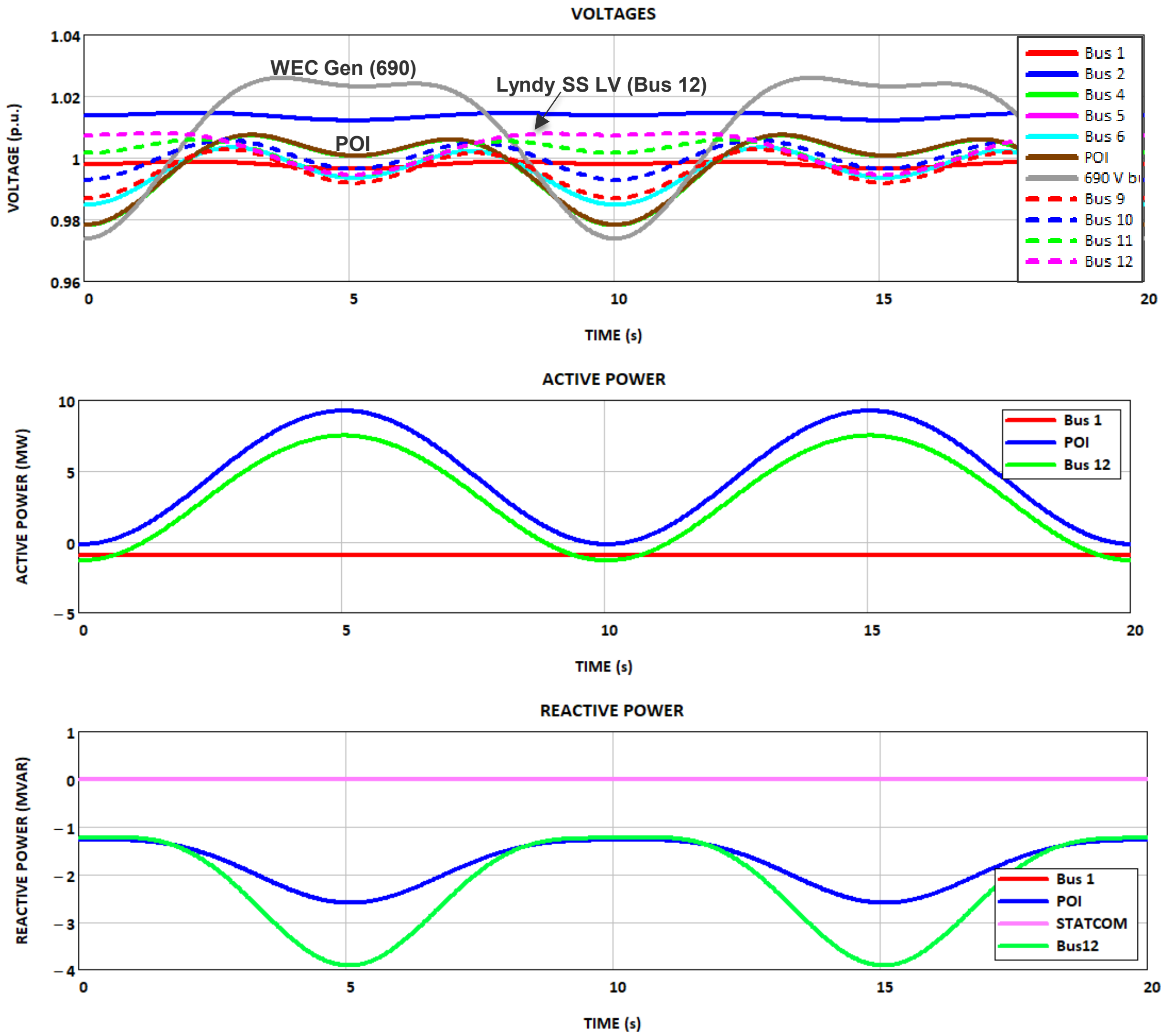


Figure 2-19. Lundy connection—compensation with 1.2-MVAR shunt reactors

See Figure 2-20 for results with the STATCOM added at PacWave in addition to the shunt reactors alone with PacWave connected to the Lundy substation. Compared to the results shown in Figure 2-19 for the shunt reactors alone, the voltage swings at the PacWave point of interconnection are reduced by approximately 50%—to approximately 1.5%. Voltage swings at the substation (Bus 2) are increased slightly.

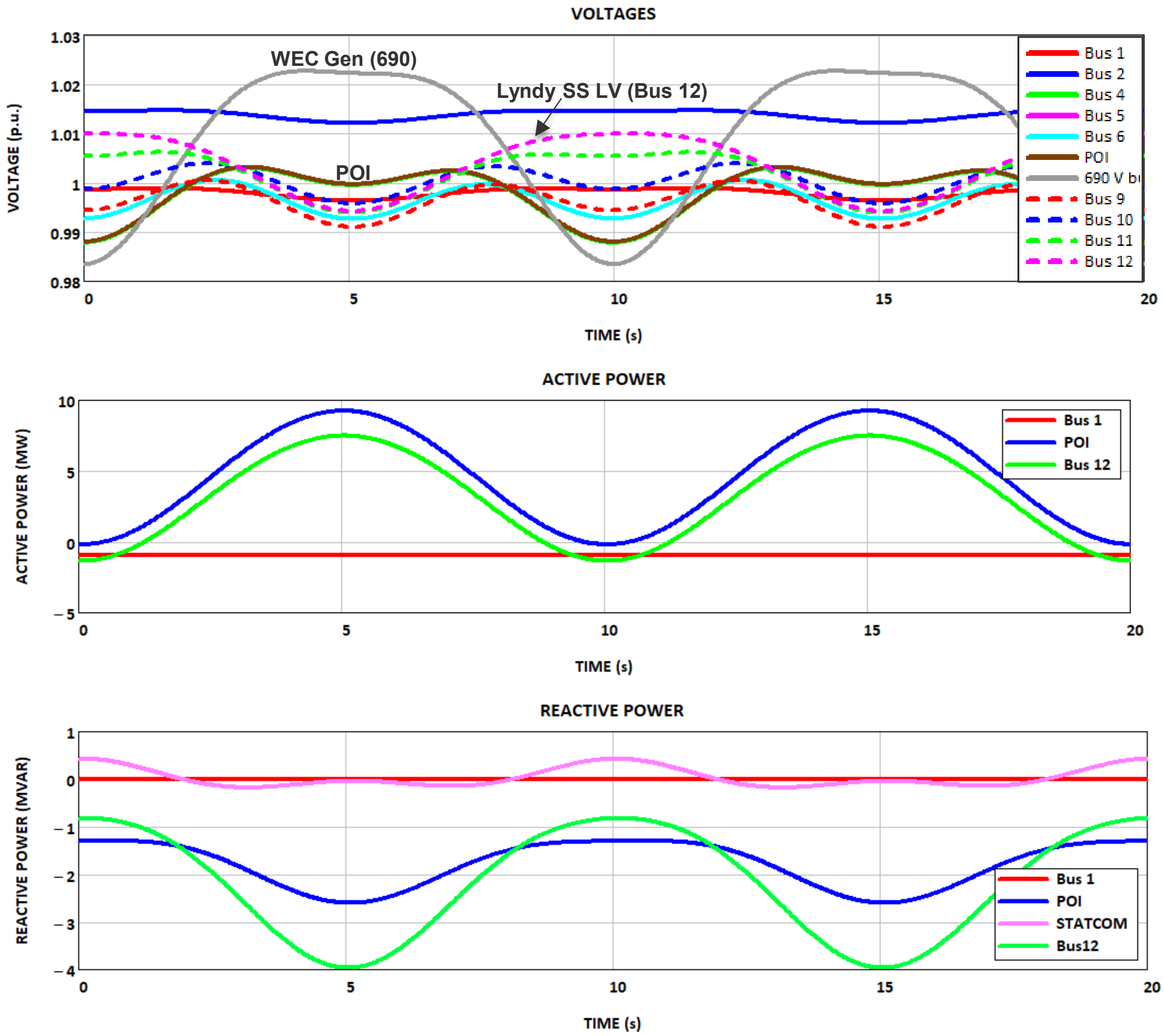


Figure 2-20. Lundy connection—compensation with 1-MVAR STATCOM and 1.2-MVAR shunt reactors

See Figure 2-21 for results with maximum feeder loads with reactive compensation using shunt reactors alone and the Lundy substation connection. This is the same configuration as shown in Figure 2-19 with the exception of the feeder loads. This case has the lowest possible distribution system voltages because of the long line lengths with the Lundy connections and maximum loads. When CLPUD on-load tap changer regulation is considered, Bus 12 (Lundy substation) will shift up into the regulation window from 1.017 p.u. to 1.042 p.u., with other distribution voltages shifting up by approximately the same amount. Considering this shift, no distribution voltages will swing lower than 0.95 p.u. The voltage swings at the substation bus are approximately 1%, so tap changer operation will not be affected. This case has PacWave point of interconnection and distribution voltage swings of approximately 4%—higher than all other cases.

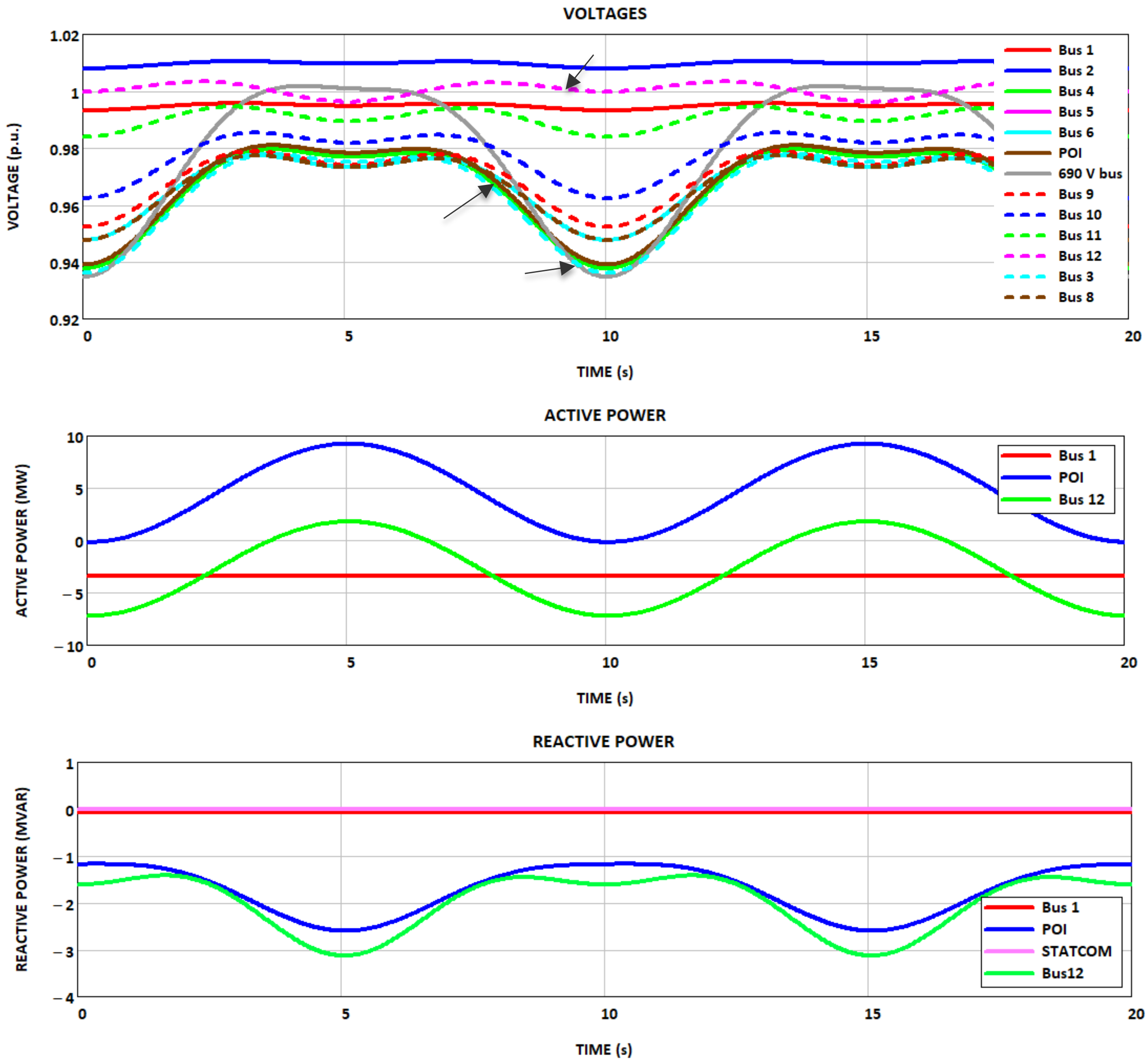


Figure 2-21. Lundy connection—compensation with 1.2-MVAR shunt reactors, maximum feeder loads

2.2 Temporary Overvoltage Results

Temporary overvoltage results are summarized in the following subsections with plots that show the arrester TOV curves together with arrester rms overvoltage versus duration from PSCAD simulation results. Complete PSCAD simulation results are included in Appendix B, with time series plots of voltage, current, and arrester energy absorption. Appendix B also includes PSCAD diagrams that show real and reactive power flow throughout the system before the TOV events occur, and also x-y plots of arrester voltage versus current.

Results are separated by Load Rejection Overvoltage and Ground Fault Overvoltage, with results for 10 MW and 700 kW PacWave generation shown for both. Three cases were simulated for both LROV and GFOV, with circuit breakers opened at the following locations: 1) 69 kV side of South Beach substation, 2) 12.47 kV side of Seal Rock substation, and 3) 12.47 kV side of Seal

Rock substation. For LROV simulations, those circuit breakers were opened with PacWave generating either 10 MW or 700 kW. For GFOV simulations, the same circuit breakers were opened for each case, and in addition single line to ground (SLG) faults were simultaneously applied at locations downstream of those circuit breakers (see Figure 1-7 and Figure 1-10 for specific fault locations).

The results for both LROV and GFOV were generally similar. PacWave generators were modeled as ac current sources in PSCAD, and CLPUD loads were modeled as resistive. PacWave generators were operated at unity power factor, with shunt reactors at the UCMF providing reactive compensation for the subsea cables and interconnection transformers. Immediately after a circuit breaker opens generation continues at the same power. When generation exceeds the CLPUD load on the "islanded" portion of the system that remains connected to the generators after the circuit breaker opens, voltage increases until resistive load power and the power absorbed by the surge arresters within the island equals generation power. When a significant overvoltage does occur, anti-islanding detection of the relays at the PacWave UCMF sense this overvoltage and open the main UCMF circuit breaker after about 200 mS. The PSCAD results show that surge arresters exceed TOV ratings when the 12.47 kV feeder circuit breaker at Seal Rock is opened with 10 MW PacWave generation during either LROV or GFOV events. In those cases, large temporary overvoltages occur for 200 mS. The islanded CLPUD load on the Seal Rock feeder is only 700 kW and the resulting temporary overvoltages far exceed the surge arrester TOV capabilities. The PSCAD results for 700 kW of PacWave generation (approximately equal to CLPUD feeder load) show that significant overvoltages do not occur and arresters remain well within their TOV capabilities for all LROV and GFOV cases. Simulations were not performed for other PacWave generation levels but it is assumed that whenever PacWave generation exceeds the CLPUD 700 kW feeder load, there is risk of temporary overvoltages that exceed TOV capabilities of CLPUD or PacWave UCMF arresters.

Although the results presented in this section show that significant temporary overvoltages can occur during LROV and GFOV events, a number of worst-case assumptions have been made for the PSCAD modeling as follows:

- PacWave generators are modeled as ac current sources that continue generating power after LROV and GFOV events without any voltage limit. In reality, when grid interconnection inverters are used to connect generators, the maximum output voltage may be limited. Also, if necessary, it may be feasible to implement fast tripping of inverters during these events.
- Anti-islanding detection at the UCMF is modeled with a 200 ms overvoltage delay per NERC PRC-024 (See Section 1.1.6) and a circuit breaker opening time of one 60 Hz cycle (16 ms). Different anti-islanding detection methods could be used at the UCMF with shorter delay times.

These worst-case assumptions are necessary for this study because details of specific PacWave generator interconnection designs are not known at this time. It is expected that results of future modeling will show reduced temporary overvoltage magnitudes and durations if details of the specific generator interconnection designs that will be used at PacWave are included. When PacWave is planning for specific WEC deployments that will result in total PacWave generation that exceeds 700 kW, further TOV modeling should be completed with both generator and

inverter details for the WECS connecting to PacWave and also anti-islanding protection included.

2.2.1 Load Rejection Overvoltage Results

The three different LROV cases listed in Table 2-8 were simulated in PSCAD with different CLPUD circuit breakers at the Seal Rock or South Beach substation opened. See Figure 1-7 (Seal Rock substation) for the location of the two Seal Rock circuit breakers and Figure 1-10 (CLPUD 69-kV subtransmission) for the location of the South Beach circuit breaker. All cases were simulated with minimum CLPUD feeder loads, both with maximum PacWave generation (10 MW total – four 2.5-MW generators) and with 700-kW PacWave generation (one 700-kW generator).

Table 2-8. LROV Cases Simulated

Case 1	South Beach substation 69-kV circuit breaker opens
Case 2	Seal Rock substation 69-kV circuit breaker opens
Case 3	Seal Rock substation 12.47-kV circuit breaker opens

See Appendix B for complete PSCAD simulation results, with time plots of system voltages and currents. The results are summarized in Figure 2-22 through Figure 2-27 for 10 MW of PacWave generation and Figure 28 through Figure 33 for 700 kW of PacWave generation. These figures show surge arrester TOV curves together with simulation results for arrestor root-mean-square voltage and duration. All voltages are shown in per unit of arrester MCOV. The arrester TOV curves are from the manufacturer's data that are included in Figure 1-12, with prior-duty curves shown when provided by the manufacturer.

The 69-kV arrester voltages are not included in the results shown in Figure 2-22 through Figure 33 for arresters on the source (Toledo BPA connection) side of the breaker that opens. In those cases, the arresters remain connected to the source, with circuit breakers open downstream, and they have normal voltage levels after the fault. For example, for Case 2, the circuit breaker opens at the Seal Rock substation; and the South Beach 69-kV arrestor voltage remains unchanged, so it is not shown.

Results for CLPUD elbow arresters shown in Figure 2-27 and Figure 33 assume that these arresters see the PSCAD simulated voltage at the PacWave point of interconnection. This is a worst-case assumption. These arresters were not included in the PSCAD model. They are located at different points along the CLPUD distribution feeder where pad-mounted transformers are located.

Each of the three LROV cases with 10 MW PacWave generation causes voltages to exceed 1.265 p.u. at the PacWave UCMF main circuit breaker. Per the NERC PRC-024 voltage trip settings shown in Table 1-4, this causes the relays to initiate opening of the circuit breaker in 200 ms. All of the LROV cases with 700 kW PacWave generation cause undervoltages that are less than 0.6 p.u. at the PacWave UCMF main circuit breaker. Per the NERC PRC-024 voltage trip

settings shown in Table 1-4, this causes the relays to initiate opening of the circuit breaker in 0.35 second.

The LROV results for 10 MW PacWave generation in Figure 2-22 through Figure 2-27 show that temporary overvoltages are high enough for all 12.47 kV arresters exceed their TOV capabilities with Case 3 (Seal Rock 12.47 kV circuit breaker opens). The 69 kV arresters at Lundy and Yachats also exceed or nearly exceed their TOV capabilities for Cases 1 and 2 (69 kV circuit breakers open at South Beach and Seal Rock).

The LROV results for 700 kW PacWave generation in Figure 28 through Figure 33 show that all arrester voltages decrease after the circuit breakers open for the three cases. For this generation scenario, PacWave generation approximately equals CLPUD load on the Seal Rock feeder, and with reactive compensation at the UCMF the power factor of generation at PacWave is very close to unity (see diagram in Appendix B for real and reactive power flow).

2.2.1.1 LROV results for 10 MW PacWave generation

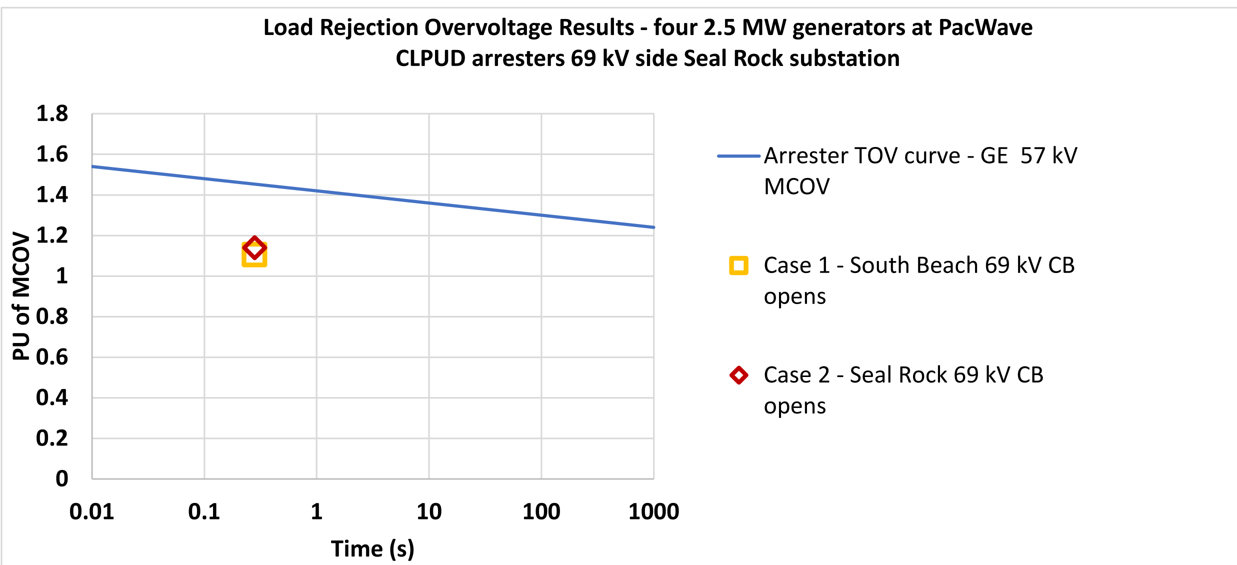


Figure 2-22. LROV results for CLPUD Seal Rock 69 kV arresters with four 2.5-MW generators

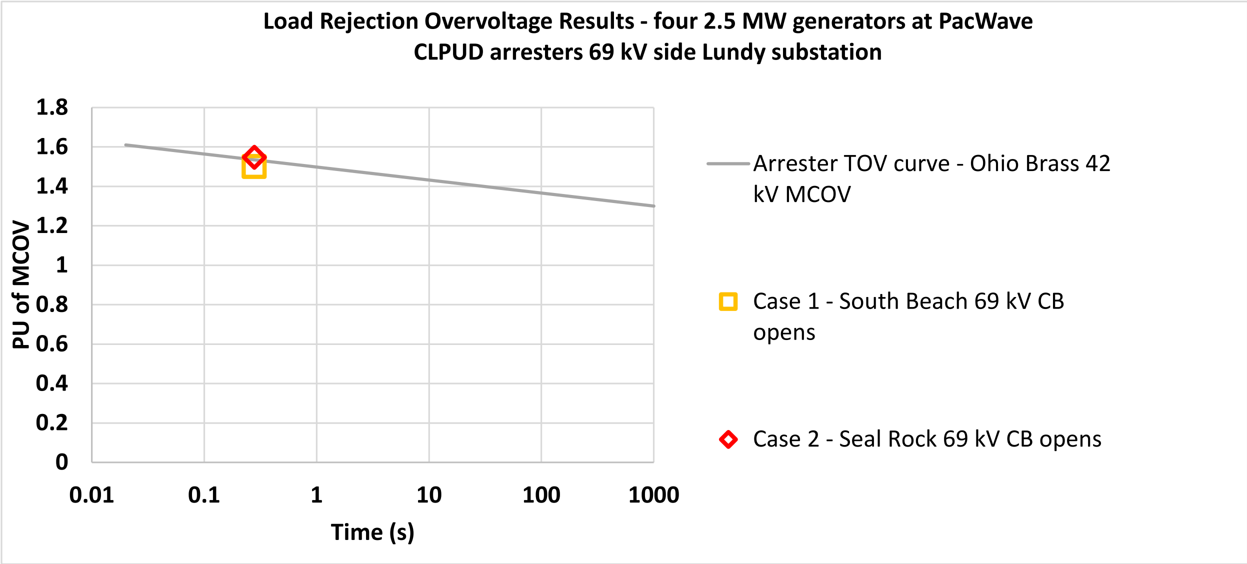


Figure 2-23. LROV results for CLPUD 69 kV Lundy arresters with four 2.5-MW generators

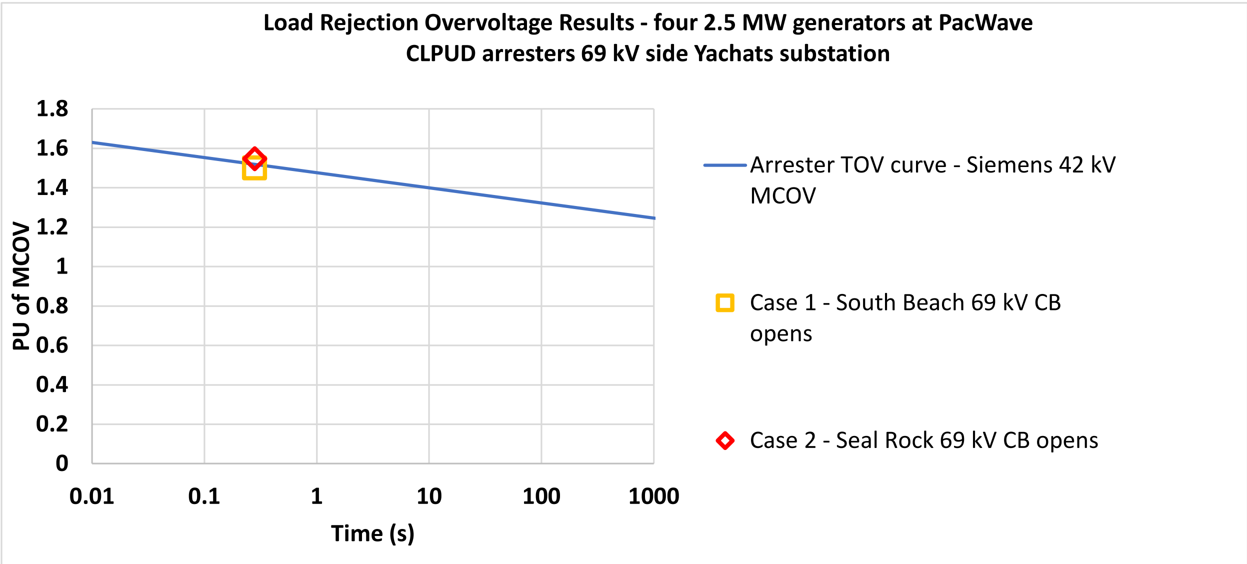


Figure 2-24. LROV results for CLPUD 69 kV Yachats arresters with four 2.5-MW generators

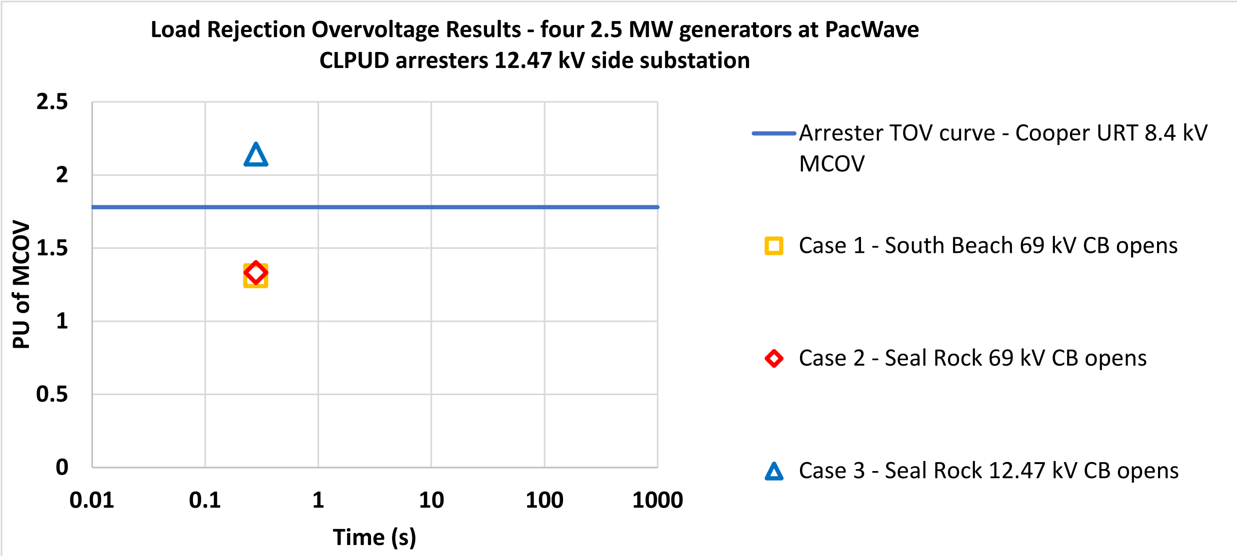


Figure 2-25. LROV results for CLPUD arrestors 12.47 kV with four 2.5-MW generators

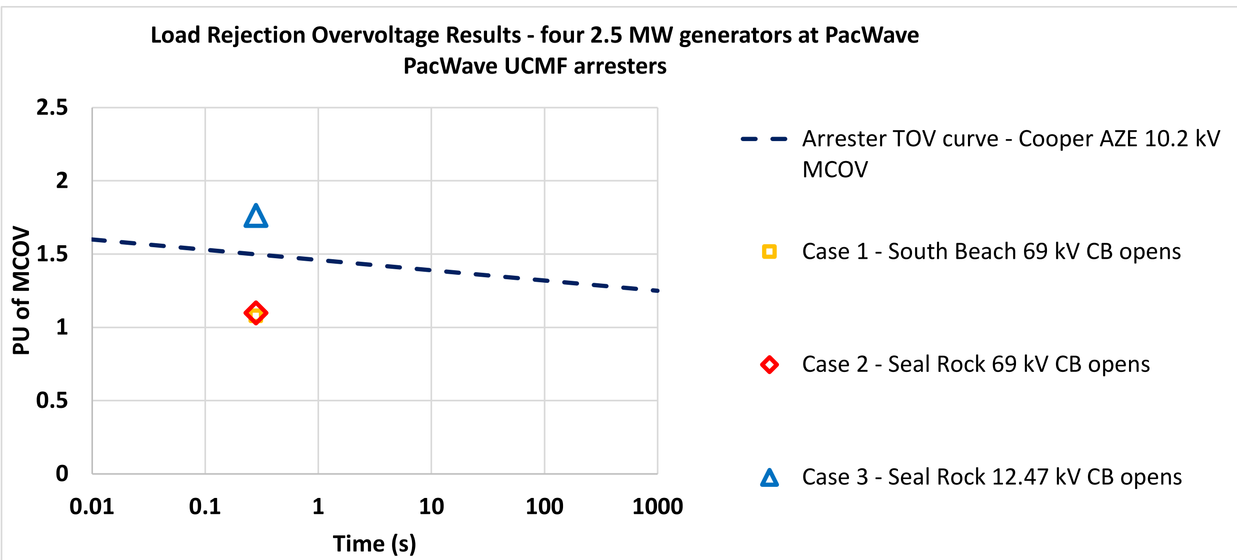


Figure 2-26. LROV results for PacWave UCMF arresters with four 2.5-MW generators

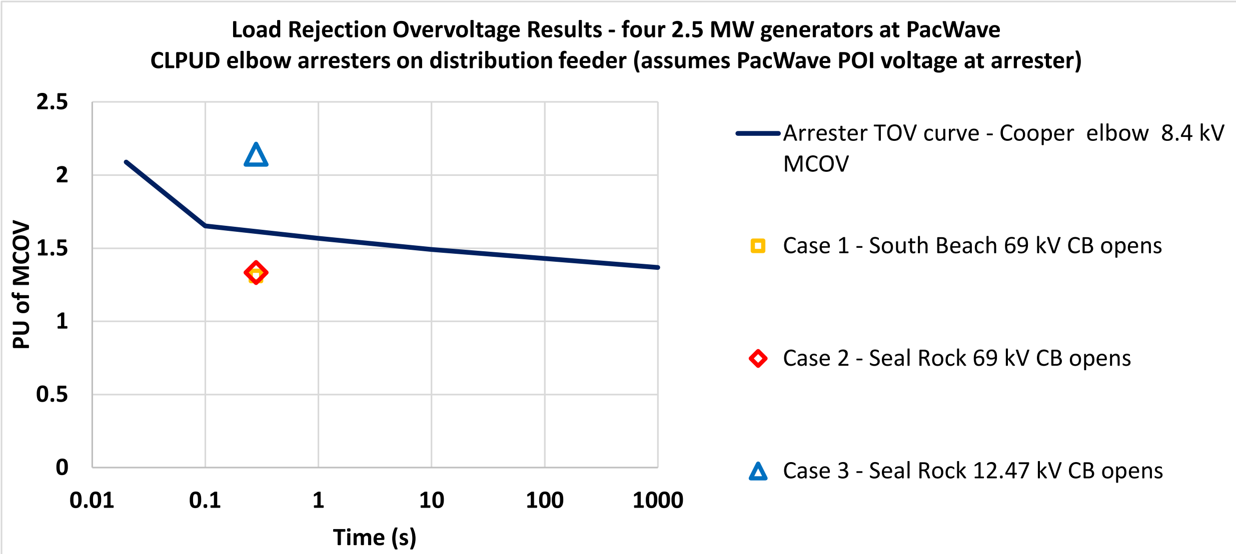


Figure 2-27. LROV results for CLPUD elbow arresters on 12.47 kV feeder with four 2.5-MW generators

2.2.1.2 LROV results for 700 kW PacWave generation

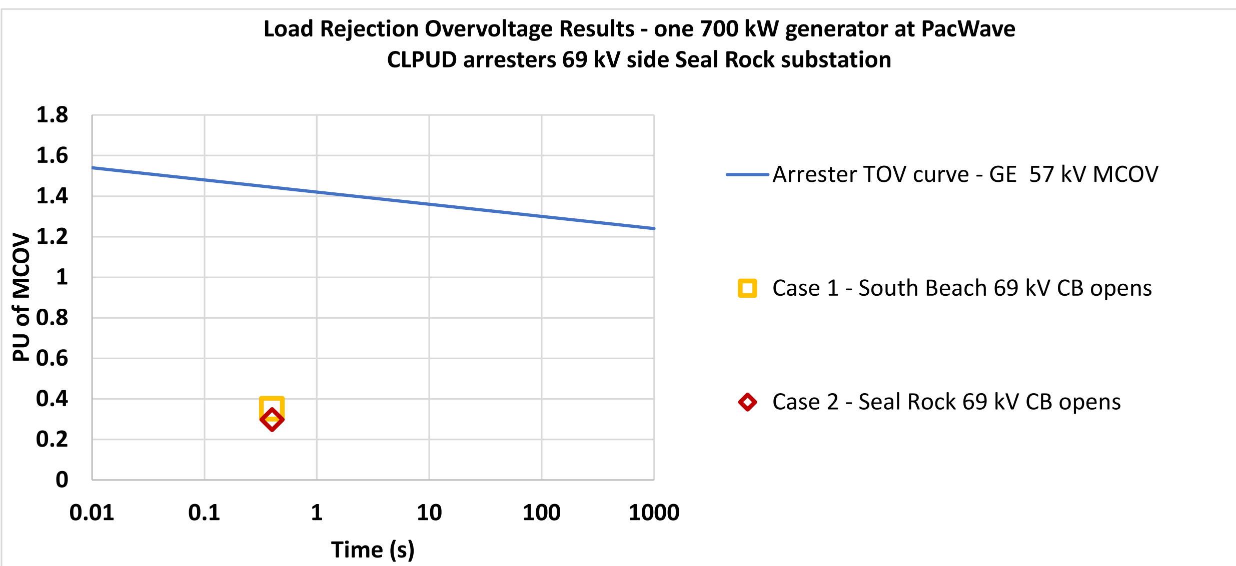


Figure 2 28 LROV results for CLPUD Seal Rock 69 kV arresters with one 700-kW generator

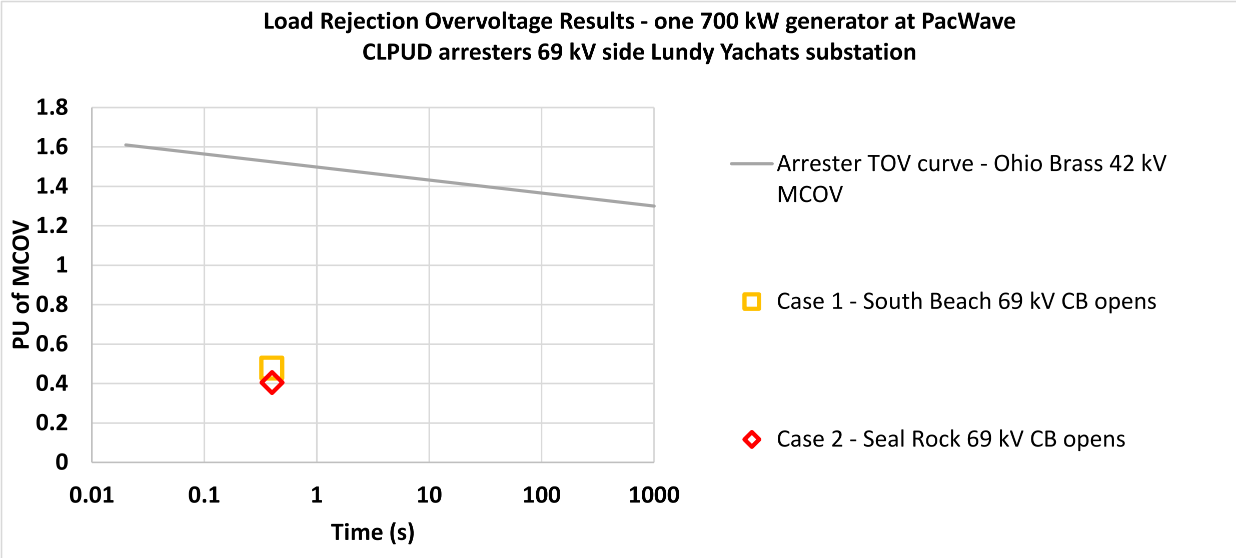


Figure 2 29 LROV results for CLPUD 69 kV Lundy arresters with one 700-kW generator

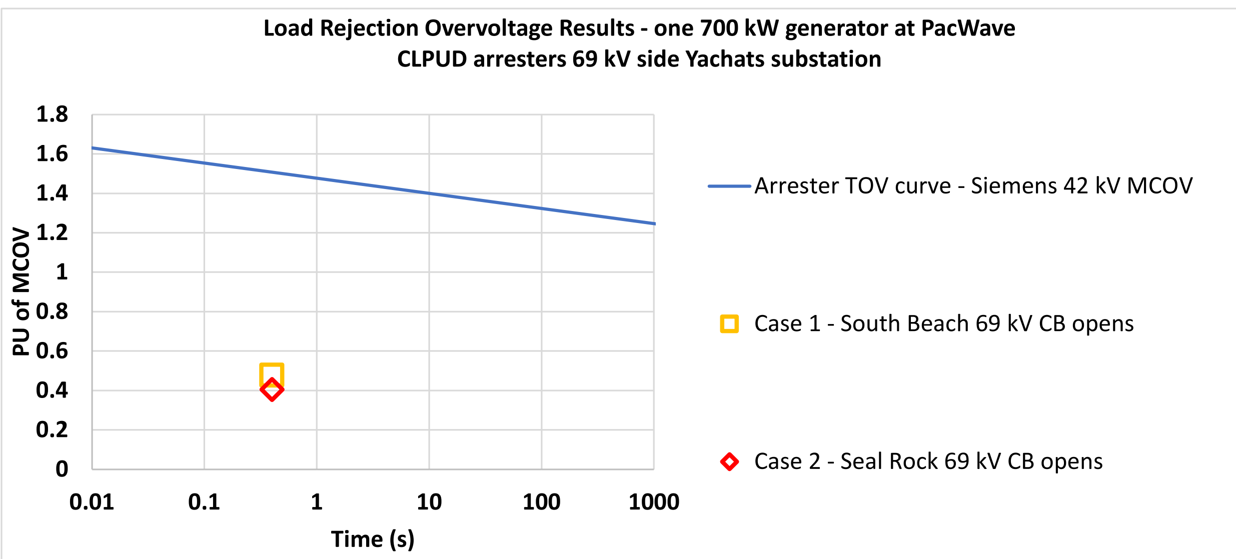


Figure 2 30 LROV results for CLPUD 69 kV Yachats arresters with one 700-kW generator

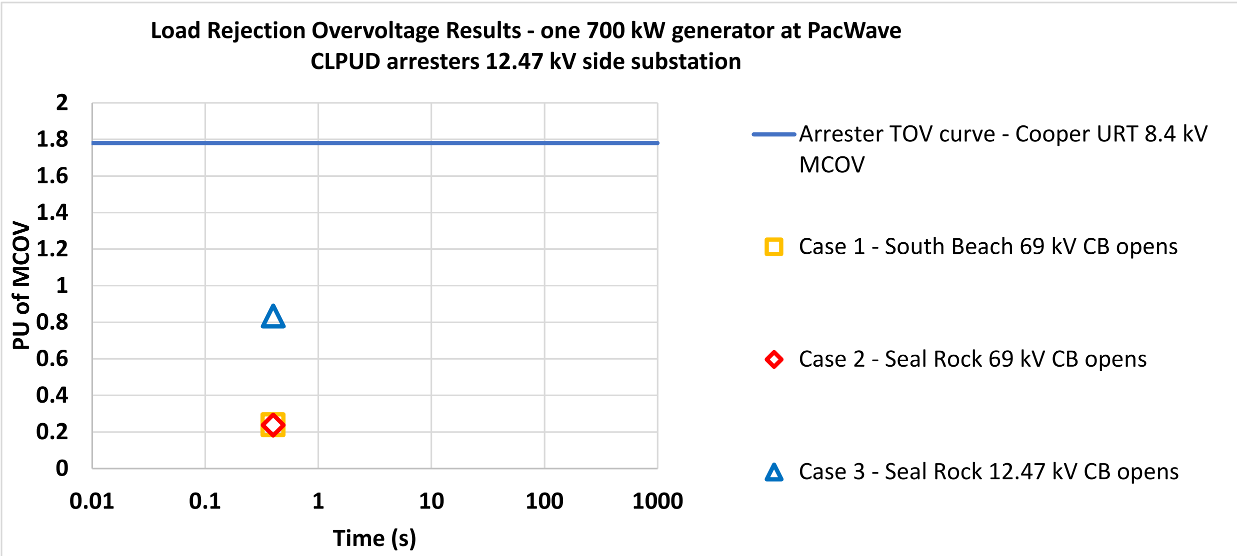


Figure 2 31 LROV results for CLPUD arrestors 12.47 kV with one 700-kW generator

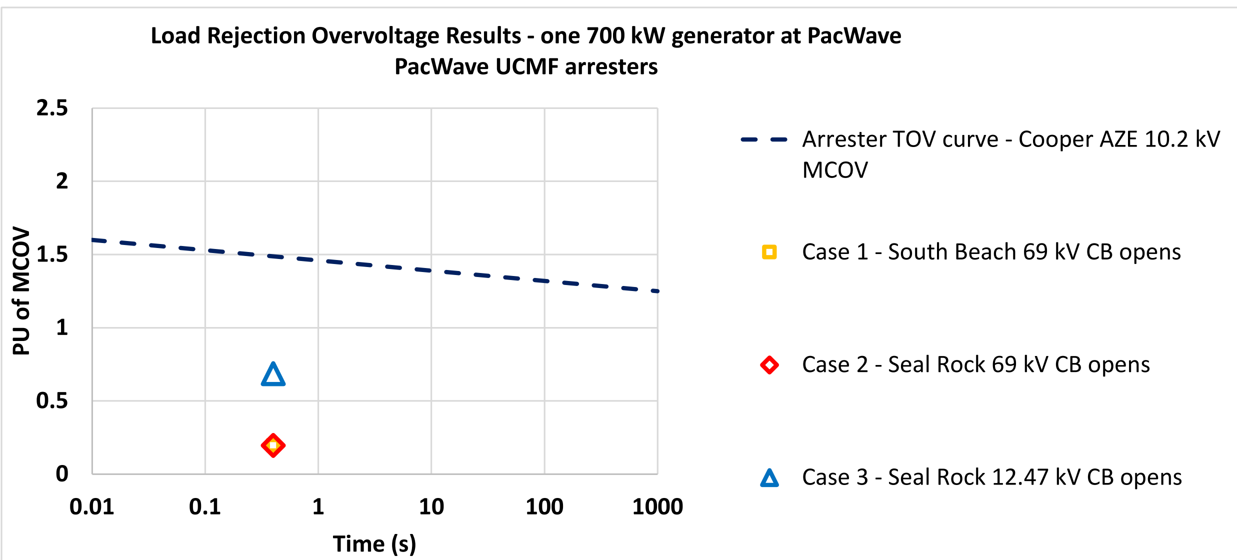


Figure 2 32 LROV results for PacWave UCMF arresters with one 700-kW generator

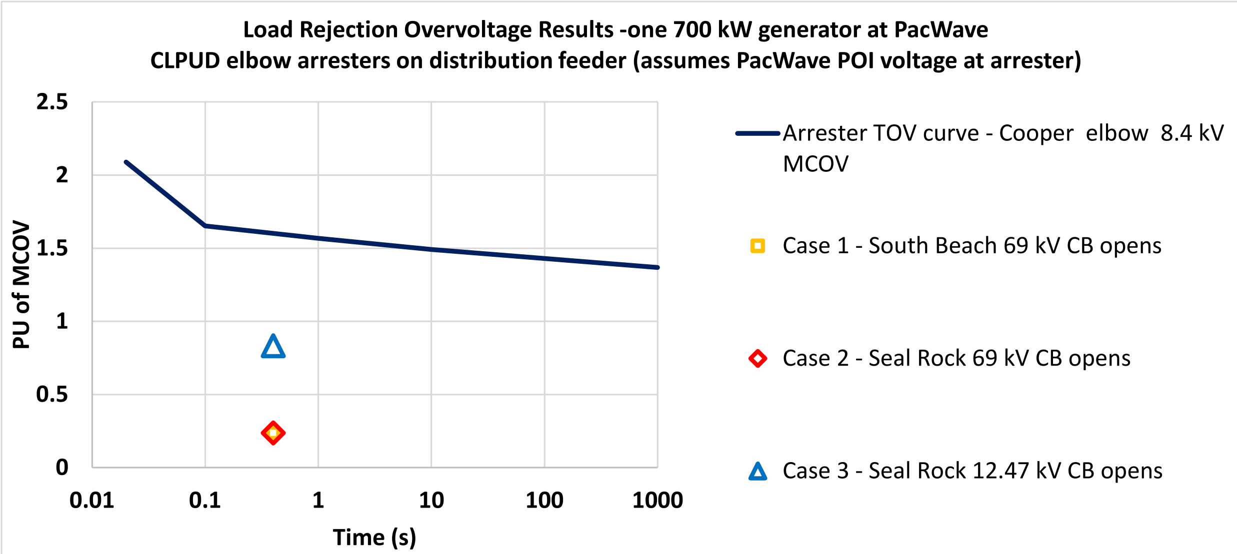


Figure 2- 33 LROV results for CLPUD elbow arresters with one 700-kW generator

2.2.2 Ground Fault Overvoltage Results

The three different GFOV cases listed in Table 2-9 were simulated in PSCAD. Each fault causes the circuit breakers corresponding to the three LROV cases described in the preceding section to open. See Figure 1-7 (Seal Rock substation) for the location of the two grounds faults at that substation and Figure 1-10 (CLPUD 69-kV subtransmission) for the location of the 69-kV ground fault at South Beach. Fault locations are also shown on the system diagrams for the PSCAD model included in both Appendix A and Appendix B. All cases were simulated with minimum CLPUD feeder loads, both with maximum PacWave generation (10 MW total – four 2.5-MW generators) and with 700-kW PacWave generation (one 700-kW generator).

Table 2-9. GFOV Cases Simulated

Case 1	Single-line-to-ground fault at 69-kV side Seal Rock substation South Beach substation 69-kV circuit breaker opens
Case 2	Single-line-to-ground fault at 12.47-kV side of Seal Rock substation Seal Rock substation 69-kV circuit breaker opens
Case 3	Single-line-to-ground fault on Seal Rock feeder Seal Rock feeder 12.47-kV circuit breaker opens

See Appendix B for complete PSCAD simulation results for GFOV with time plots of system voltages and currents. These results are summarized in Figure 2-34 through Figure 2-45, with arrestor TOV from the simulation results shown in per unit of arrester MCOV plotted together with arrestor TOV curves, similar to the LROV figures in the previous section. The 69-kV arrester voltages are not included in the results shown in Figure 2-34 for arresters on the source (Toledo BPA connection) side of the breaker that opens because the voltages on those arresters do not change after the fault. Results for the CLPUD elbow arresters shown in Figure 2-39 and

Figure 2-45 assume that these arresters see the PSCAD simulated voltage at the PacWave point of interconnection, which is a worst-case assumption.

Each of the three GFOV cases with 10 MW PacWave generation causes voltages to exceed 1.265 p.u. at the PacWave UCMF main circuit breaker. Per the NERC PRC-024 voltage trip settings shown in Table 1-4, this causes the relays to initiate opening of the circuit breaker in 200 ms. The GFOV results are nearly identical to the LROV results for 10 MW PacWave generation. 12.47 kV arrester voltages significantly exceed arrester TOV ratings for Case 3, when the 12.47 kV Seal Rock circuit breaker opens. For the PacWave generation scenario with four 2.5 MW generators, each PacWave generator is interconnected by grounded wye transformers at the UCMF (see Figure 1-2). For Case 3 when the circuit breaker at the 12.47 kV side of the Seal Rock substation opens, these transformers provide 12.47 kV grounding sources after the circuit breaker opens. This avoids a neutral shift from occurring when there is a SLG fault on one phase. The SLG fault causes fault currents on a single phase that are limited by the PacWave generators, and overvoltages occur on the other two phases similar to the LROV results.

Most of the GFOV cases with 700 kW PacWave generation cause undervoltages that are less than 0.6 p.u. at the PacWave UCMF main circuit breaker. Per the NERC PRC-024 voltage trip settings shown in Table 1-4, this causes the relays to initiate opening of the circuit breaker in 0.35 second. For Case 3 (SLG fault on 12.47 kV side of Seal Rock substation), 12.47 kV arrester voltages do increase after the fault (see Figure 2-43, Figure 2-44, and Figure 2-45) unlike seen in the LROV results. During the GFOV, for Case 3 the voltages at the UCMF exceed 1.265 p.u. and the UCMF circuit breaker starts opening after 200 ms. Although the surge arrester voltages do increase, the overvoltages are well within the surge arrester TOV limits. The reason that these arrester voltages are higher for the GFOV than the LROV simulations is that for the 700 kW PacWave generation scenario, there is no grounded wye transformer at the UCMF like are used for the 10 MW PacWave generation scenario (see Figure 1-4). Without the grounded wye transformer at the UCMF, there is no 12.47-kV grounding source after the circuit breaker opens, so a neutral shift occurs that causes two phase voltages to increase after the fault occurs.

2.2.2.1 GFOV results for 10 MW PacWave generation

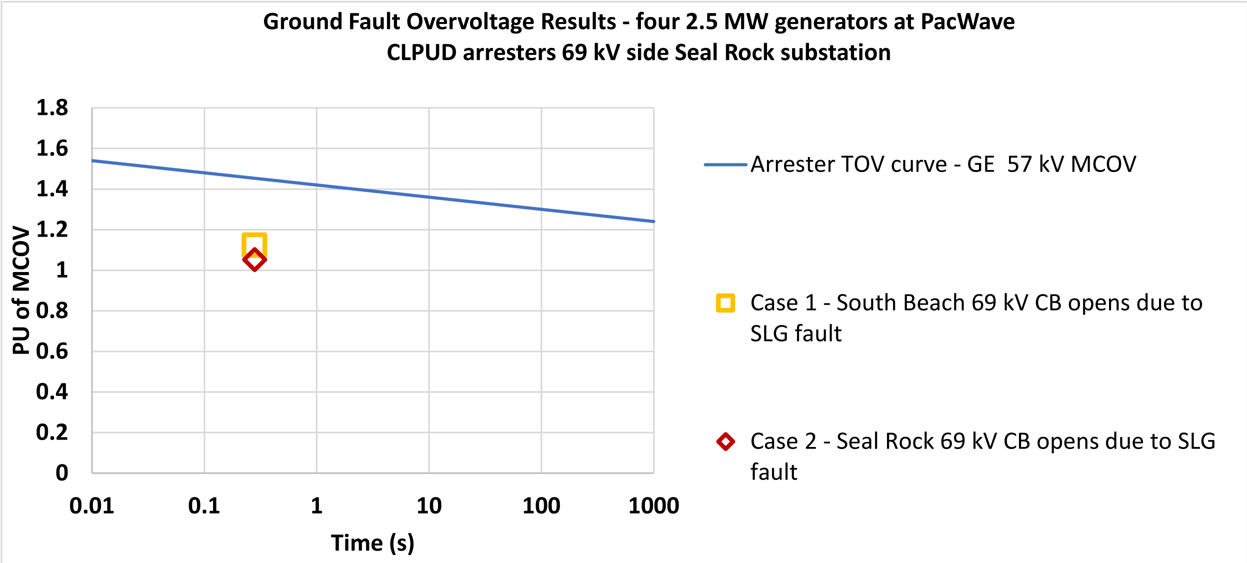


Figure 2-34. GFOV results for CLPUD Seal Rock arrestors 69 kV with four 2.5-MW generators

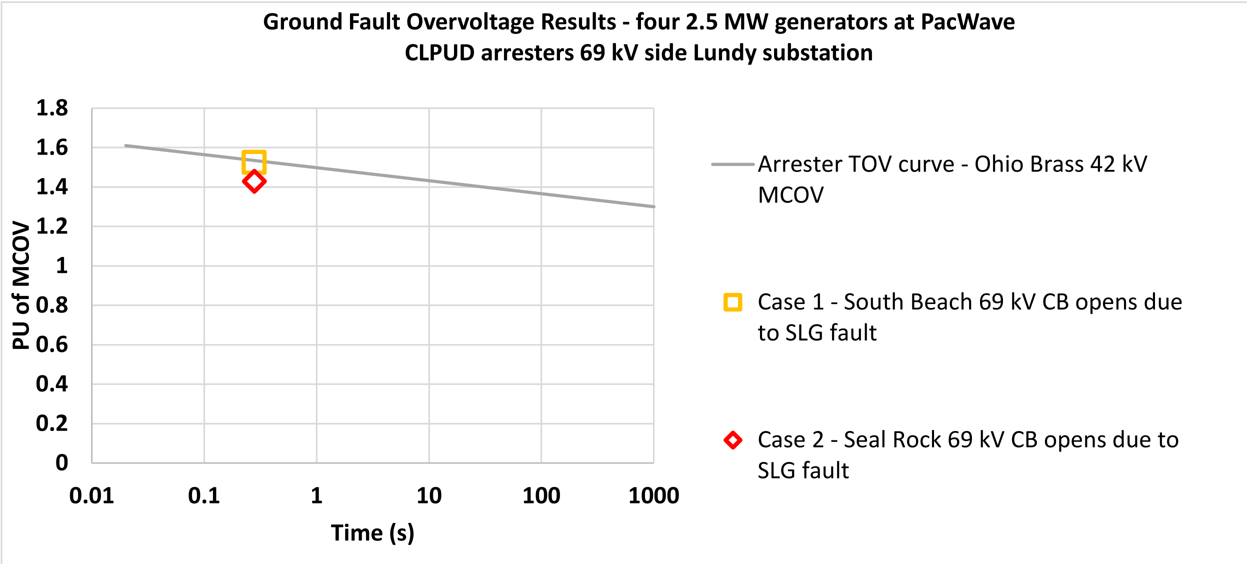


Figure 2-35. GFOV results for CLPUD 69 kV Lundy arresters with four 2.5-MW generators

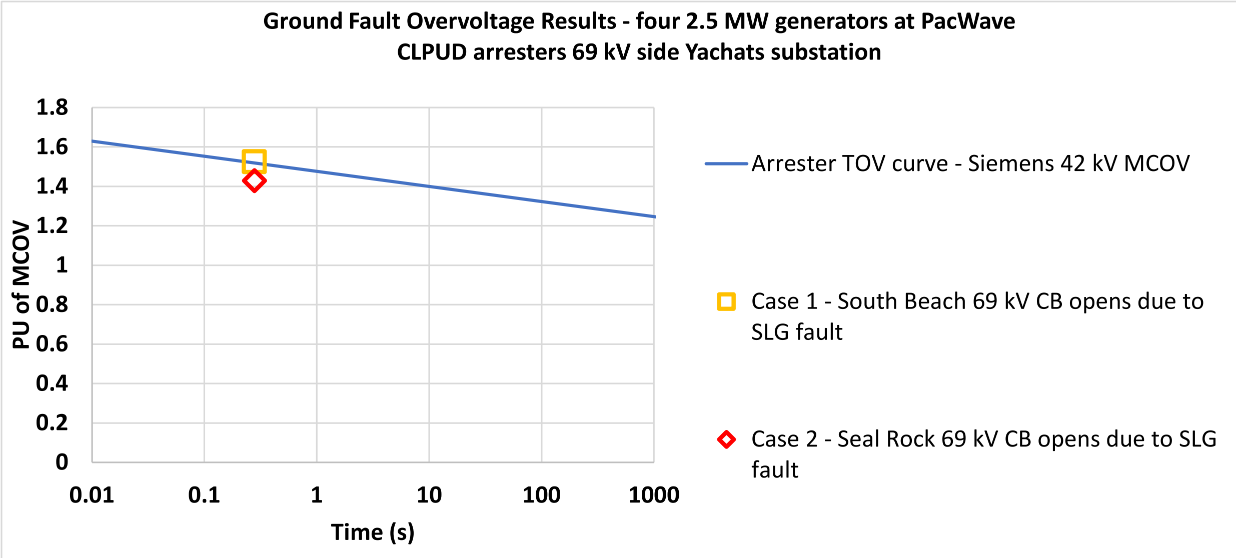


Figure 2-36. GFOV results for CLPUD 69 kV Yachats arresters with four 2.5-MW generators

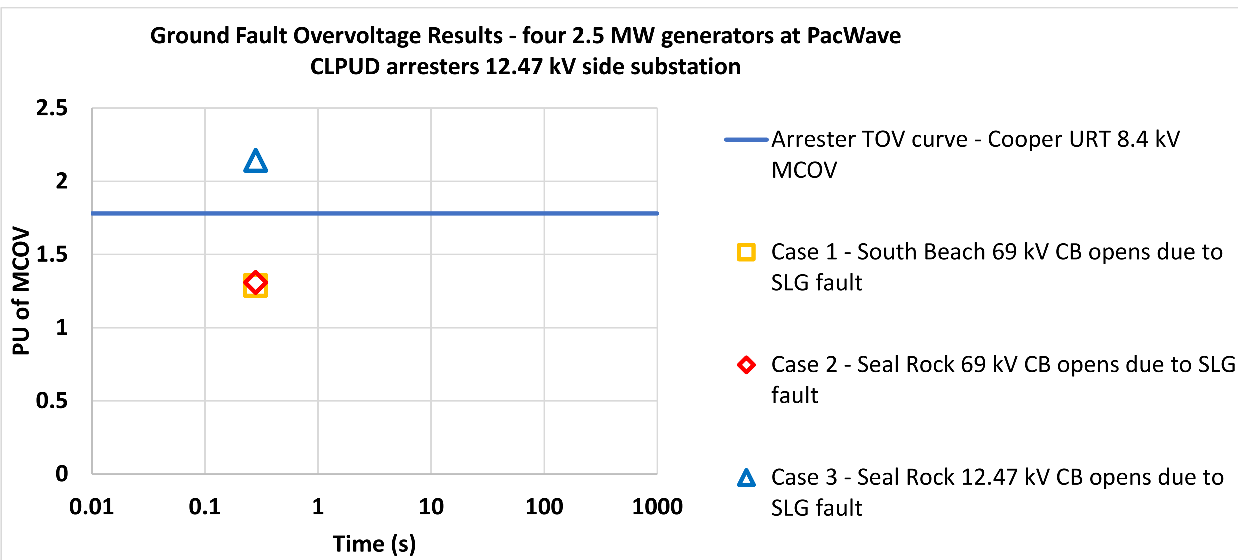


Figure 2-37. GFOV results for CLPUD arrestors 12.47 kV with four 2.5-MW generators

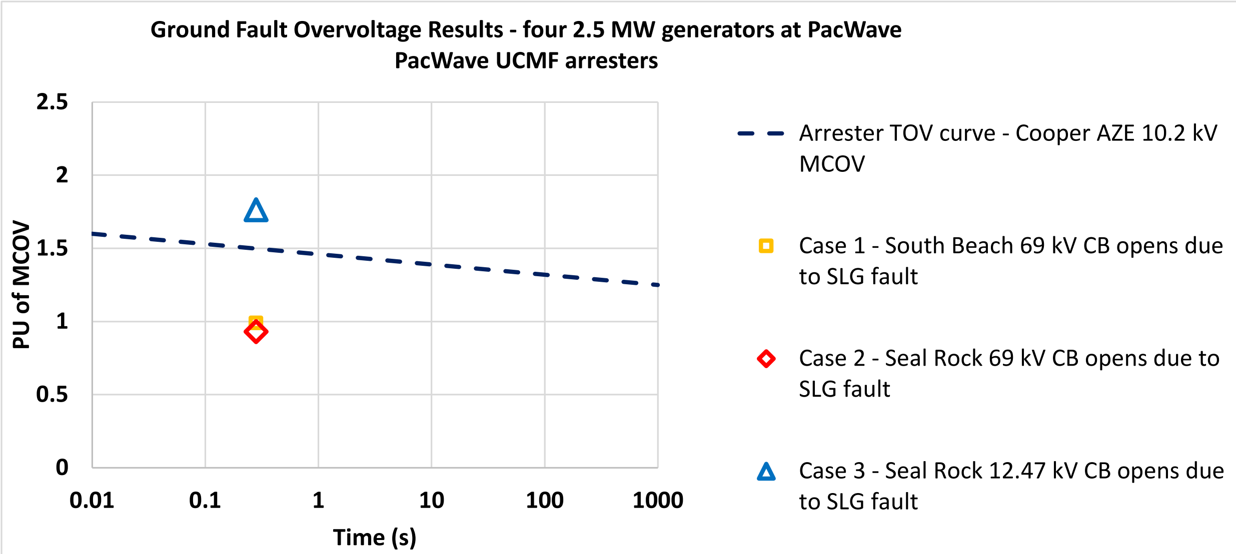


Figure 2-38. GFOV results for PacWave UCMF arrestors with four 2.5-MW generators

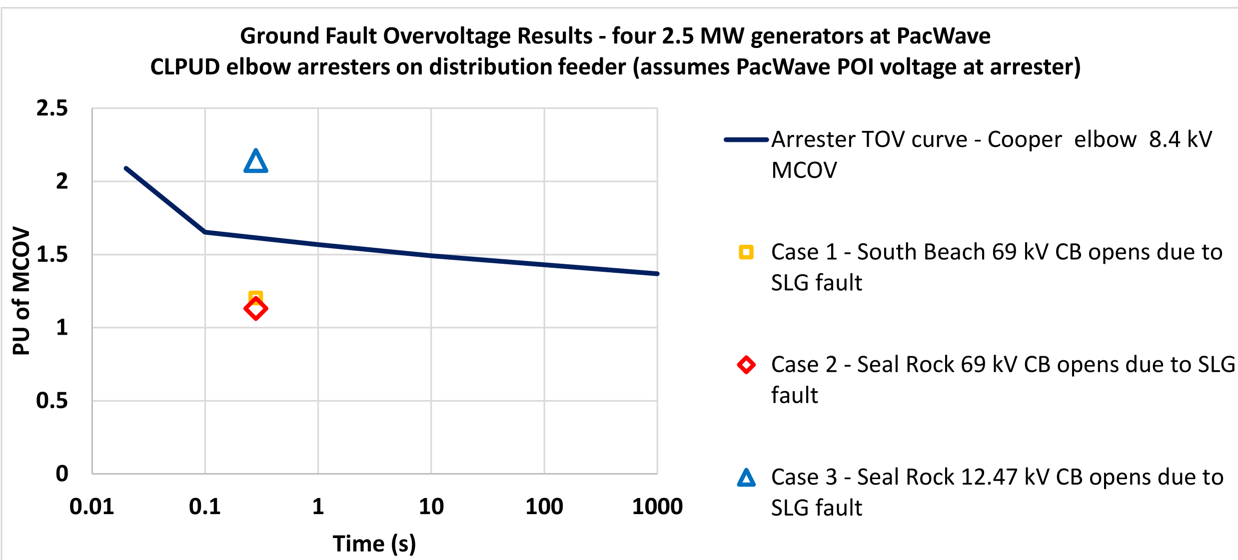


Figure 2-39. GFOV results for CLPUD elbow arresters on 12.47-kV feeder with four 2.5-MW generators

2.2.2.2 GFOV results for 700 kW PacWave generation

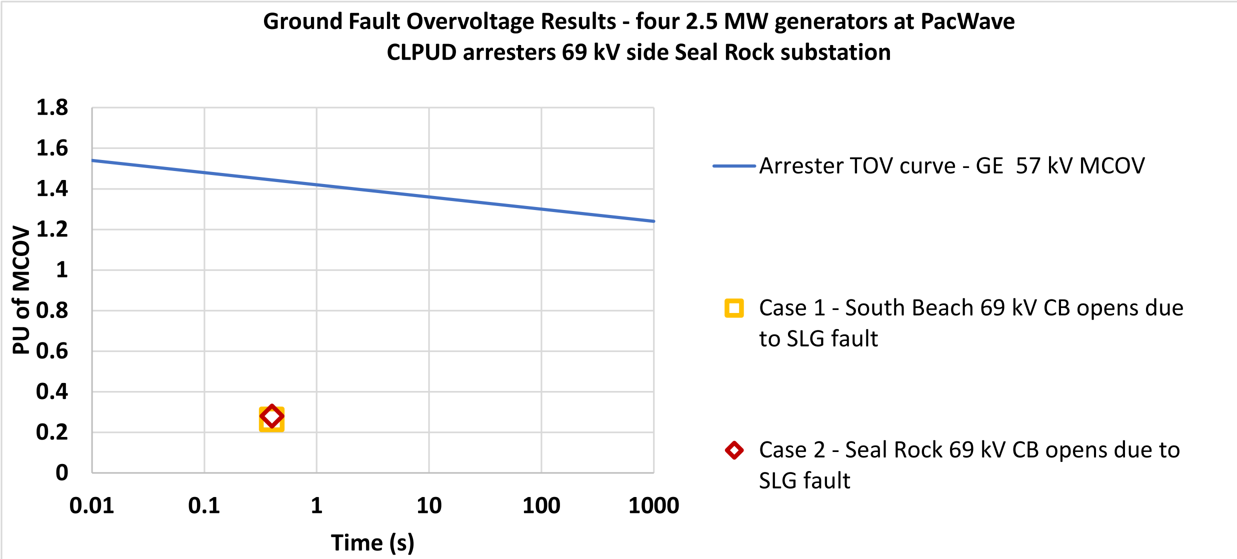


Figure 2-40. GFOV results for CLPUD Seal Rock arrestors 69 kV with one 700-kW generator

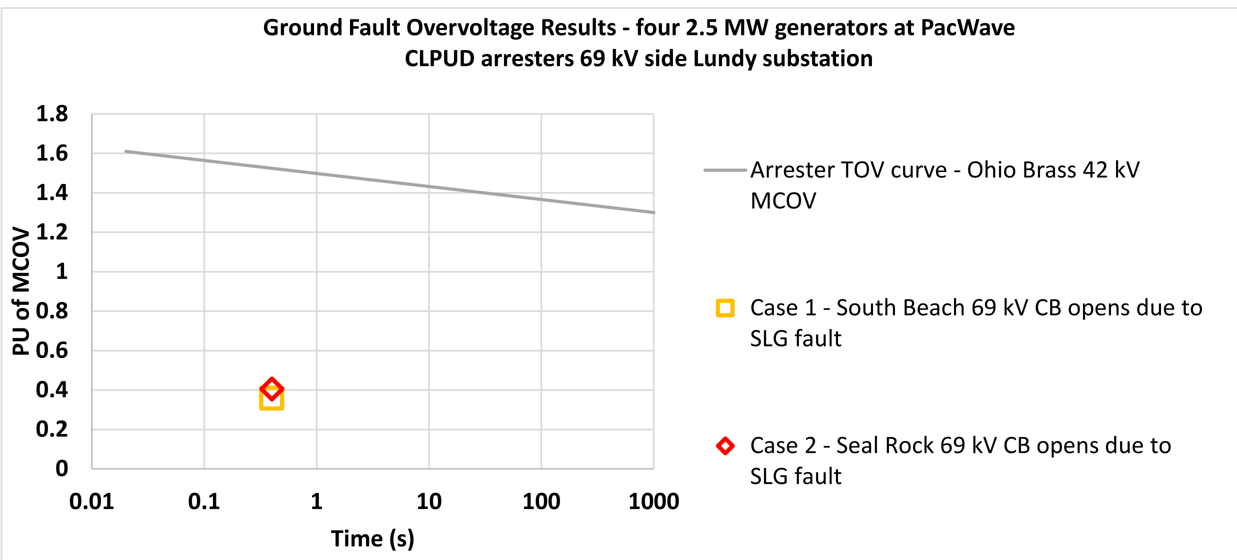


Figure 2-41. GFOV results for CLPUD 69 kV Lundy arresters with four 2.5-MW generators

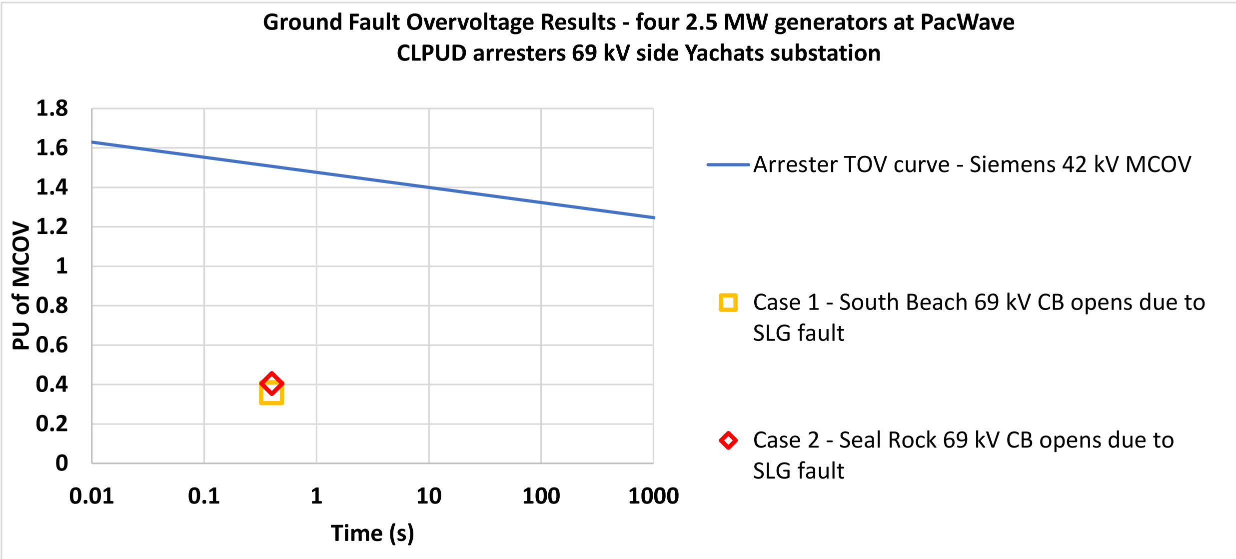


Figure 2-42. GFOV results for CLPUD 69 kV Yachats arresters with four 2.5-MW generators

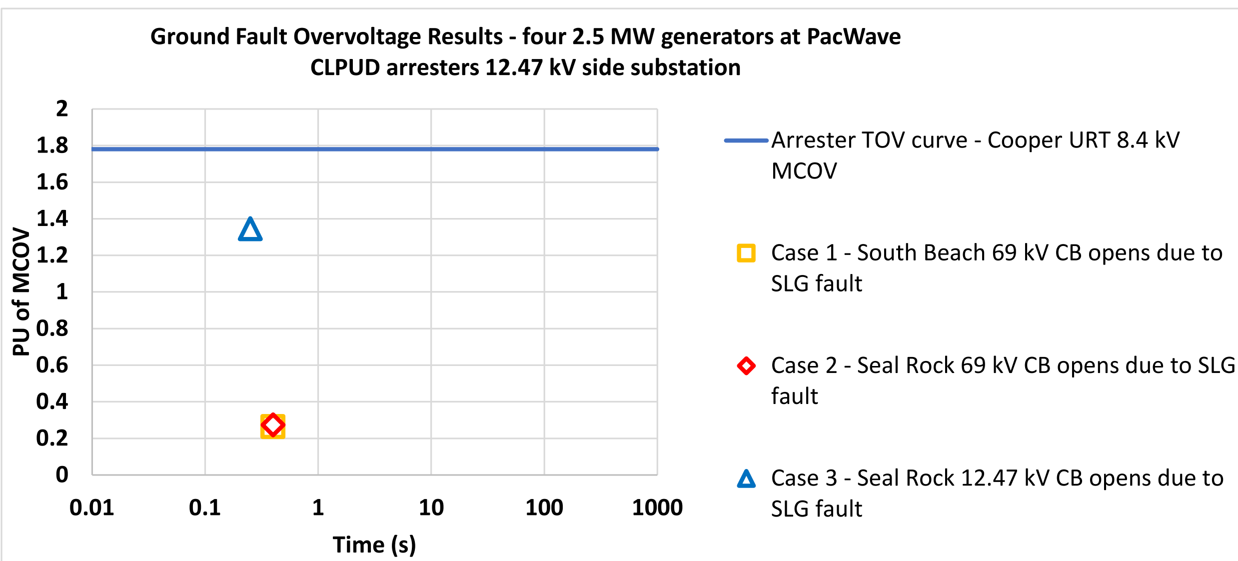


Figure 2-43. GFOV results for CLPUD arrestors 12.47 kV with one 700-kW generator

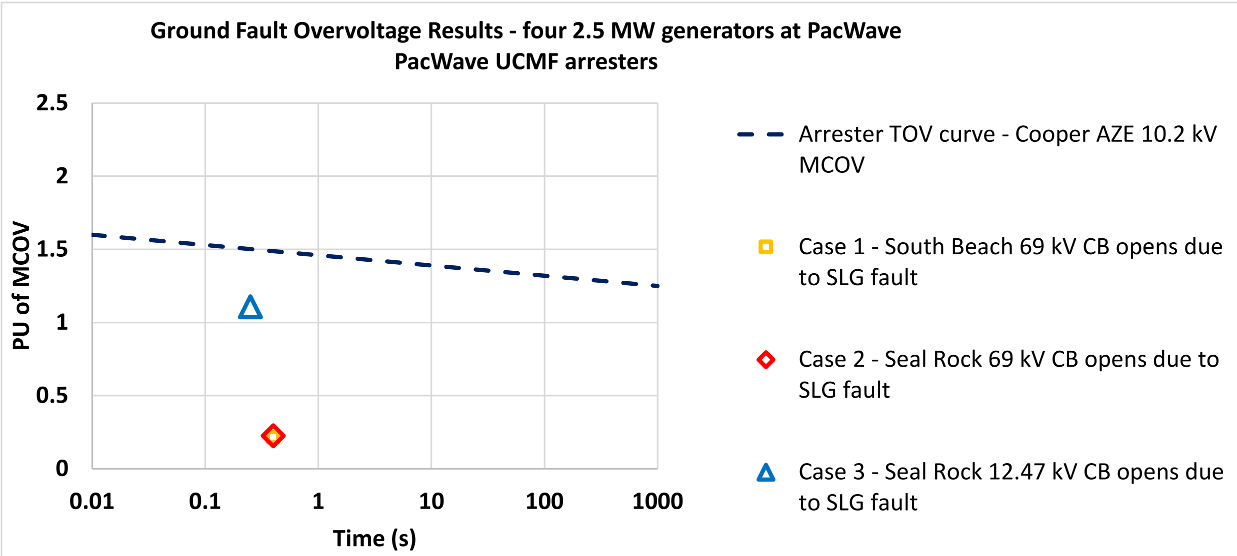


Figure 2-44. GFOV results for PacWave UCMF arrestors with one 700-kW generator

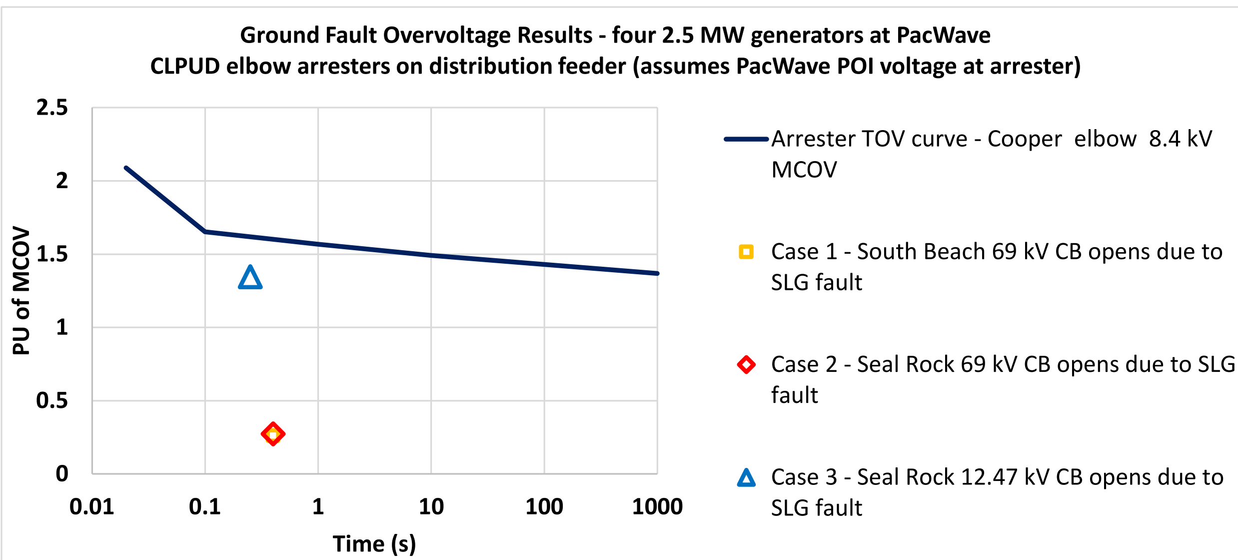


Figure 2-45. GFOV results for CLPUD elbow arresters on 12.47-kV feeder with one 700-kW generator

3 Conclusions

Simulation results confirm that reactive compensation at the PacWave UCMF will be necessary to avoid adverse effects on the CLPUD distribution system and substations when maximum worst-case coincident PacWave generation occurs with minimum CLPUD customer loads. The results show that the addition of the 1.2-MVAR shunt reactors (30-kV) alone will be sufficient to avoid adverse effect on CLPUD distribution customers and CLPUD substation operations. These shunt reactors can be installed on the subsea cable side of the transformers at the UCMF so that reactive compensation will be matched for different subsea cable voltages. With shunt reactor compensation added at the PacWave UCMF, PSCAD results show that CLPUD Seal Rock feeder customers will not experience voltage swings that exceed 2%–3%. During the limited times that PacWave is connected to the Lundy feeder, customers on that feeder will not experience voltage swings that exceed 3%–4%. Distribution voltages are not expected to increase significantly greater than 1.05 p.u.—even when substation on-load tap changers are at the high end of their voltage regulation band. The results show that voltage swings at both substations will always be less than 2%, so PacWave operations should not cause frequent switching of the on-load tap changers, which could increase maintenance or reduce life.

If a 1-MVAR STATCOM is installed at the PacWave UCMF in addition to the shunt reactors, voltage swings at the PacWave point of interconnection and CLPUD customer services nearby can be reduced compared to the voltage swings that will occur with shunt reactors alone. The voltage swings at the substations will not be reduced with the STATCOM added, however, and they could be increased by a small amount. The benefits of adding a STATCOM at the UCMF will probably not be enough to justify the installation and maintenance costs of such a unique piece of equipment. It should be acknowledged that these simulations are all worst-case scenarios and not likely to occur on a regular basis. Given the uncertain nature of generation at this prototype testing facility, we cannot yet determine how often the voltage might swing. As such, if in practice the voltage is swinging too much or is noticeable to CLPUD customers on this feeder, we feel that a reasonable solution is to have voltage regulators installed on the feeder (perhaps even on the riser pole where PacWave generation connects). Additionally, prior to the integration of any combination of WECs that can generate more than approximately 5 MW, Oregon State University and CLPUD might want to verify the Seal Rock tap changer set point for the Seal Rock secondary and verify that the set point is appropriate for the generation condition. This will likely only be necessary 5–10 years in the future if and when some combination of devices can begin to approach the 10-MW rating of the plant, and as such it should not be implemented immediately.

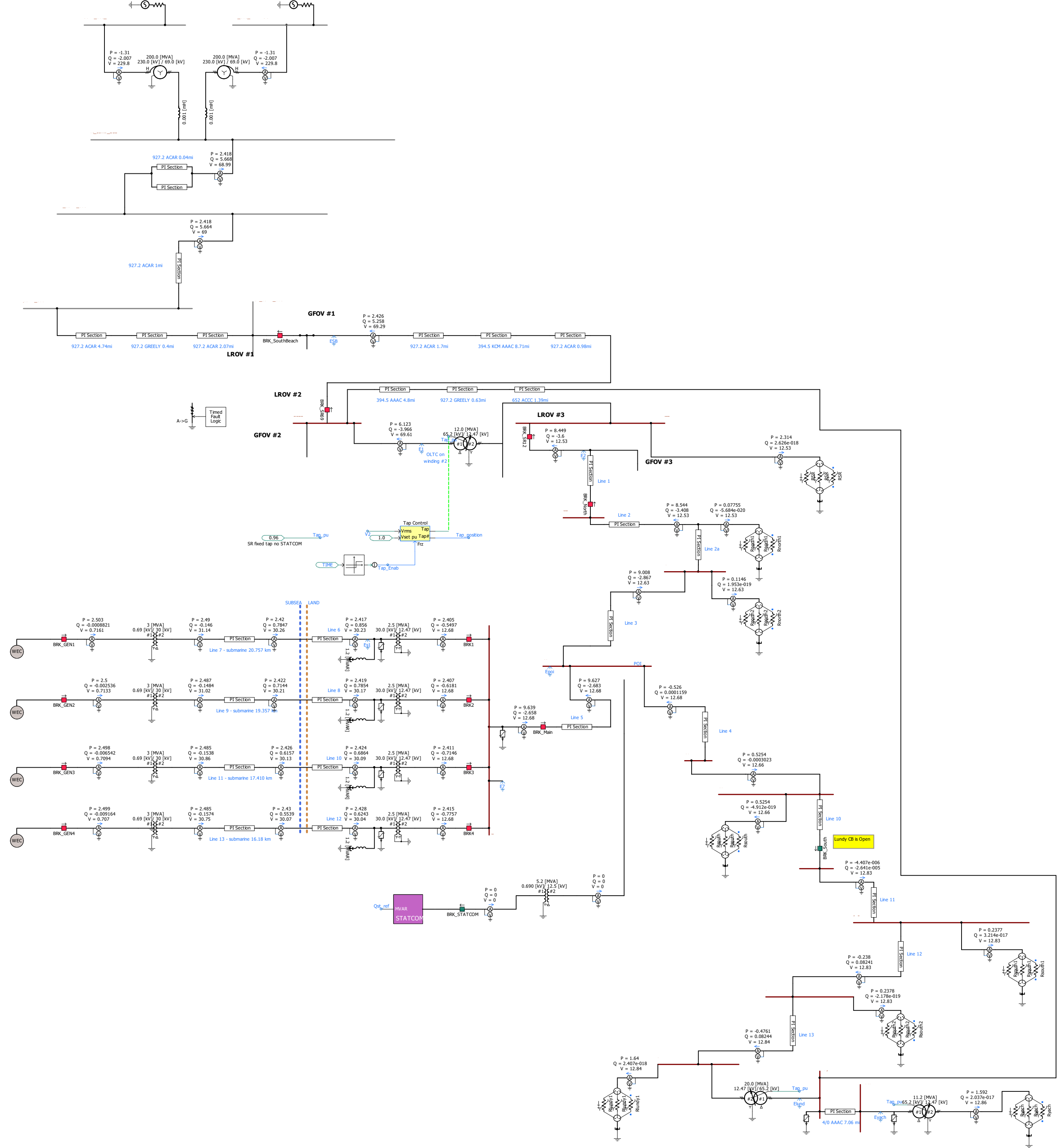
The TOV simulation results show that when PacWave generation exceeds the load on CLPUD's 12.47 kV feeder that PacWave connects to, the 12.47 kV surge arrester voltages can exceed TOV ratings during both LROV and GFOV events. The minimum load for that feeder is 700 kW, based on July 2018 substation data provided by CLPUD. Results with 700 kW of PacWave generation at unity power factor show that surge arrester voltages did not exceed arrester TOV limits during either LROV or GFOV events. When PacWave is planning for specific WEC deployments that will result in total PacWave generation that exceeds 700 kW, further TOV modeling should be completed with both generator and inverter details for the WECS connecting to PacWave and also anti-islanding protection included.

Because specific information about generators connecting to PacWave were not available for this work, a worst-case PacWave generation model was used where all generators modeled as ac current sources with no voltage limit. Also, UCMF anti-islanding detection was modeled with a 200 ms overvoltage delay per NERC PRC-024. Actual generators connecting at PacWave will likely be inverter connected and the inverter outputs will be voltage limited. This may reduce the magnitude of arrester overvoltages during LROV and GFOV events. In addition, faster anti-islanding detection could be used to reduce the duration of the arrester overvoltages.

LROV and GFOV cases were not simulated where the UCMF main or feeder circuit breakers open because those cases will need to be modeled with more specific WEC generation models to give accurate results. These LROV and GFOV cases are expected to impact arresters only at the PacWave UCMF, not the CLPUD arresters. These LROV and GFOV cases should be considered for each WEC deployment at PacWave. Device protection settings will need to be coordinated with land-based relay settings to protect the subsea cables and the equipment at the UCMF.

The PSCAD model used for this work used preliminary subsea and terrestrial cable lengths and parameters because cable suppliers have not been selected. Once cable suppliers are selected and the designs are finalized, results should be updated if cable parameters or lengths significantly change.

Appendix A. PSCAD Model


GFOV #1
LROV #1
BRK_SouthBeach
927.2 ACAR 4.74mi
927.2 GREELY 0.4mi
927.2 ACAR 2.07mi
927.2 ACAR 1.7mi
394.5 KCM AAAC 6.71mi
927.2 ACAR 0.98mi
927.2 ACAR 0.04mi
927.2 ACAR 1mi
LROV #2
GFOV #2
394.5 AAAC 4.8mi
927.2 GREELY 0.63mi
652 ACCC 1.39mi
LROV #3
GFOV #3
Timed Fault Logic
OLTC on winding #2
Tap Control
SR fixed tap no STATCOM
SUBSEA
LAND
Line 7 - submarine 20.757 km
Line 9 - submarine 19.357 km
Line 11 - submarine 17.410 km
Line 13 - submarine 16.18 km
BRK_GEN1
BRK_GEN2
BRK_GEN3
BRK_GEN4
WEC
BRK1
BRK2
BRK3
BRK4
BRK_Main
POI
STATCOM
BRK_STATCOM
Lundy CB is Open
4/0 AAAC 7.06 mi

Appendix B. PSCAD TOV Plots

PacWave TOV simulations

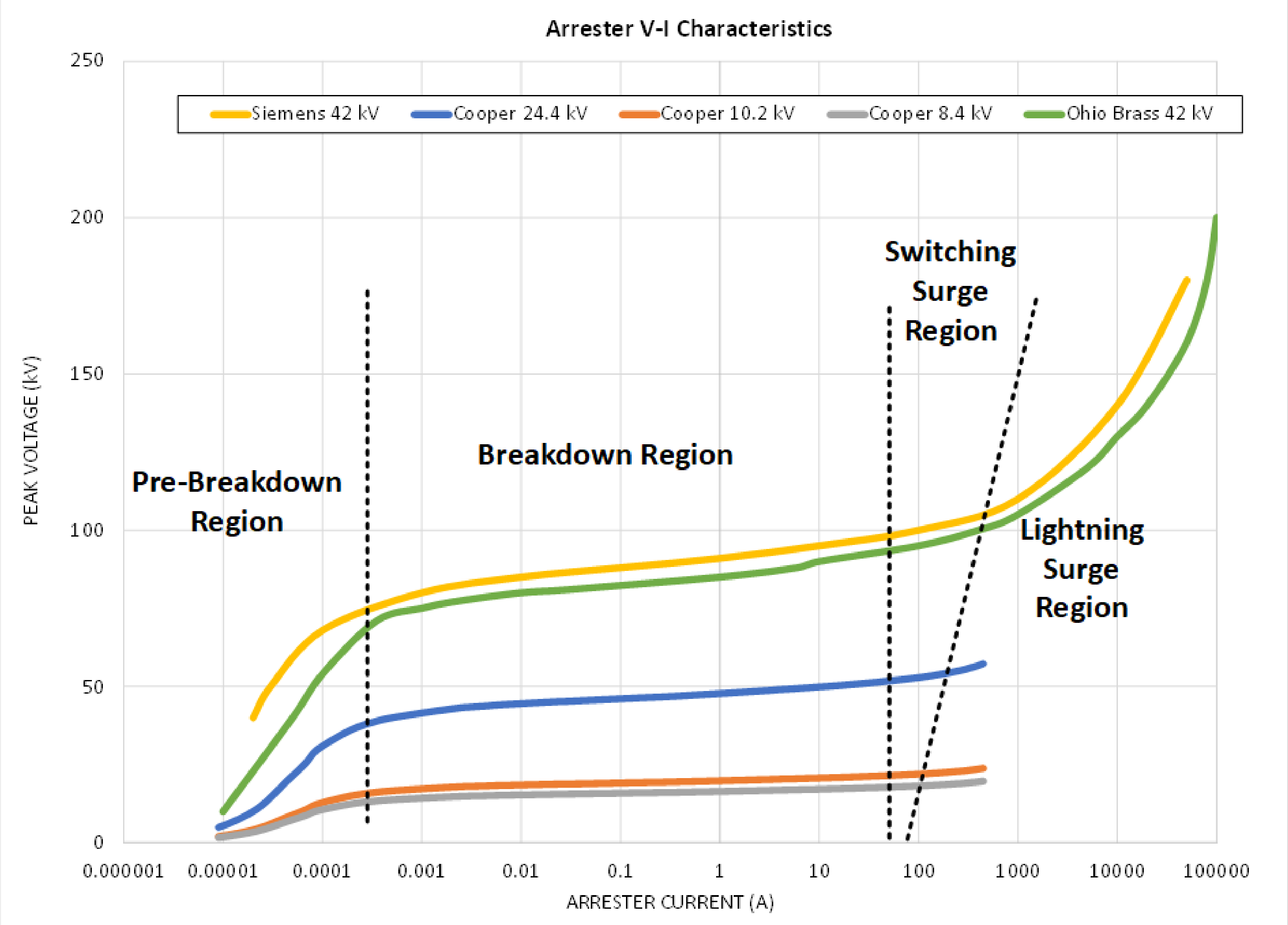
Light load case

10 MW PacWave generation

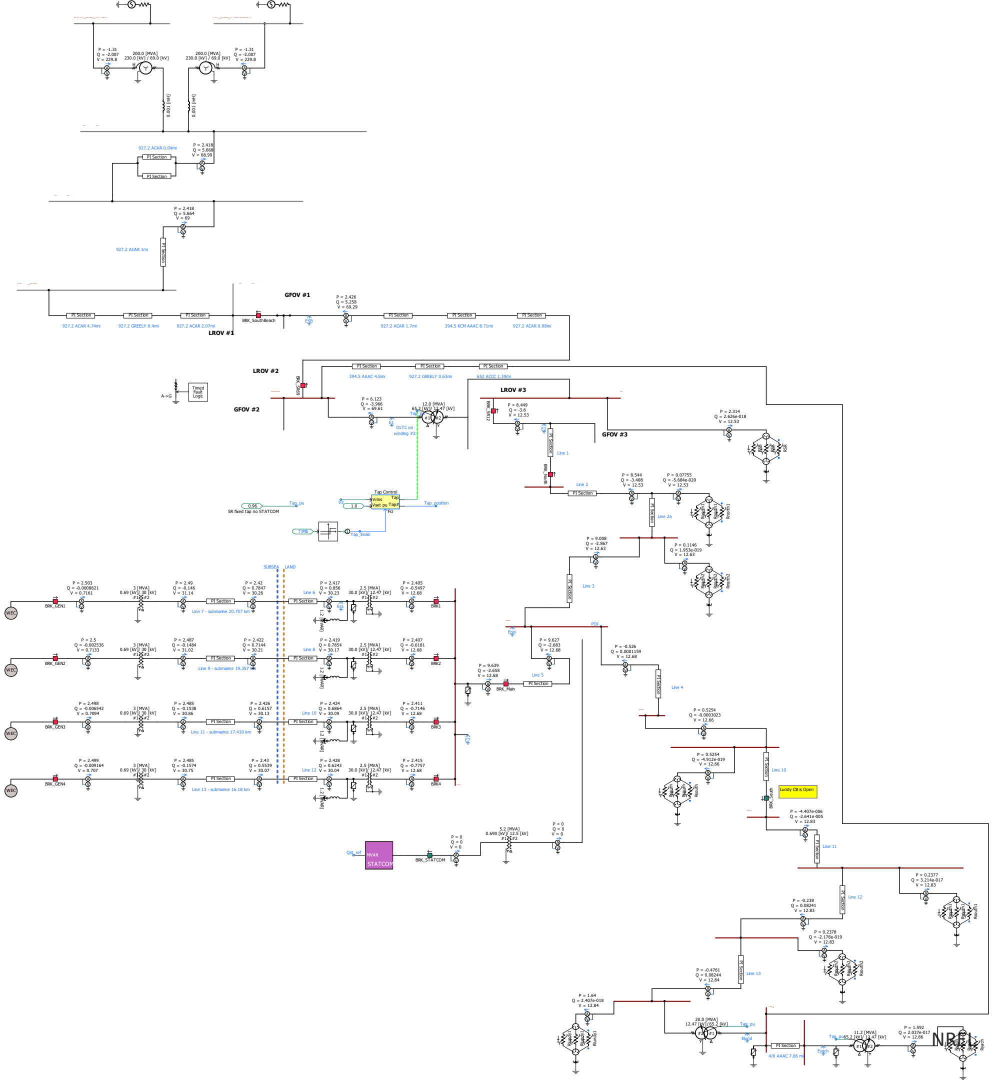
V. Gevorgian

NREL

October 4, 2021


Arrester V-I Characteristics
Siemens 42 kV
Cooper 24.4 kV
Cooper 10.2 kV
Cooper 8.4 kV
Ohio Brass 42 kV
PEAK VOLTAGE (kV)
250
200
150
100
50
0
0.000001
0.00001
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
100000
ARRESTER CURRENT (A)
Pre-Breakdown Region
Breakdown Region
Switching Surge Region
Lightning Surge Region

System diagram with power flow, 700 kW generation



Changes in model and Scenarios
10 MW generation

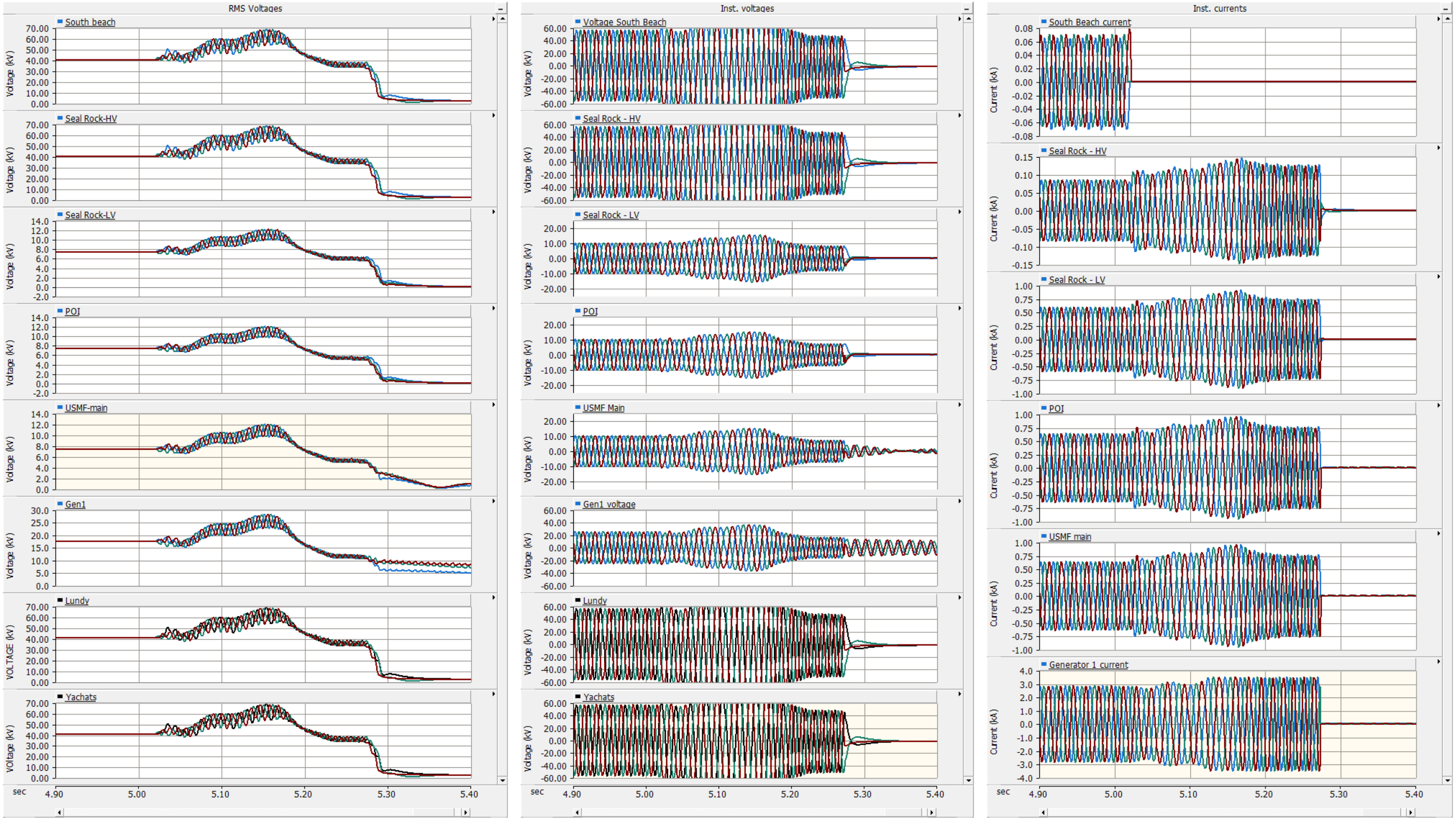
- Reduced Lundy additional load to 1.55 MW

- New X-Y plots show arrestors inst. voltages (L-to-G) vs. inst. currents for all three phases

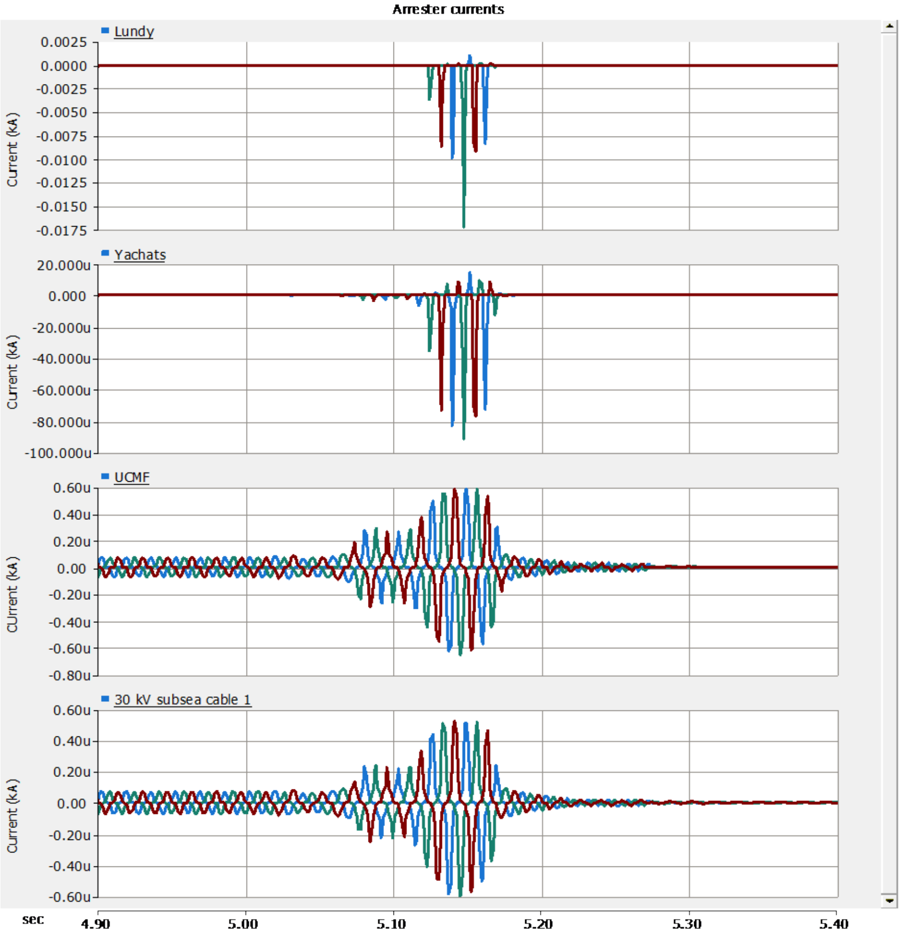
Scenarios simulated:

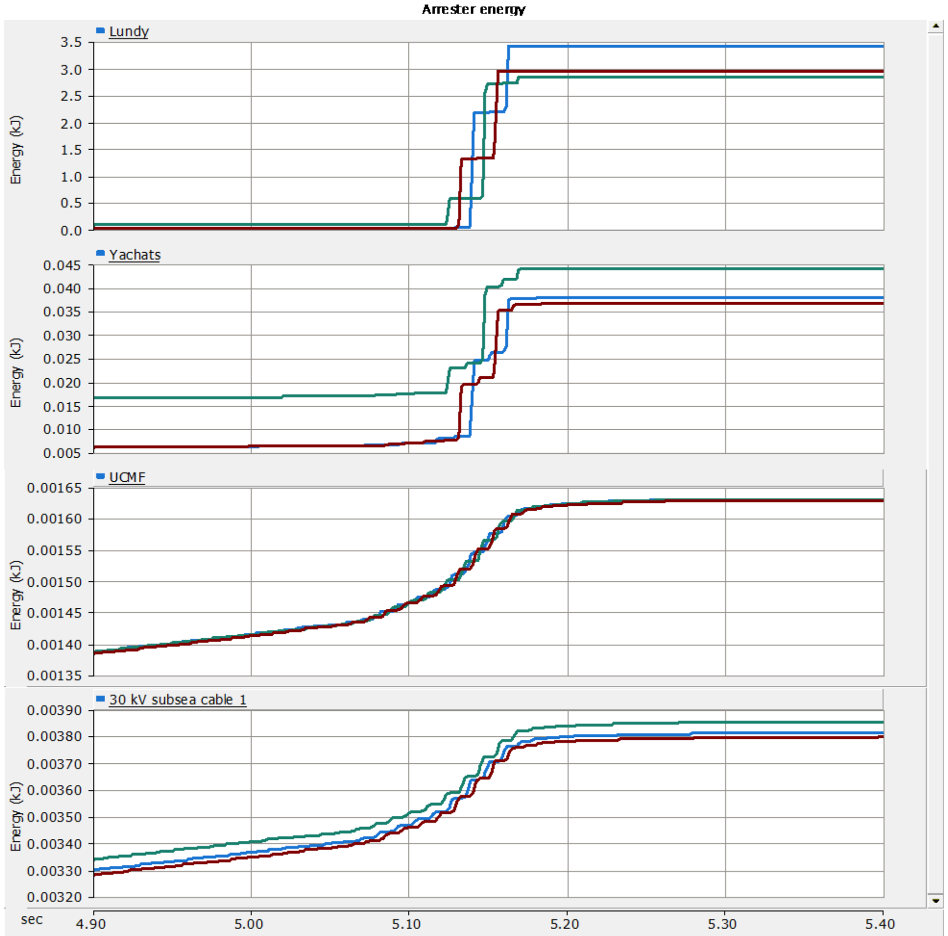
- LROV 1: South Beach 69 kV breaker opens at T=5s
- LROV 2: Seal Rock 69 kV breaker opens at T=5s
- LROV 3: Seal Rock 12.47 kV breaker opens at T=5s
- GFOV 1: Single L-to-G fault on right side of 69 kV South Beach breaker, South Beach 69 kV breaker opens at T=5.016 s
- GFOV 2: Single L-to-G fault at 69 kV side of Seal Rock transformer, Seal Rock 69 kV breaker opens at T=5.016 s
- GFOV 3: Single L-to-G fault at PacWave side of 12.47 kV Seal Rock breaker, Seal Rock 12.47 kV breaker opens at T=5.016 s

LROV1: South Beach 69 kV breaker opens at T=5 s open 10 MW generation

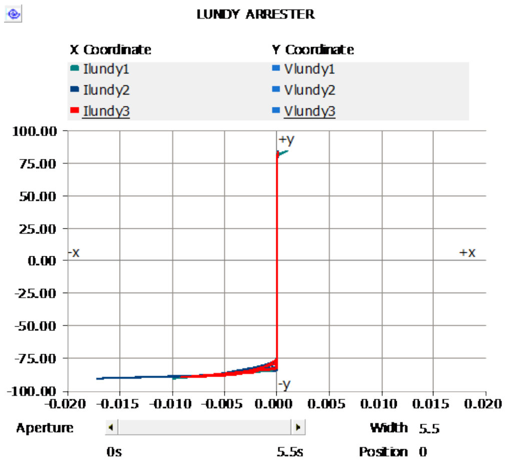


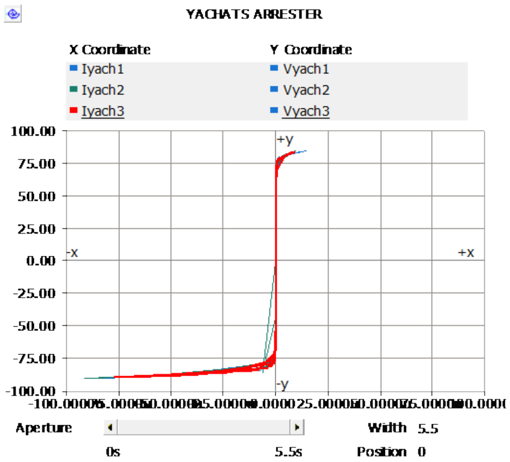
LROV1: South Beach 69 kV breaker opens at T=5 s open 10 MW generation

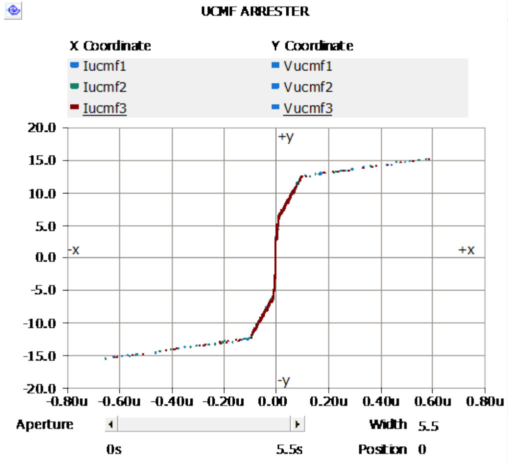


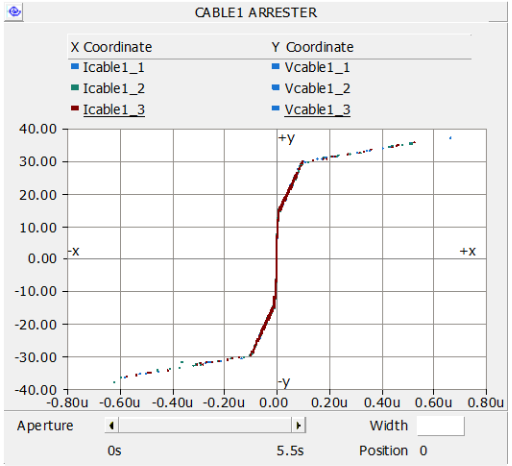


LROV1: South Beach 69 kV breaker opens at T=5 s open 10 MW generation

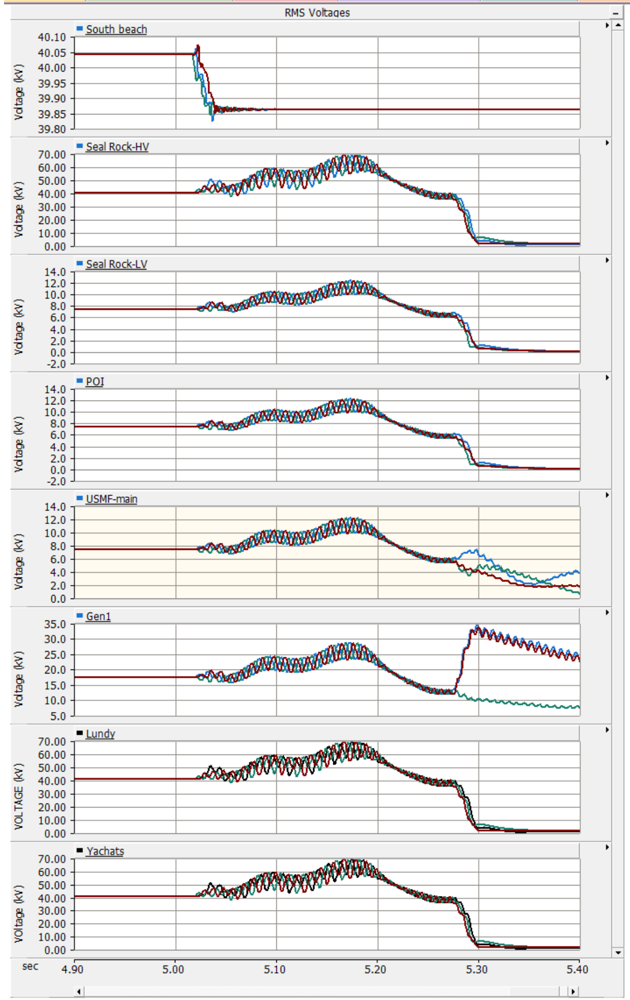


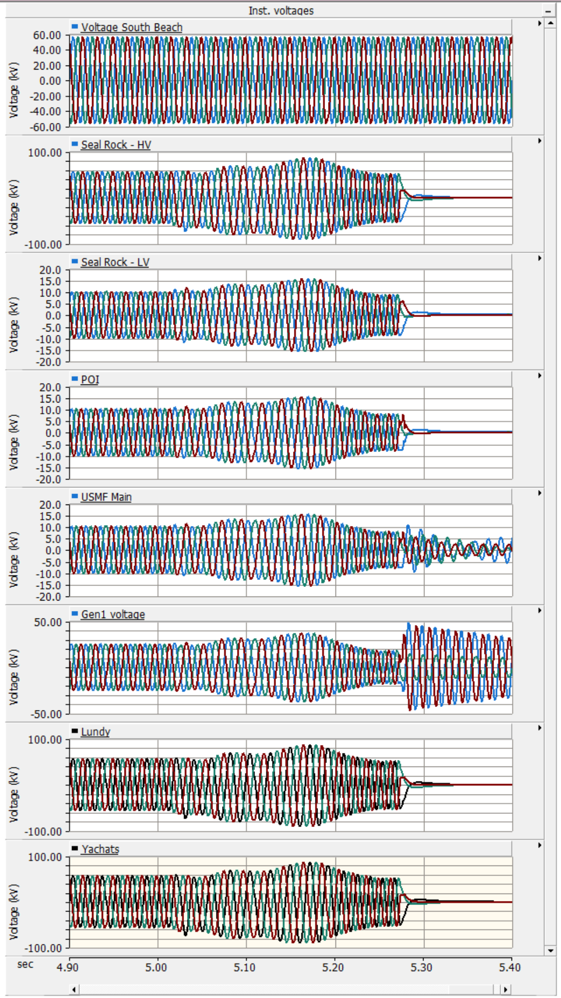


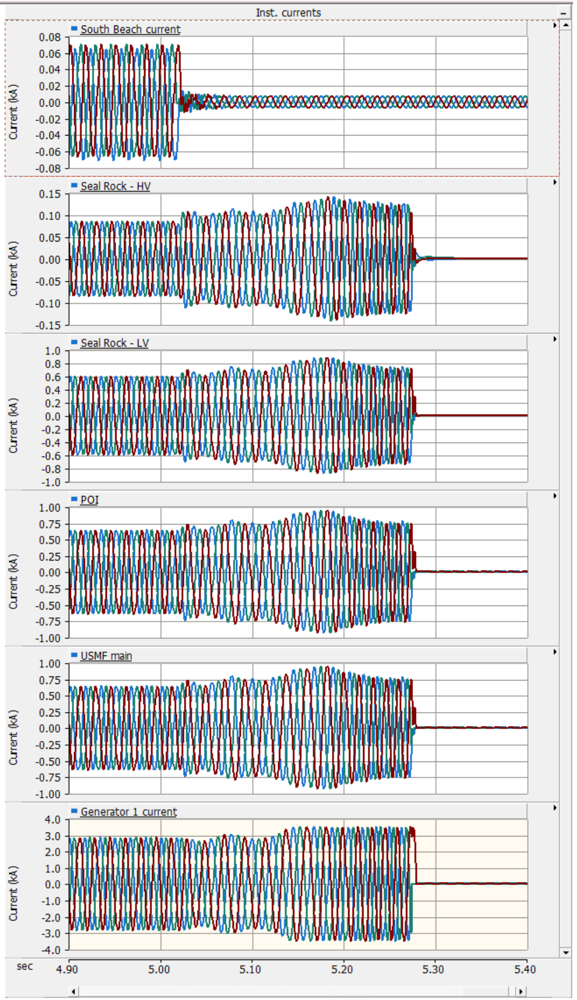




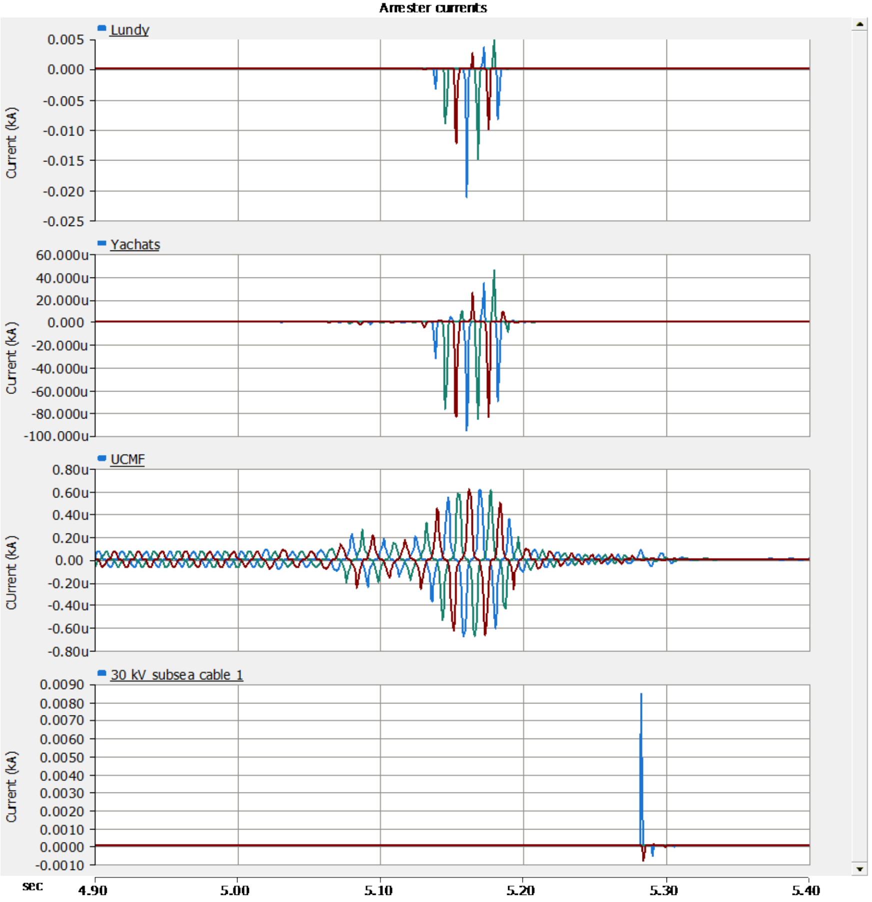
LROV 2: Seal Rock 69 kV breaker opens at T=5 s open 10 MW generation

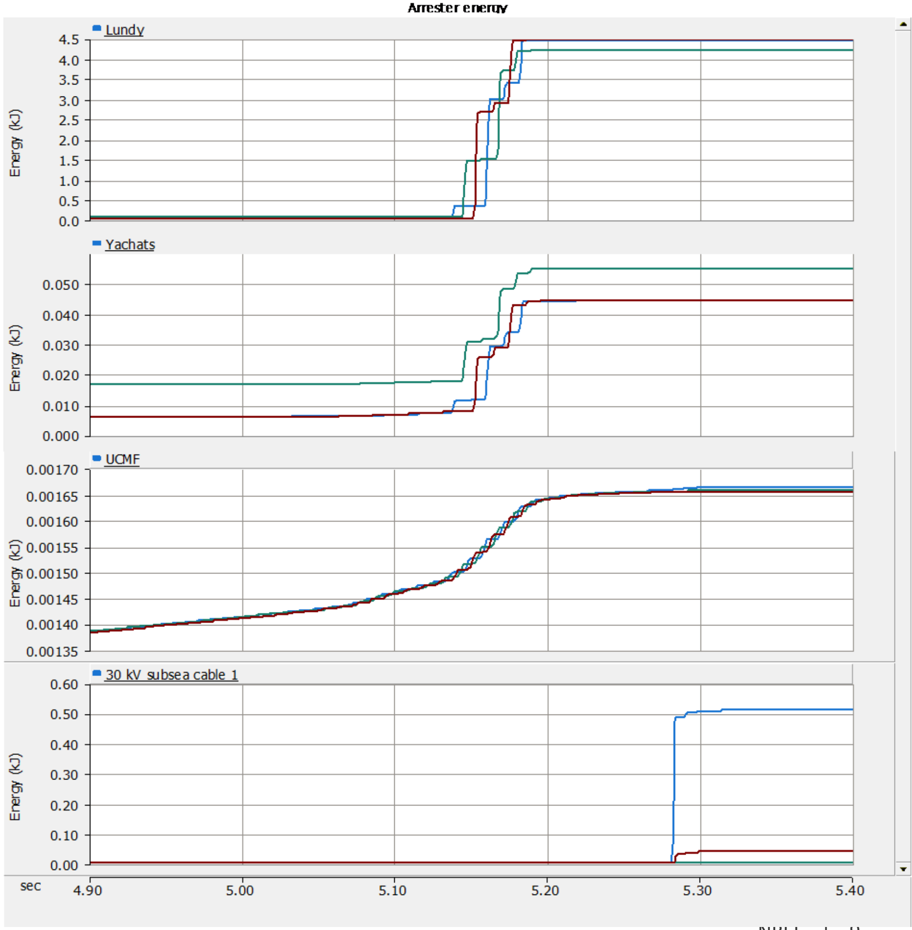




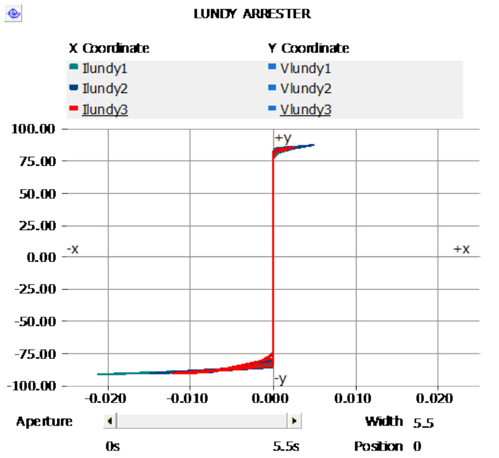


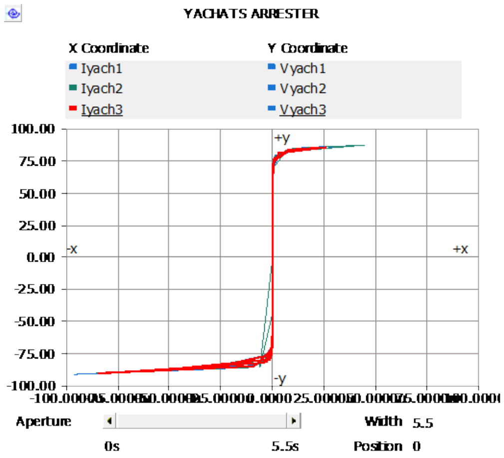
LROV 2: Seal Rock 69 kV breaker opens at T=5 s open 10 MW generation

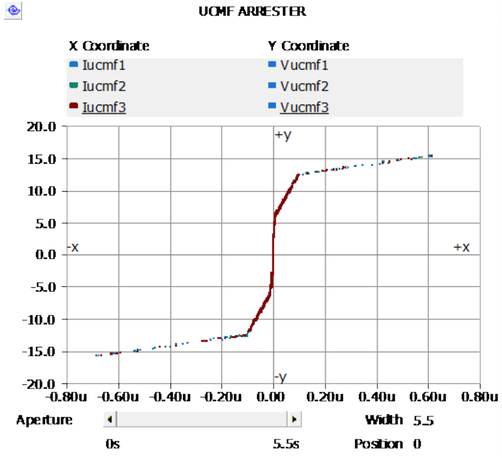


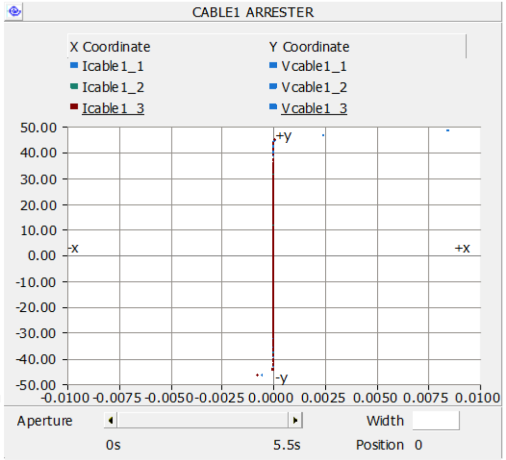


LROV 2: Seal Rock 69 kV breaker opens at T=5 s open 10 MW generation

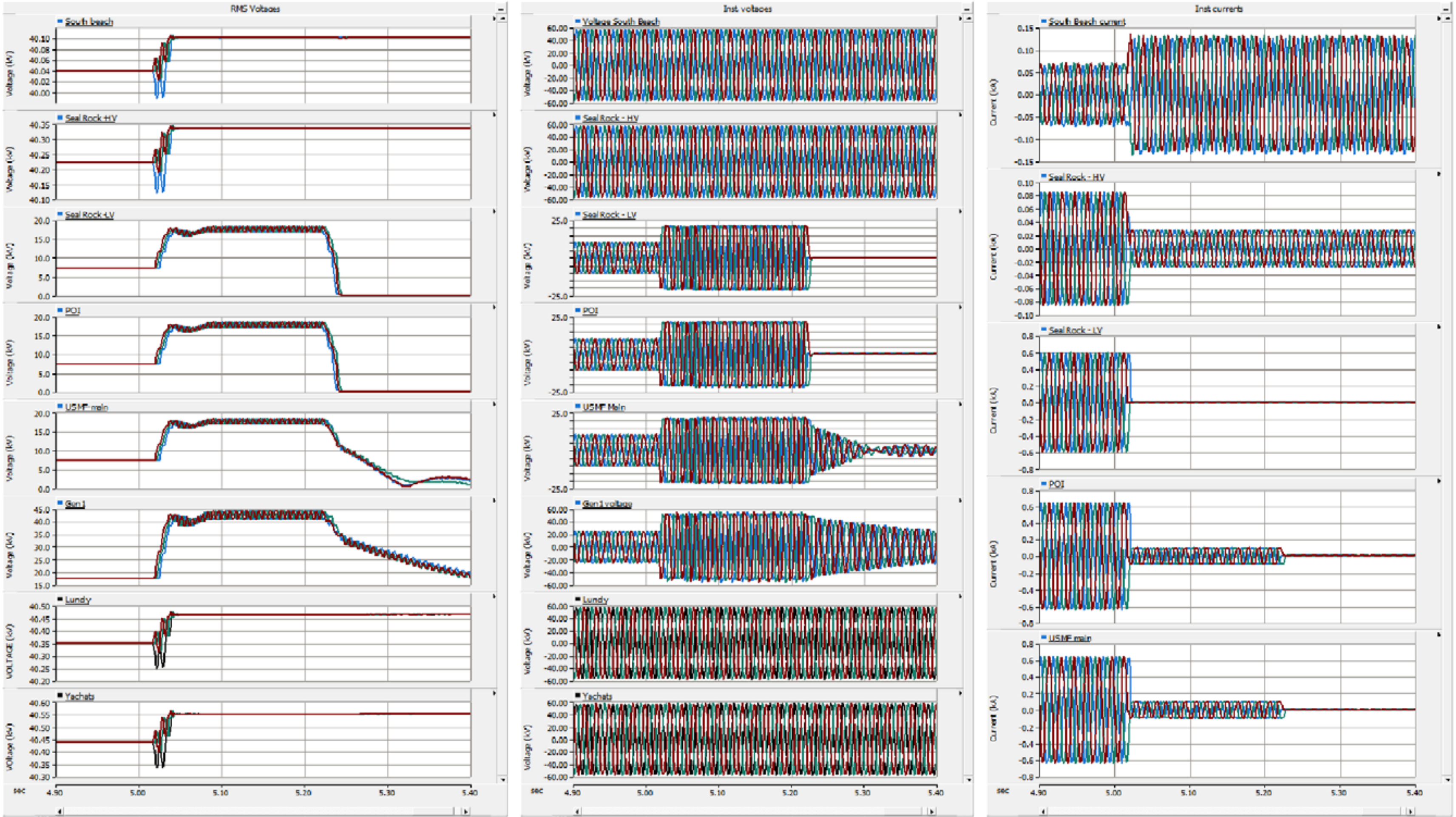




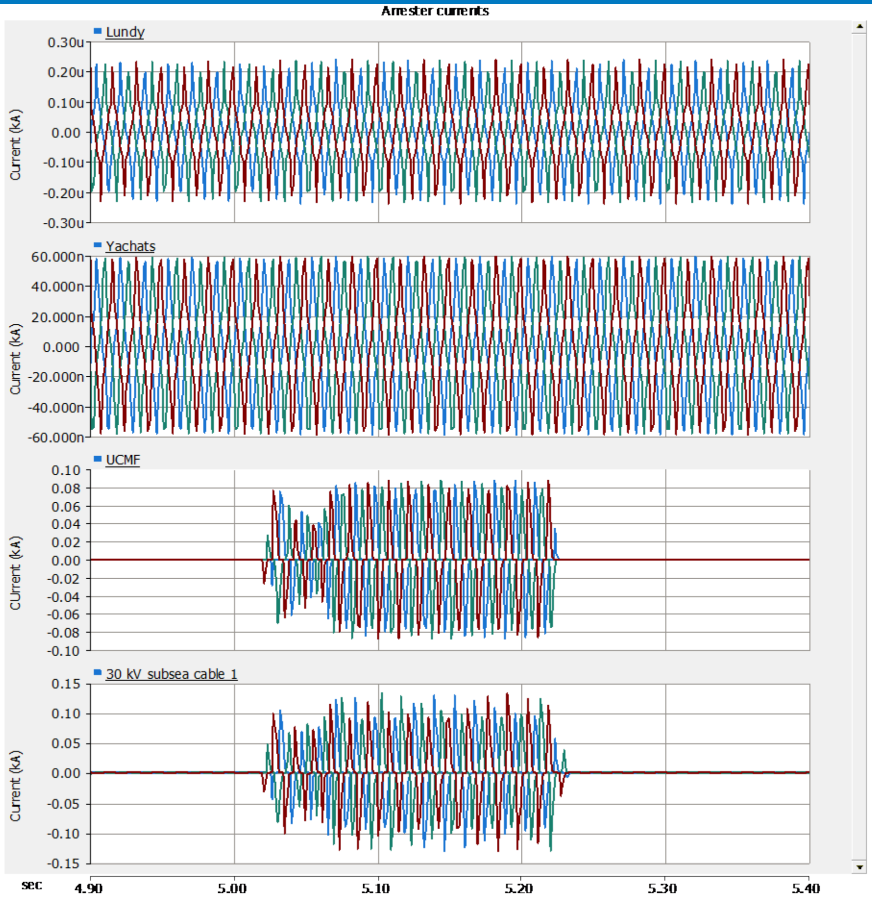


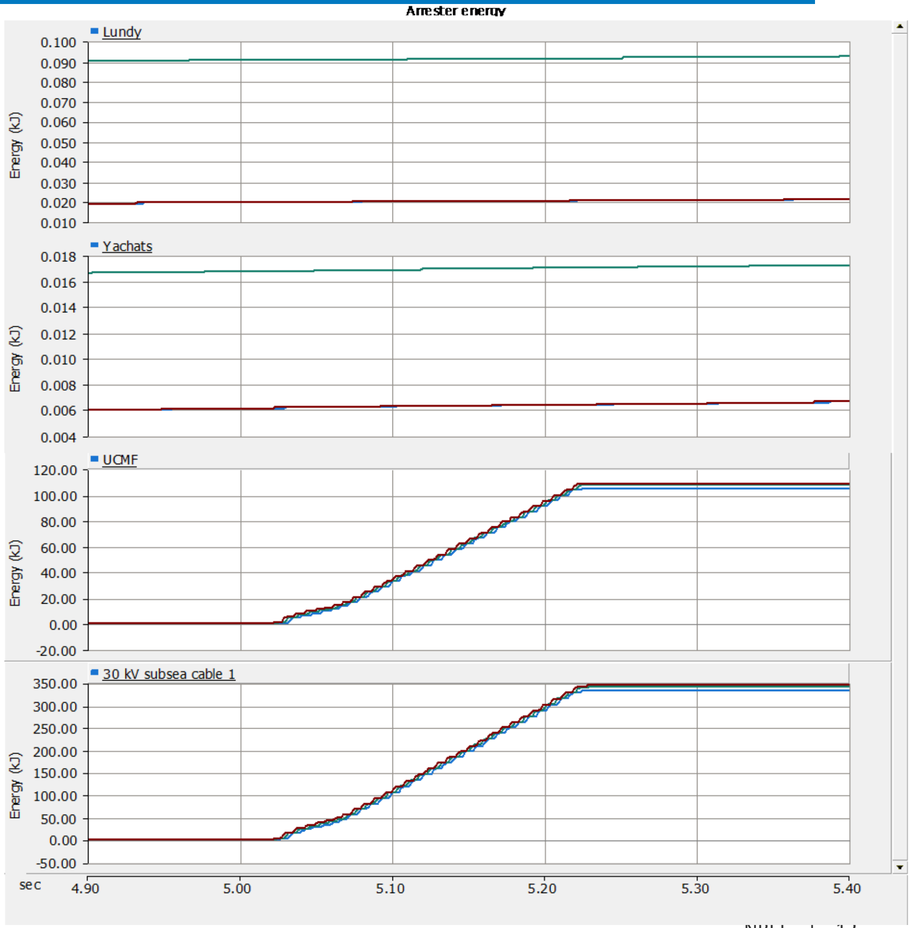


LROV 3: Seal Rock 12. 47 kV breaker opens at T=5s 10 MW generation

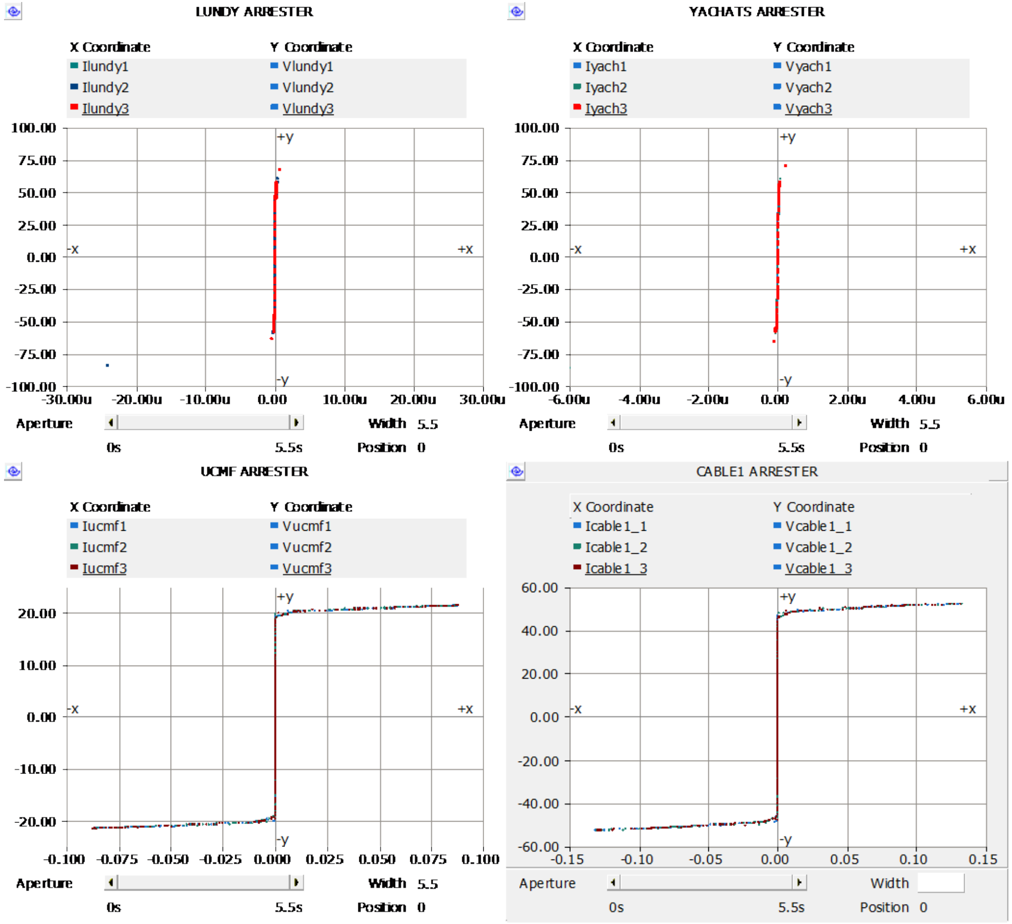


LROV 3: Seal Rock 12. 47 kV breaker opens at T=5s 10 MW generation

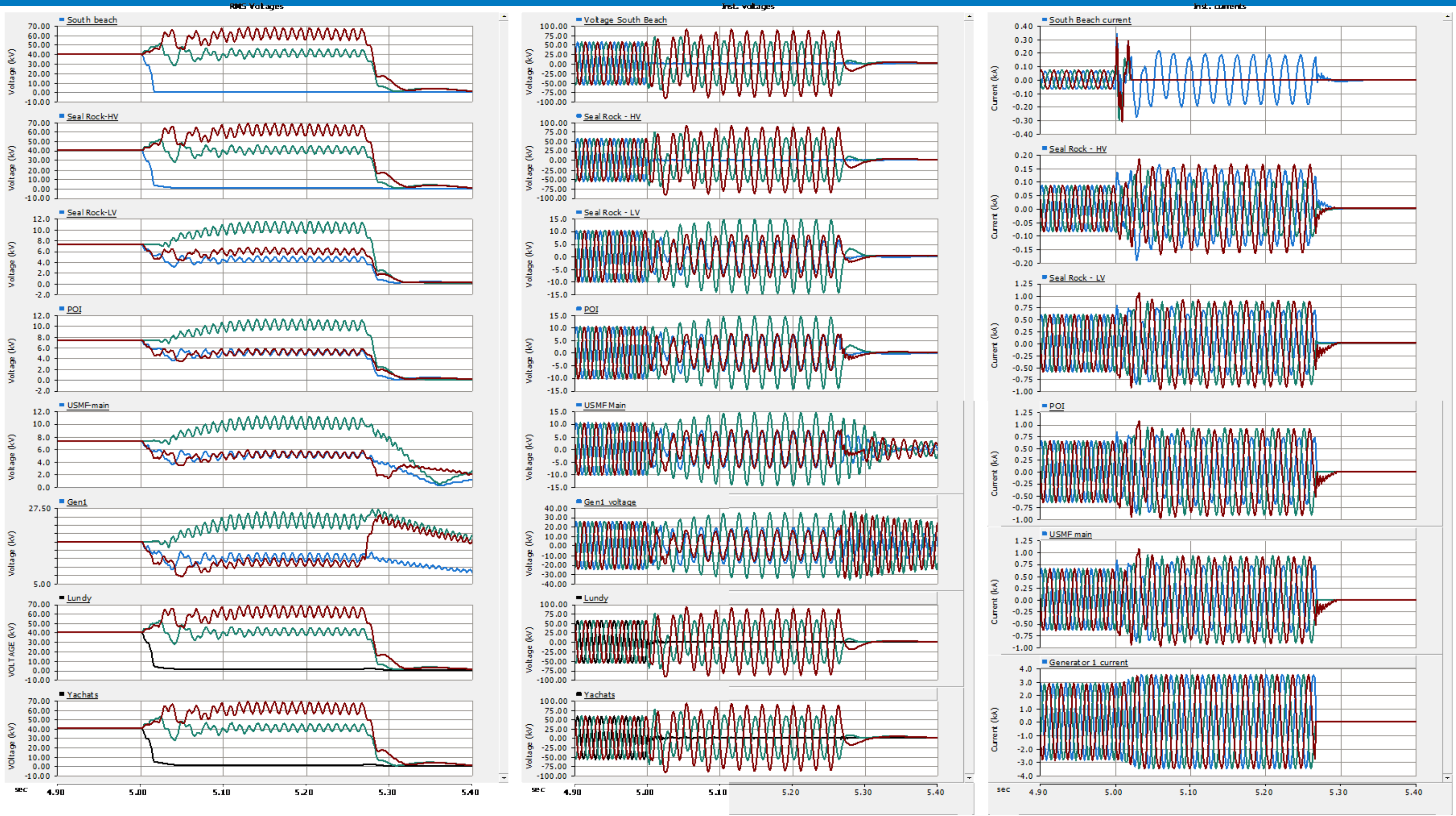




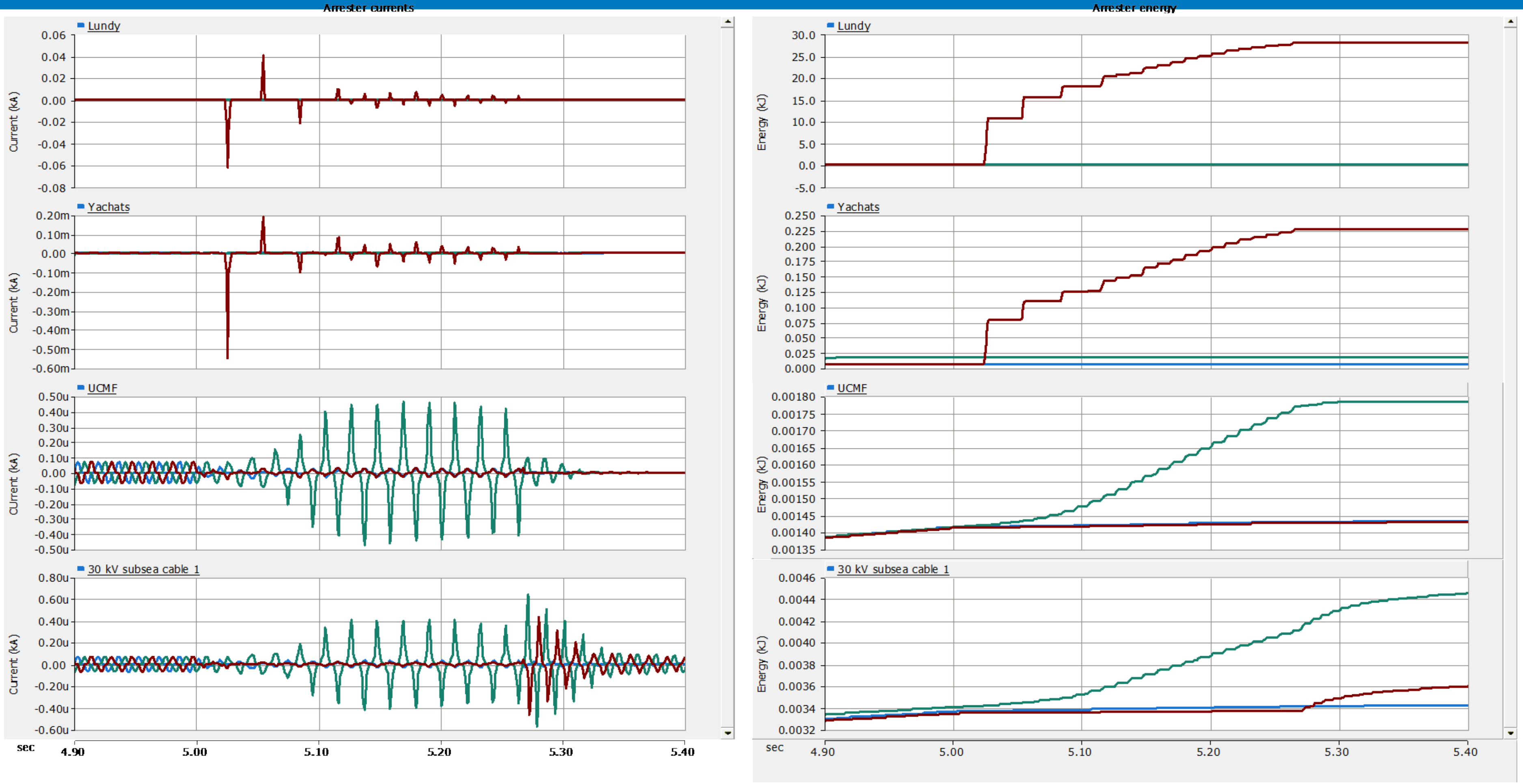
LROV 3: Seal Rock 12. 47 kV breaker opens at T=5s 10 MW generation



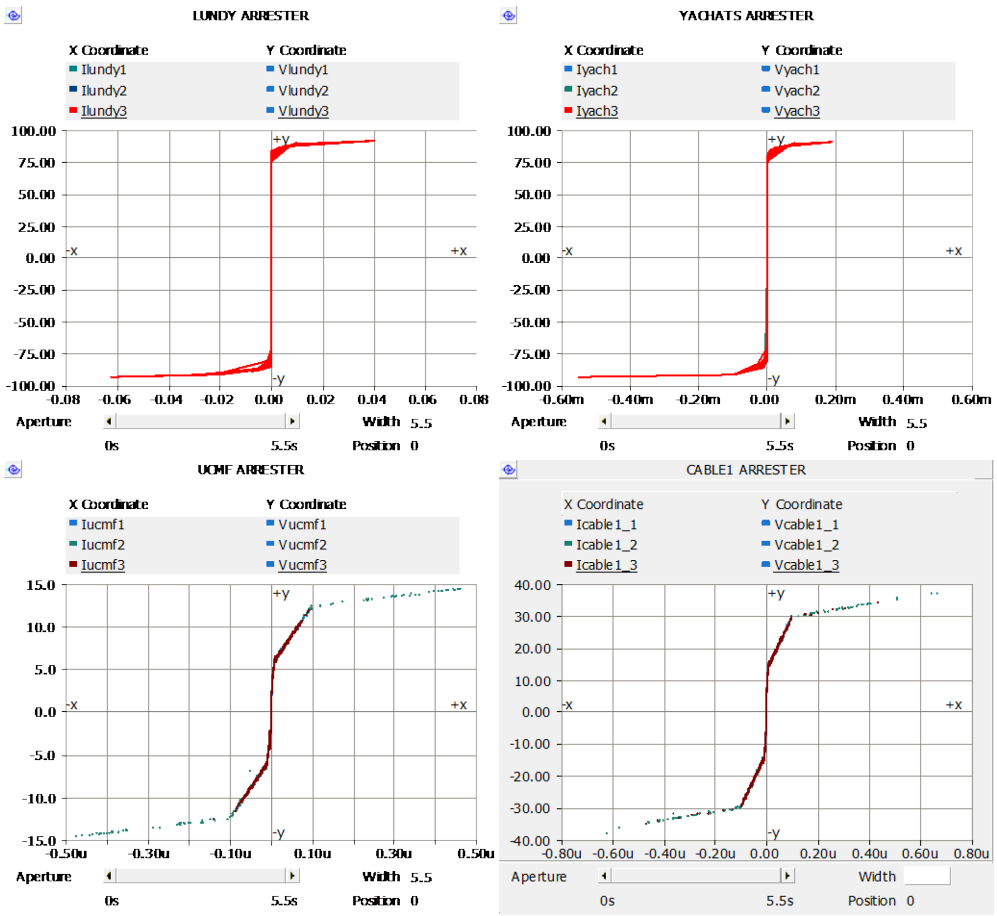
GFOV 1: Fault at 69 kV side of SR xfmr, SB 69 kV breaker opens at T=5.016 s 10 MW generation



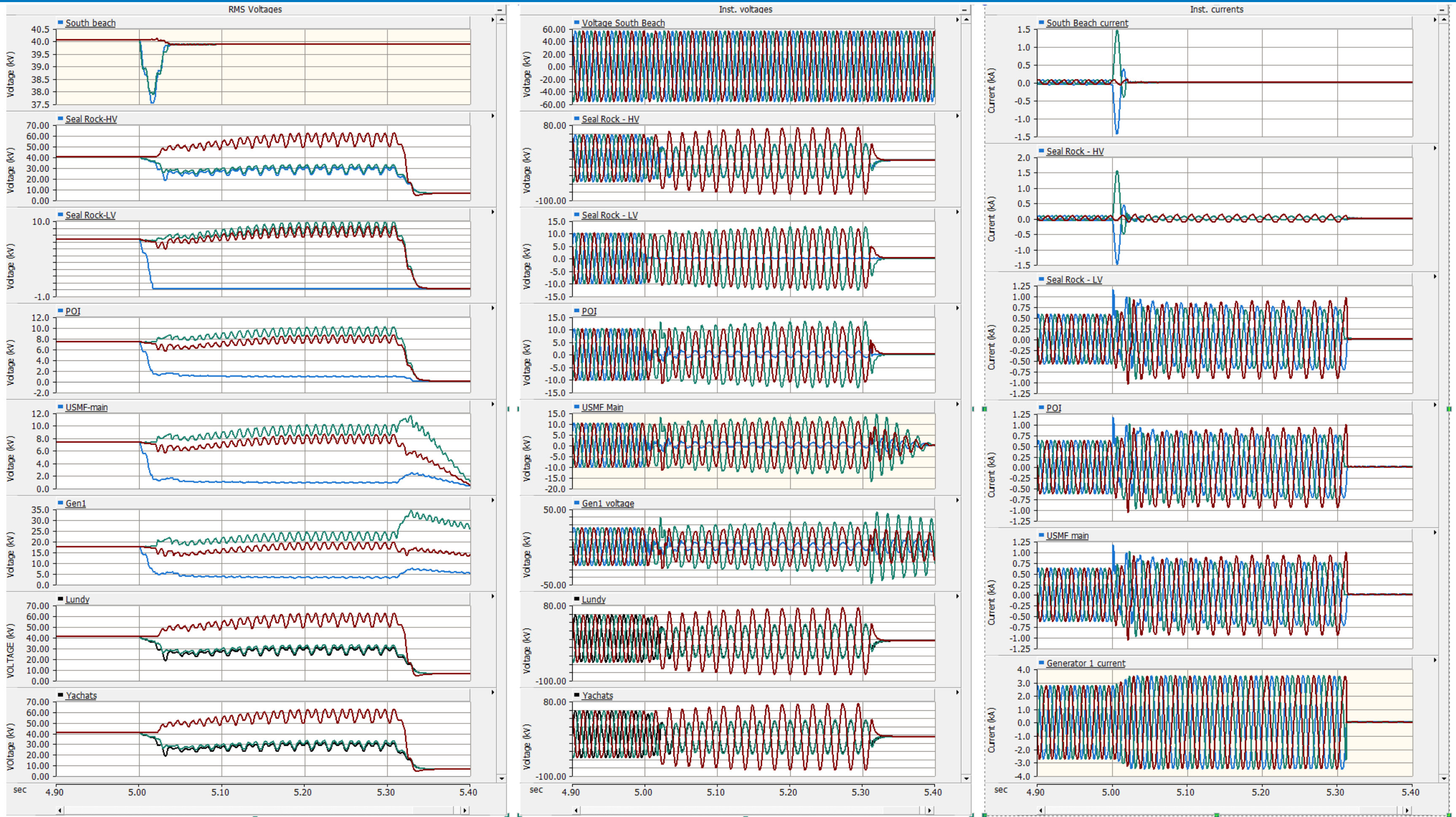
GFOV 1: Fault at 69 kV side of SR xfmr, SB 69 kV breaker opens at T=5.016 s 10 MW generation



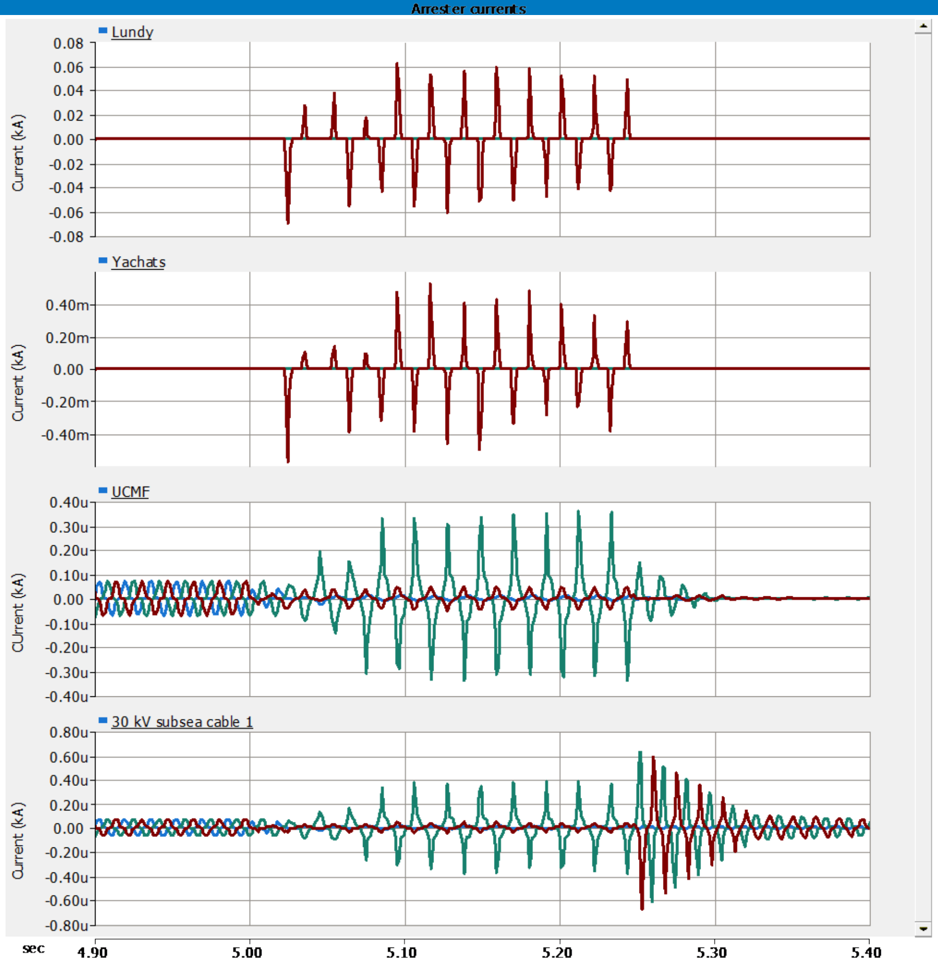
GFOV 1: Fault at 69 kV side of SR xfmr, SB 69 kV breaker opens at T=5.016 s 10 MW generation

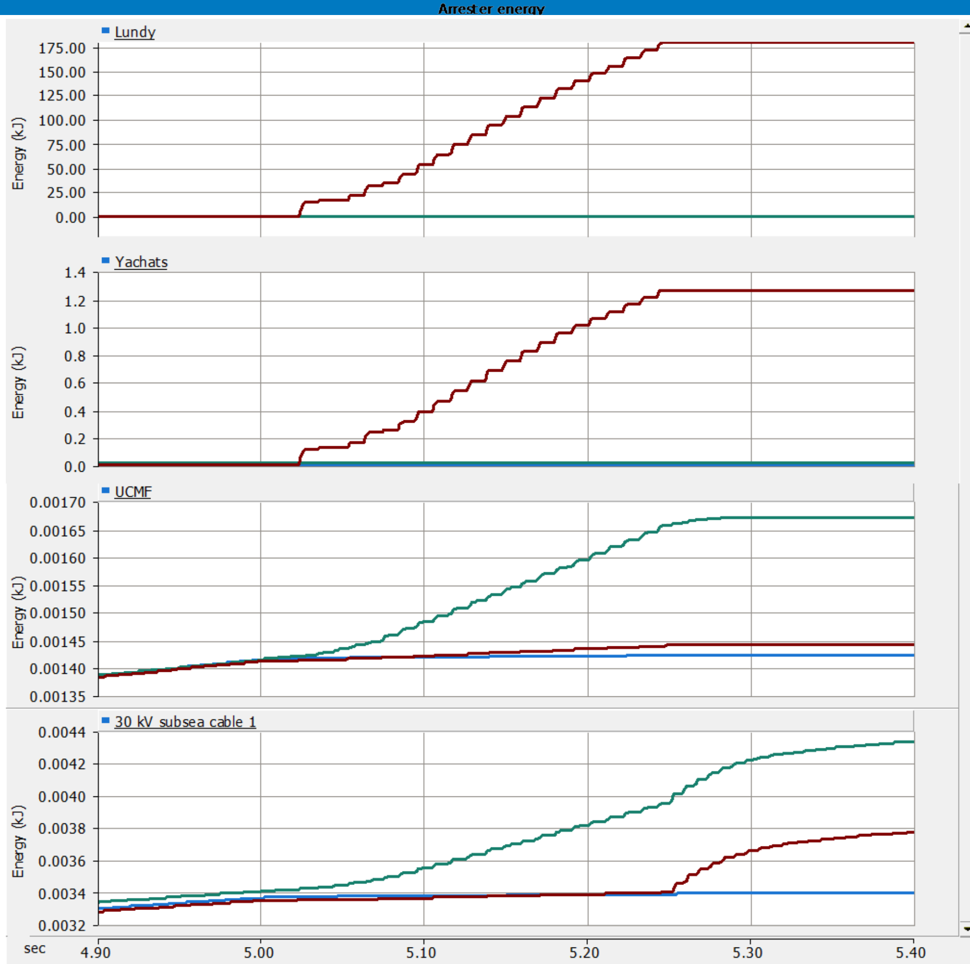


GFOV 2: Fault at 12.47 kV side of SR xfmr, SR 69kV breaker opens at T=5.016s 10 MW gen

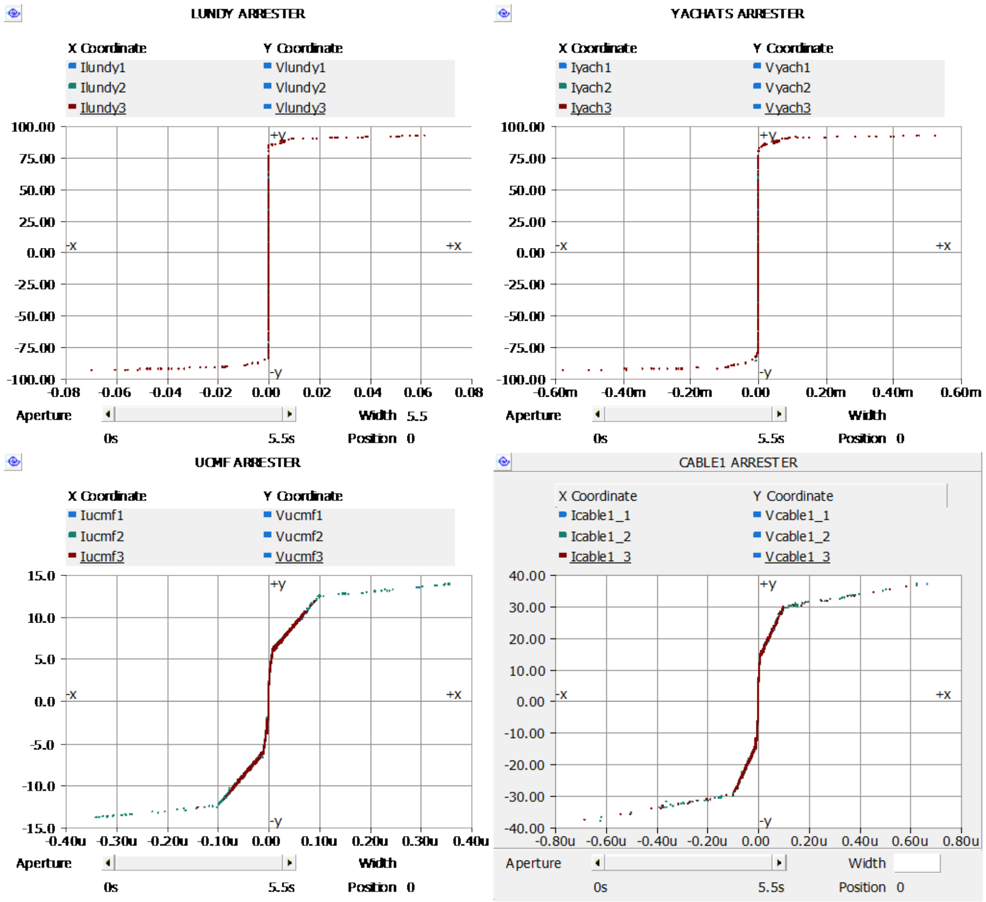


GFOV 2: Fault at 12.47 kV side of SR xfmr, SR 69kV breaker opens at T=5.016s 10 MW gen

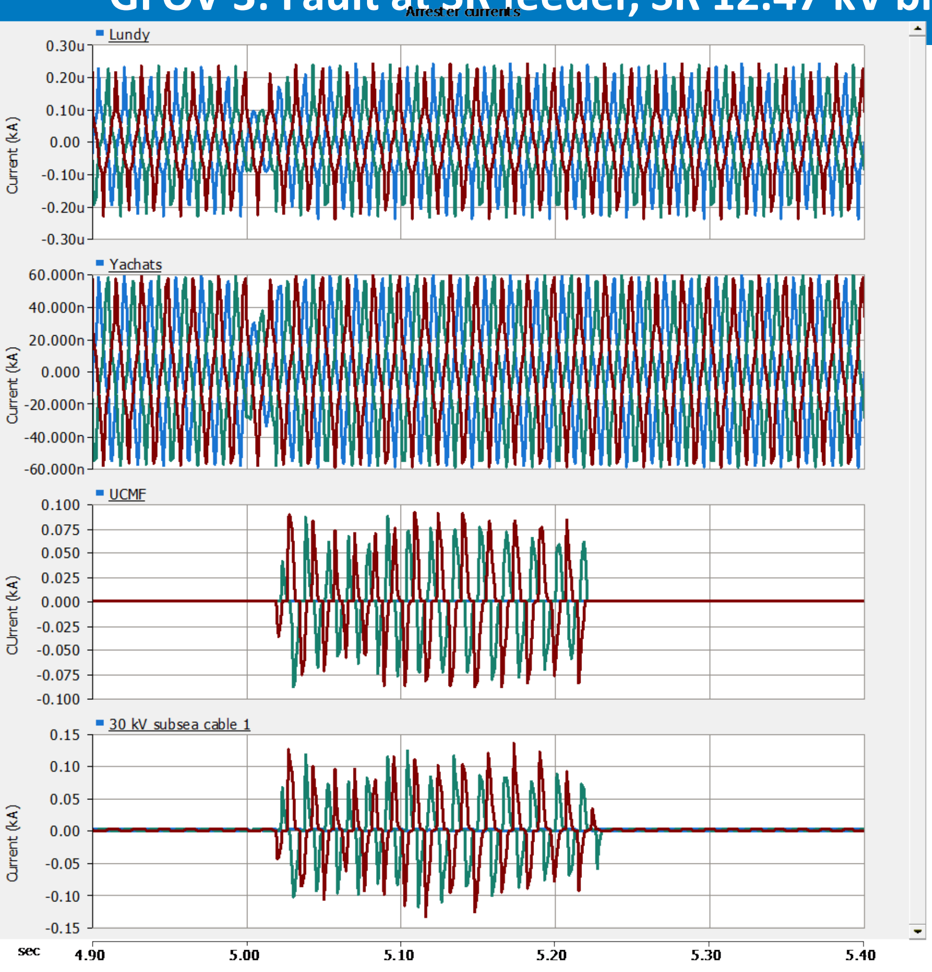


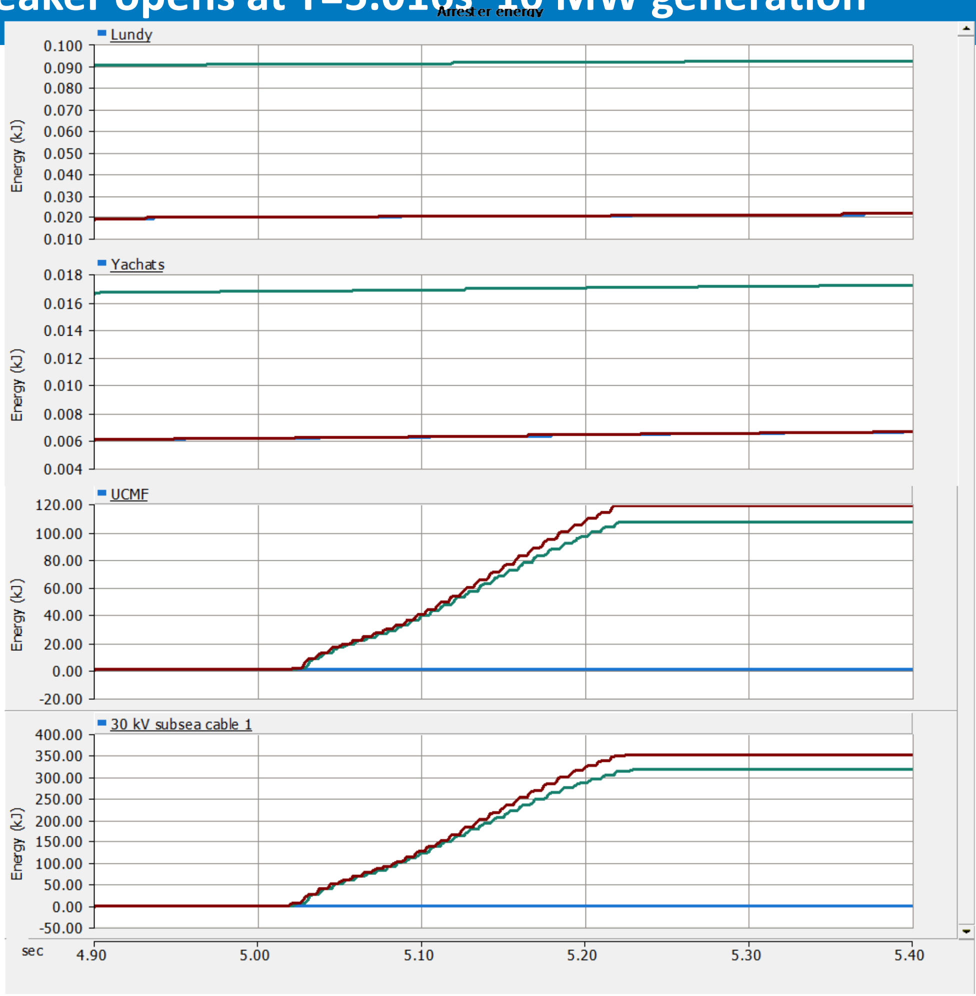


GFOV 2: Fault at 12.47 kV side of SR xfmr, SR 69kV breaker opens at T=5.016s 10 MW gen

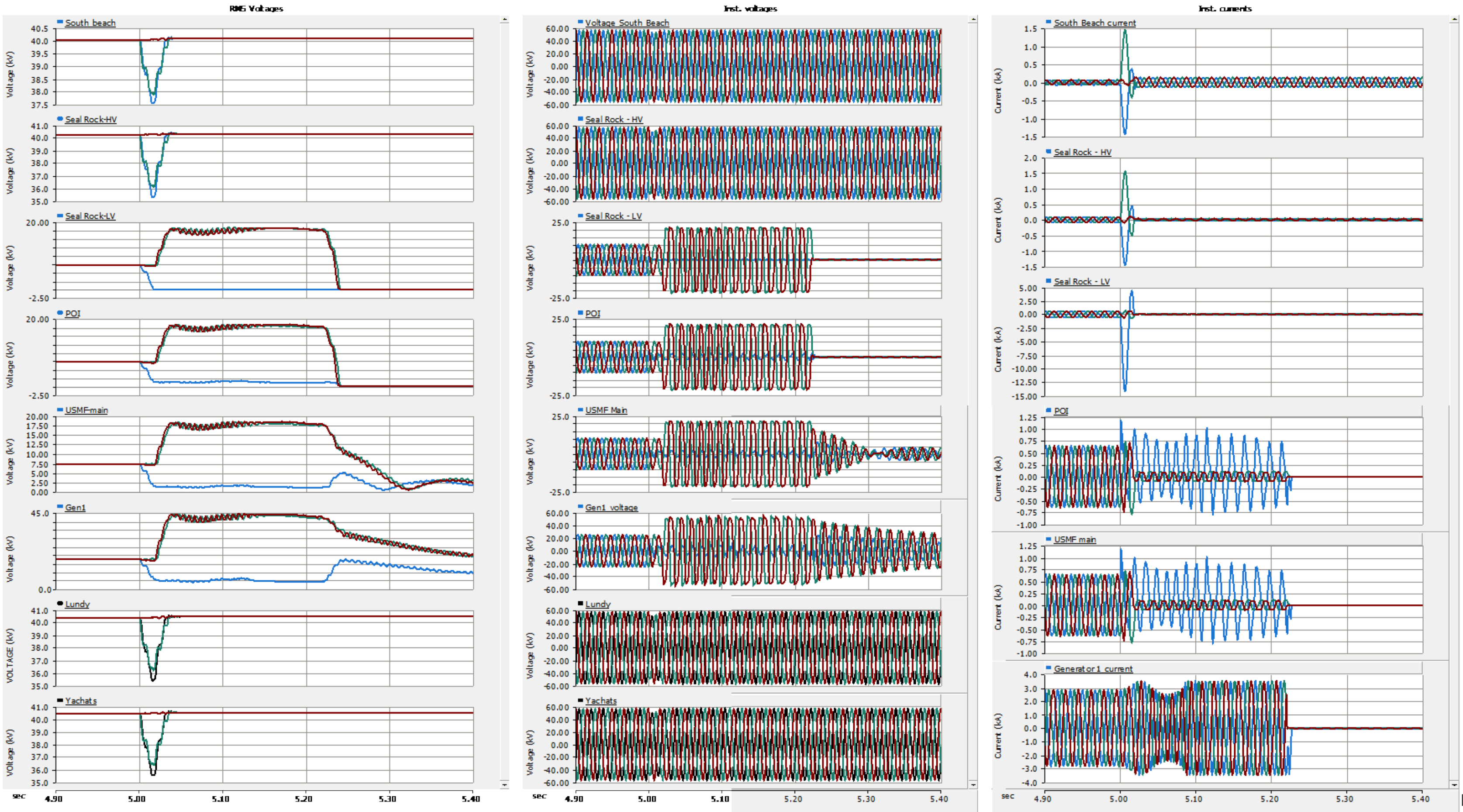


GFOV 3: Fault at SR feeder, SR 12.47 kV breaker opens at T=5.016s, 10 MW generation

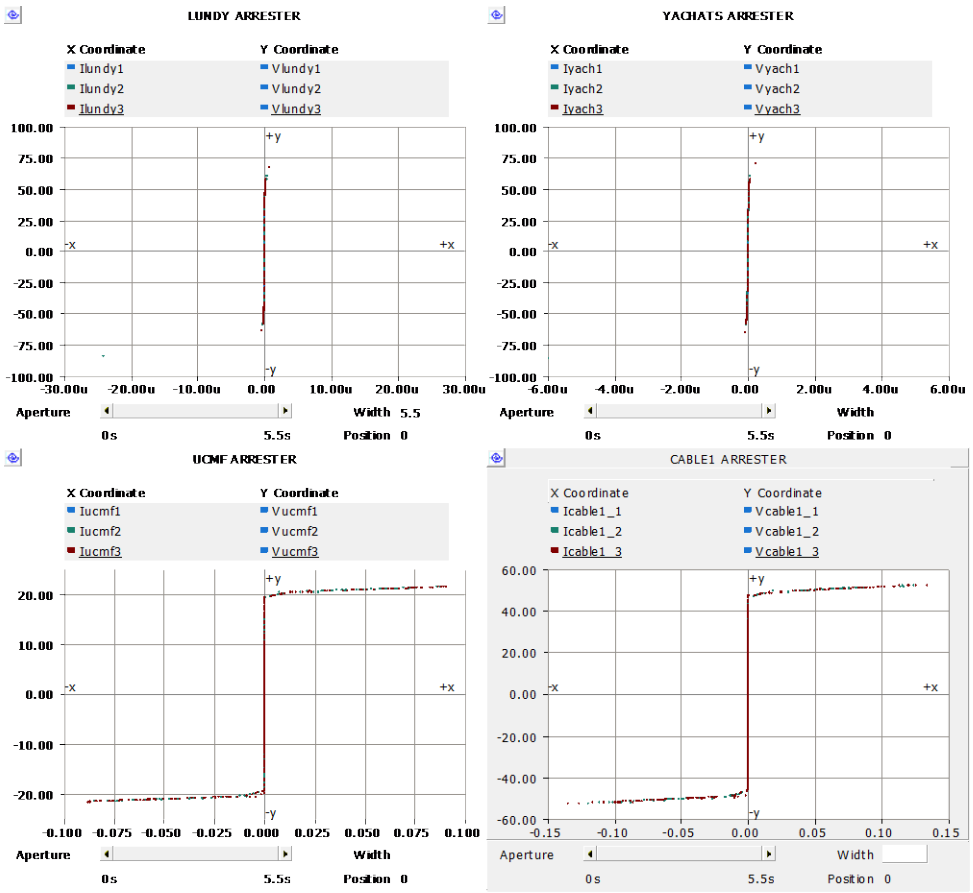




GFOV 3: Fault at SR feeder, SR 12.47 kV breaker opens at T=5.016s 10 MW generation



GFOV 3: Fault at SR feeder, SR 12.47 kV breaker opens at T=5.016s 10 MW generation

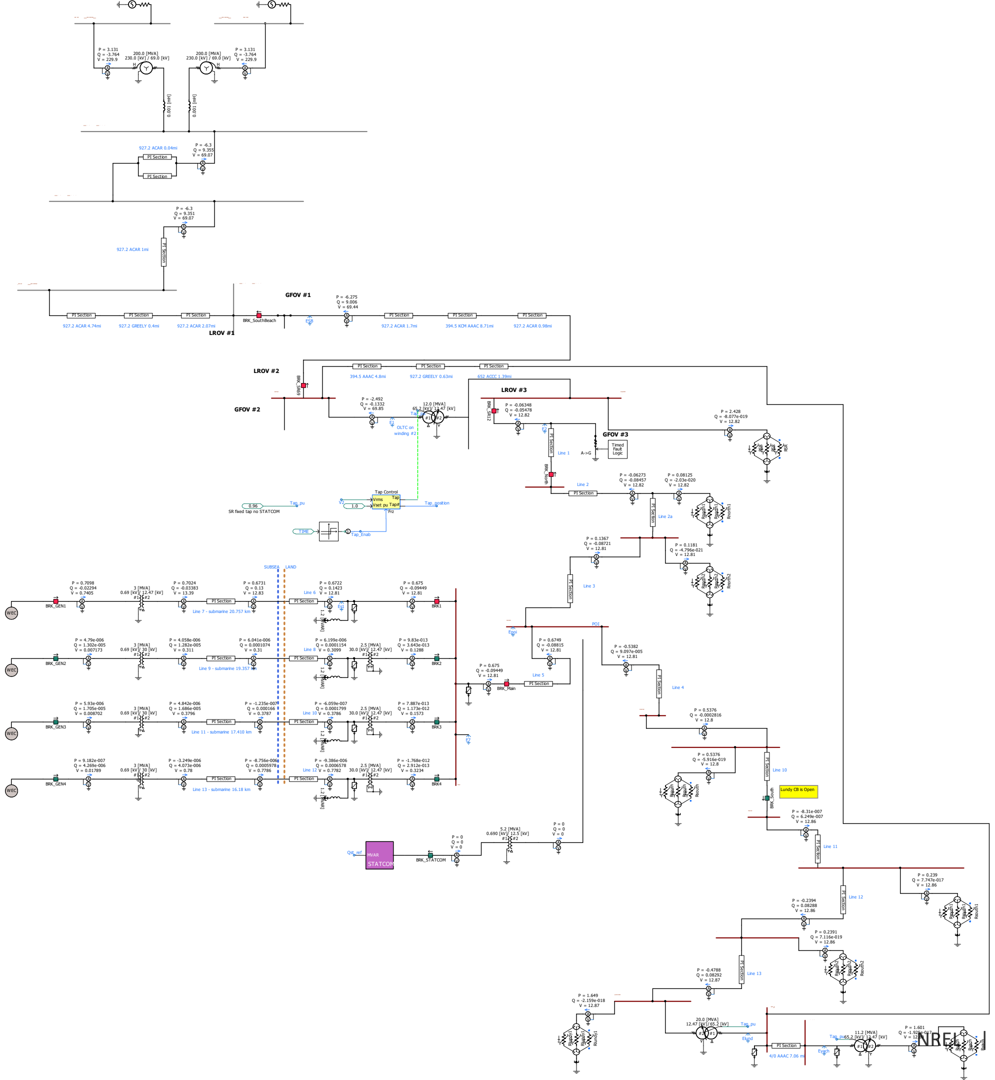


PacWave TOV simulations
Light load case
700 kW PacWave generation

V. Gevorgian
NREL

October 30, 2021

System diagram with power flow, 700 kW generation



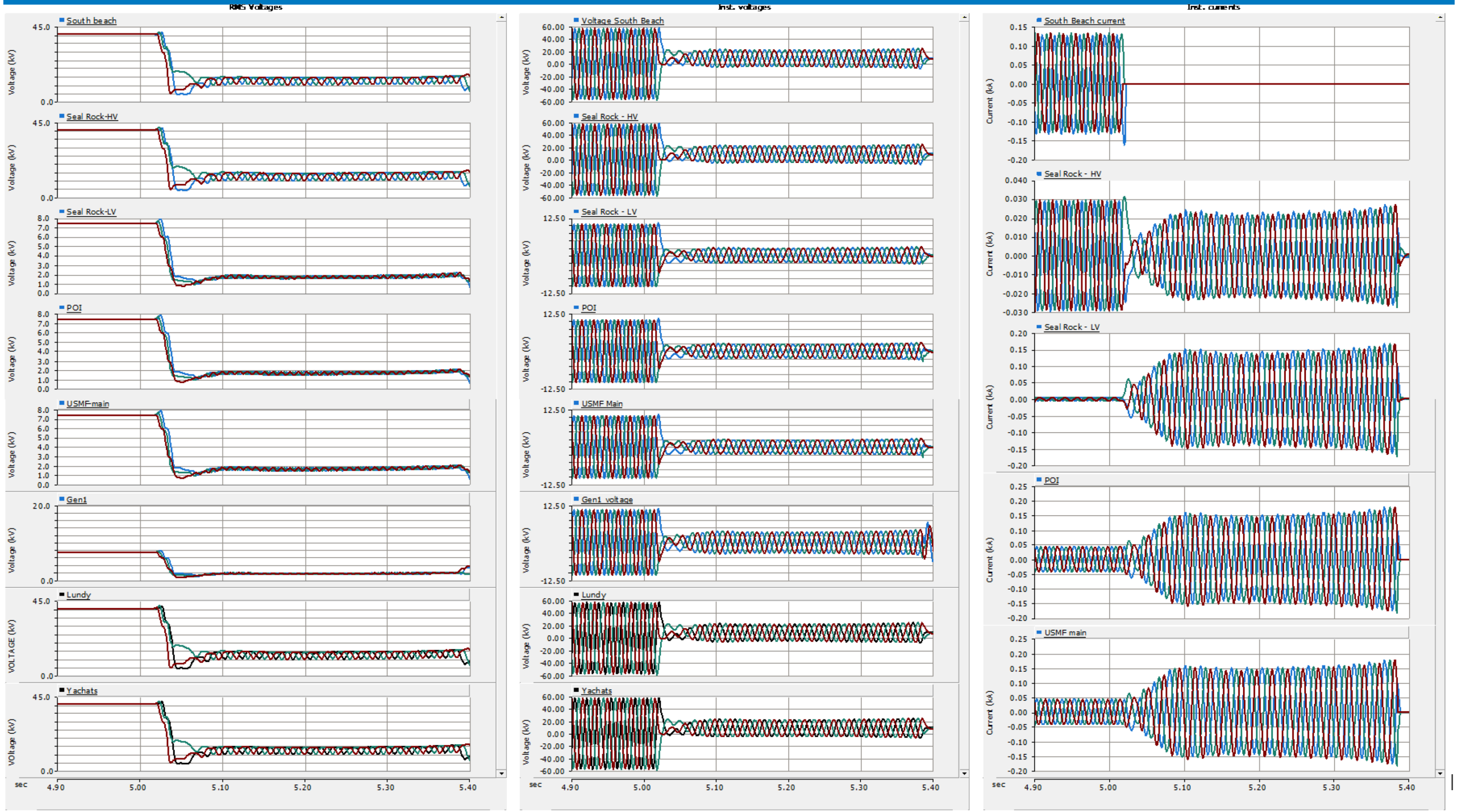
Changes in model and Scenarios
700 kW generation

Active power set points - 700 kW for Gen 1

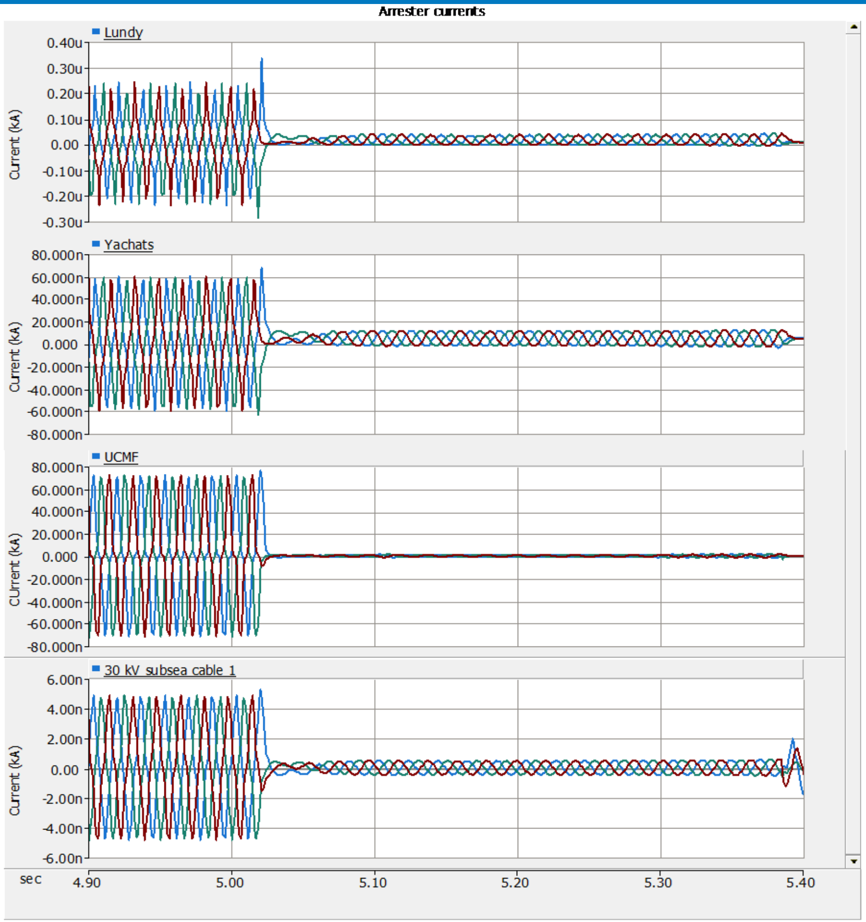
Cables 2, 3 and 4 are disconnected

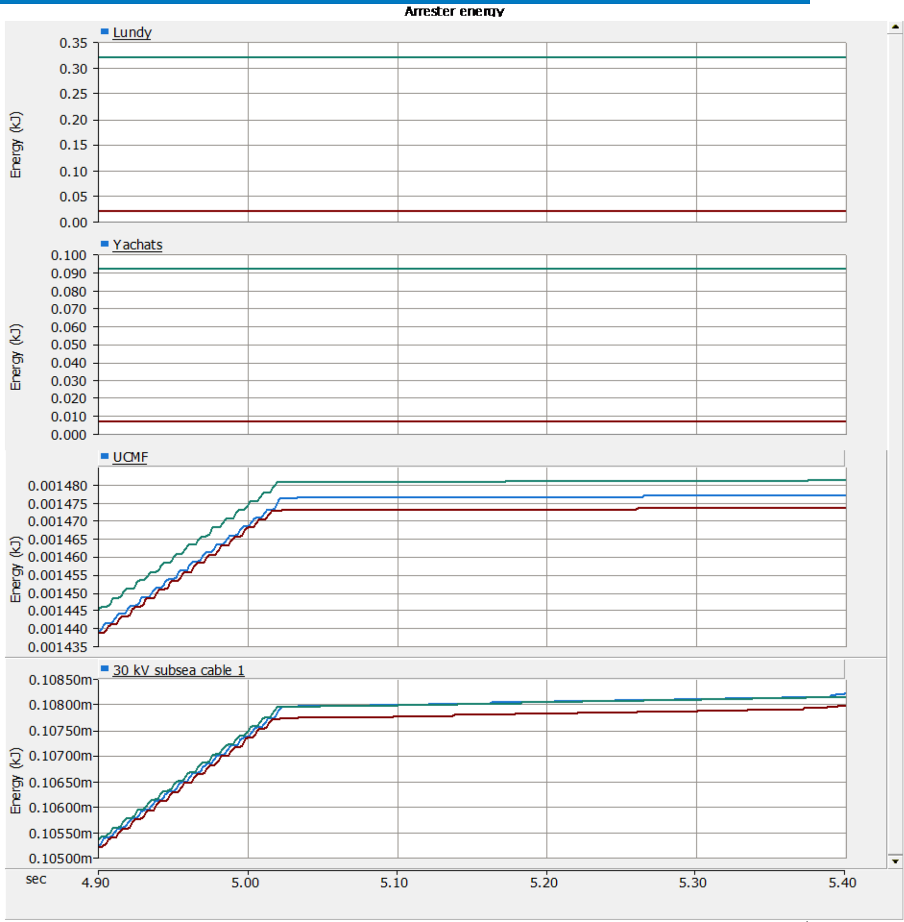
No 30/12.47 kV onshore transformer in Cable 1

LROV 1: South Beach 69 kV breaker opens at T=5s 10 MW generation

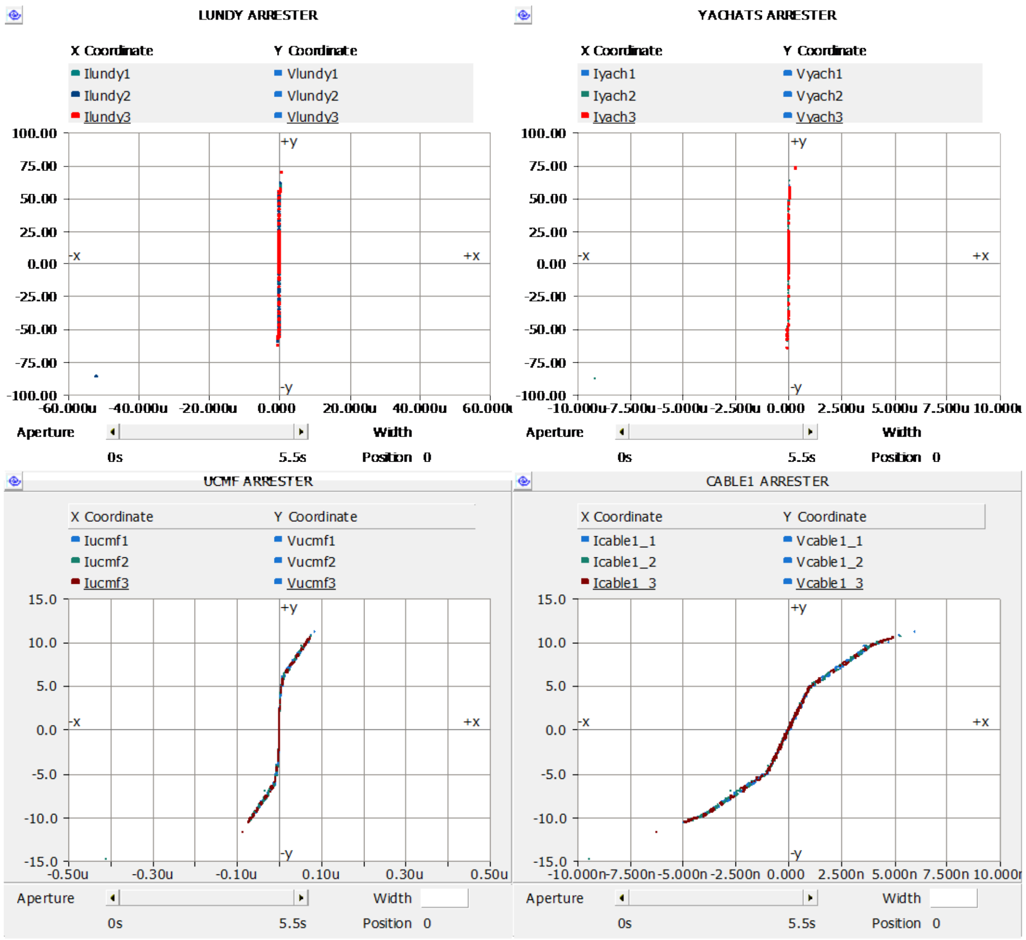


LROV 1: South Beach 69 kV breaker opens at T=5s 10 MW generation

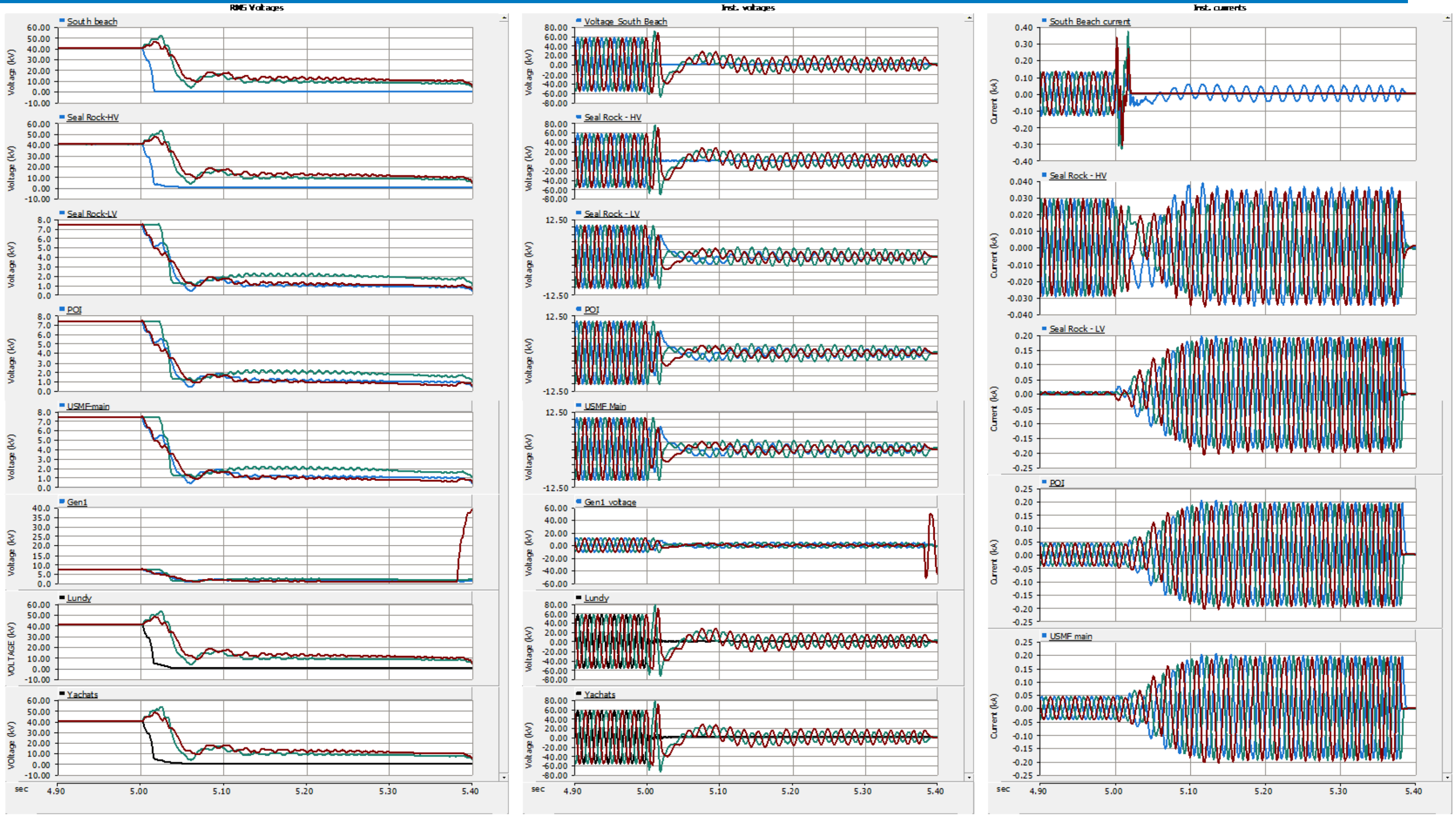




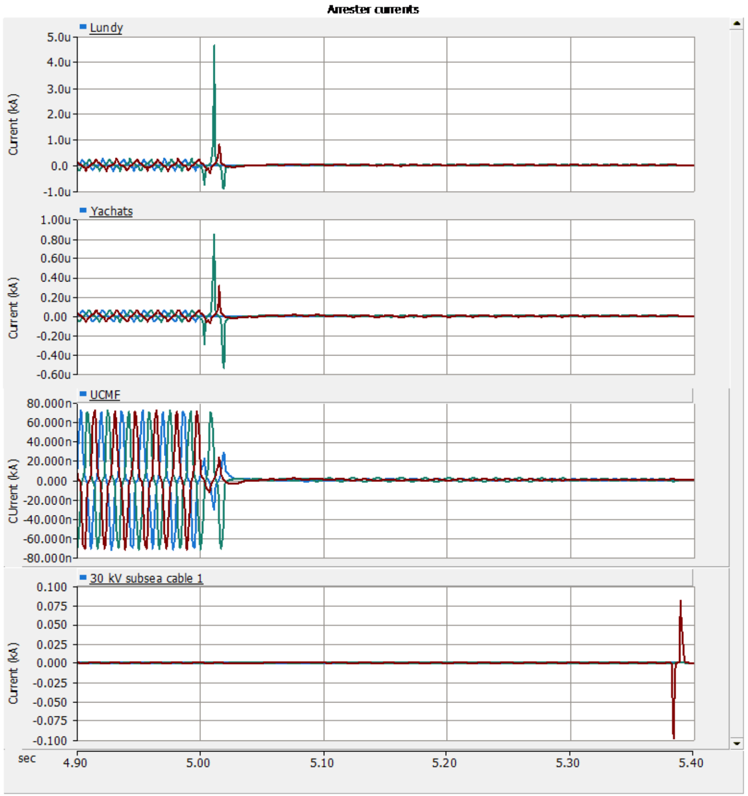
LROV 1: South Beach 69 kV breaker opens at T=5s 10 MW generation

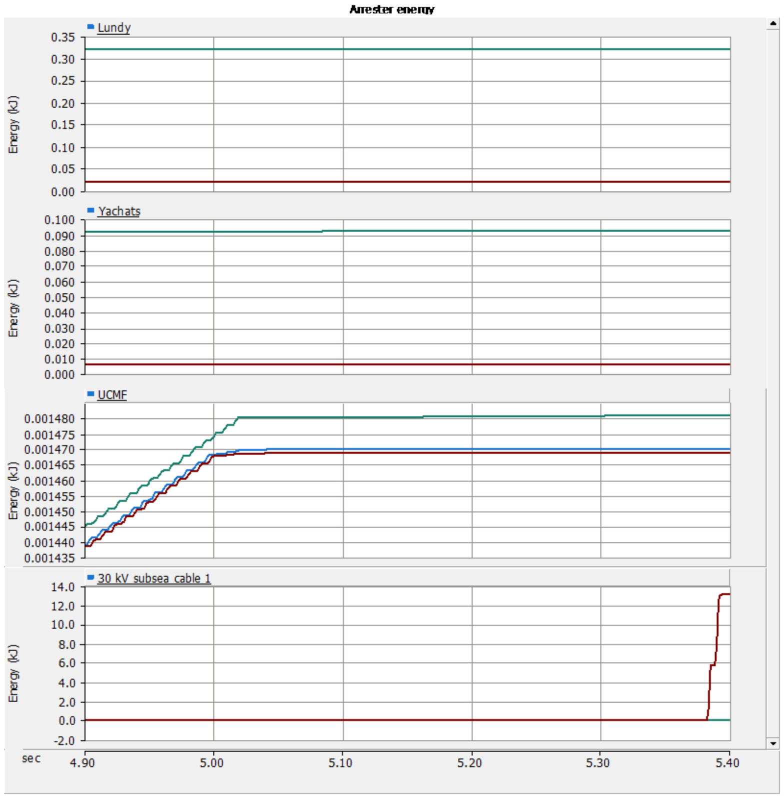


GFOV 1: Fault at SB feeder, SB 69 kV breaker opens at T=5.016s 10 MW gen

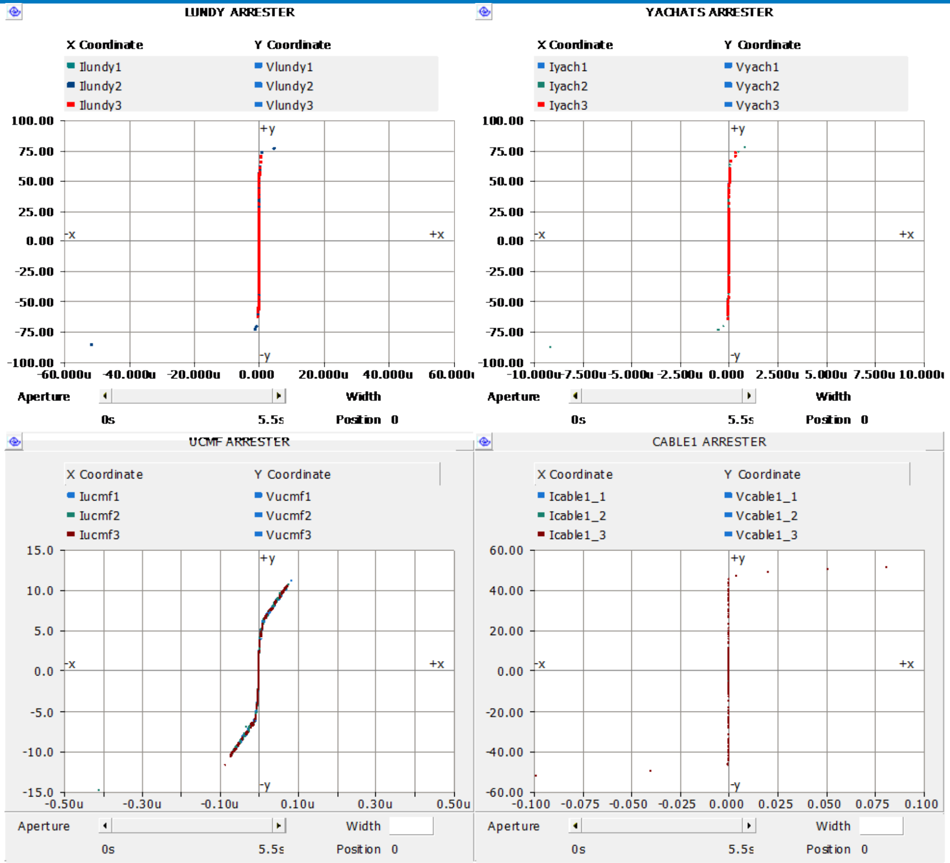


GFOV 1: Fault at SB feeder, SB 69 kV breaker opens at T=5.016s 10 MW gen

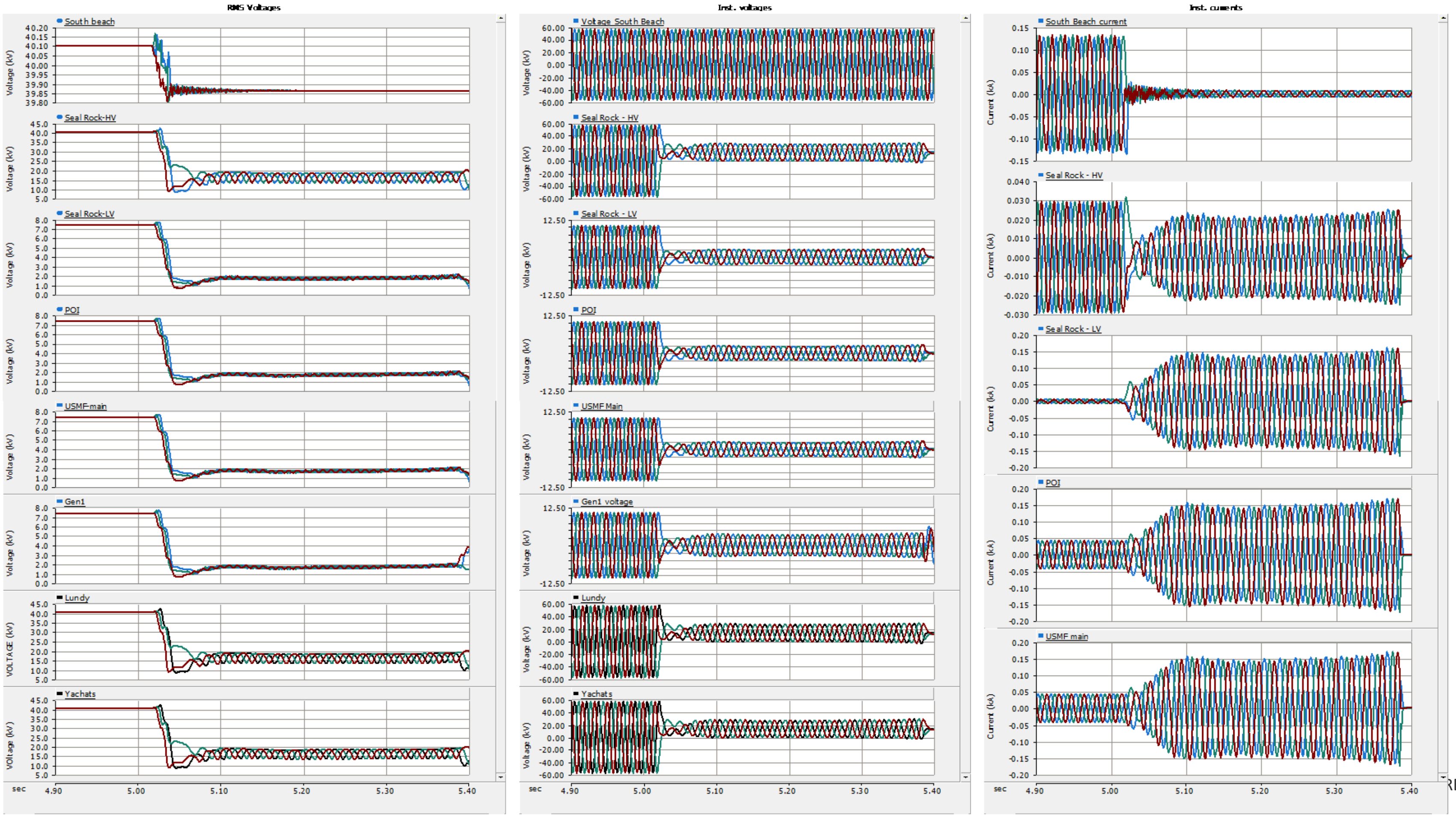




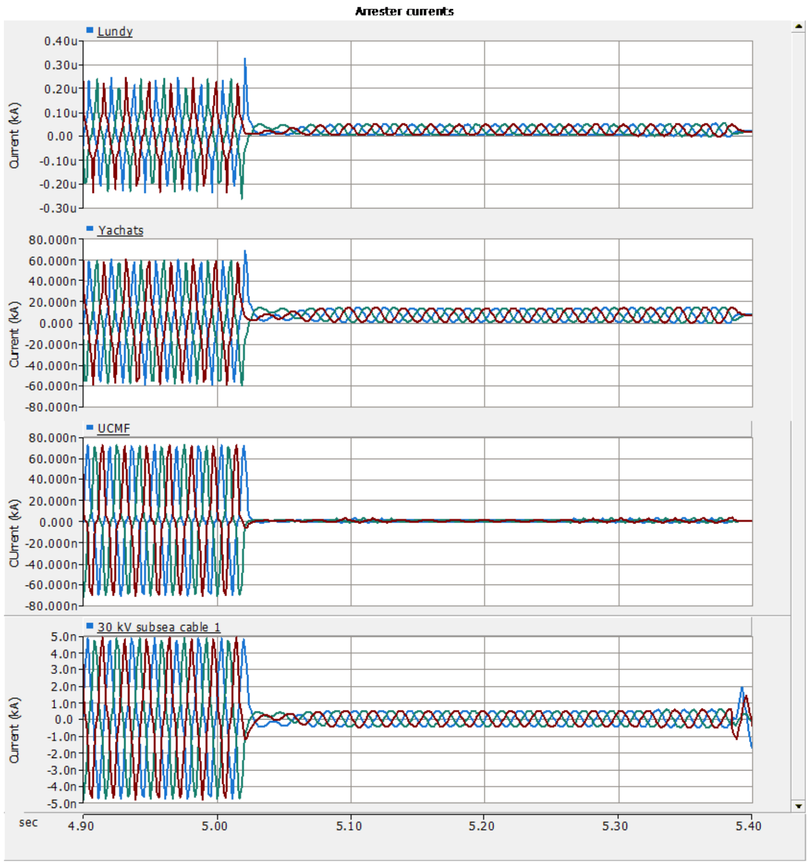
GFOV 1: Fault at SB feeder, SB 69 kV breaker opens at T=5.016s 10 MW gen

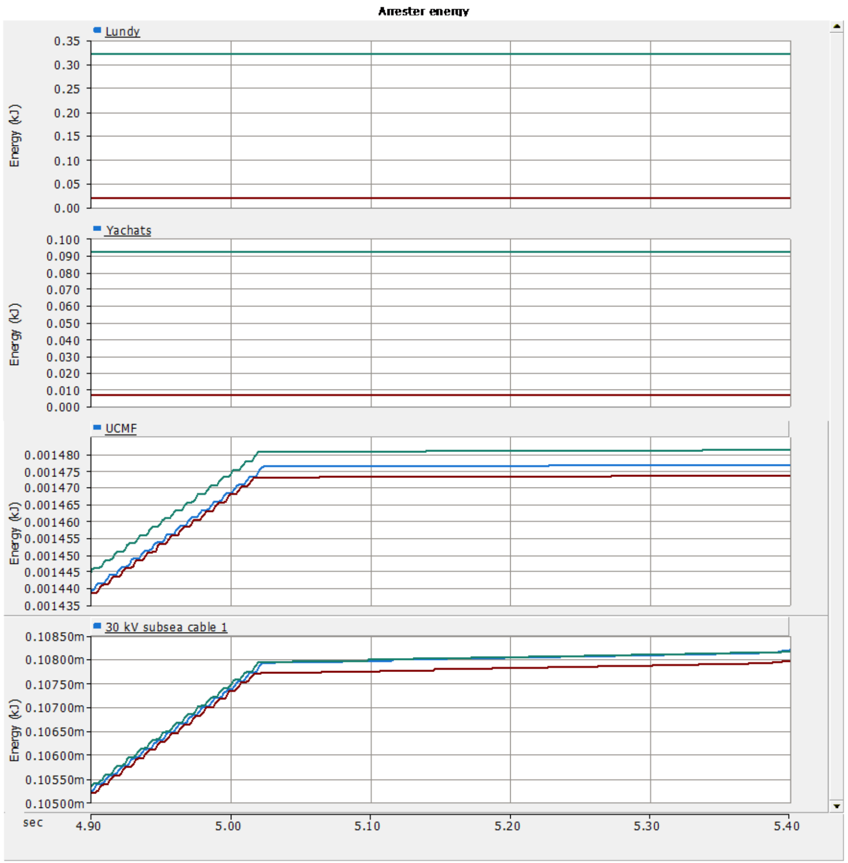


LROV 2: Seal Rock 69 kV breaker opens at T=5s 10 MW generation

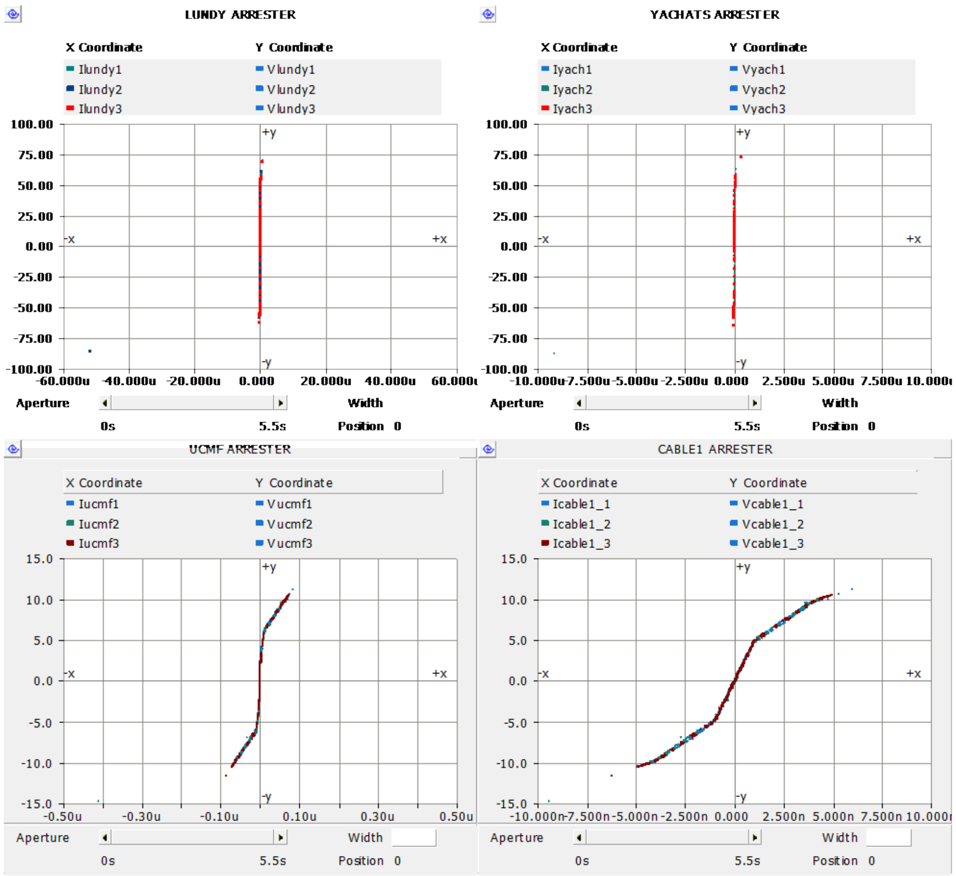


LROV 2: Seal Rock 69 kV breaker opens at T=5s 10 MW generation

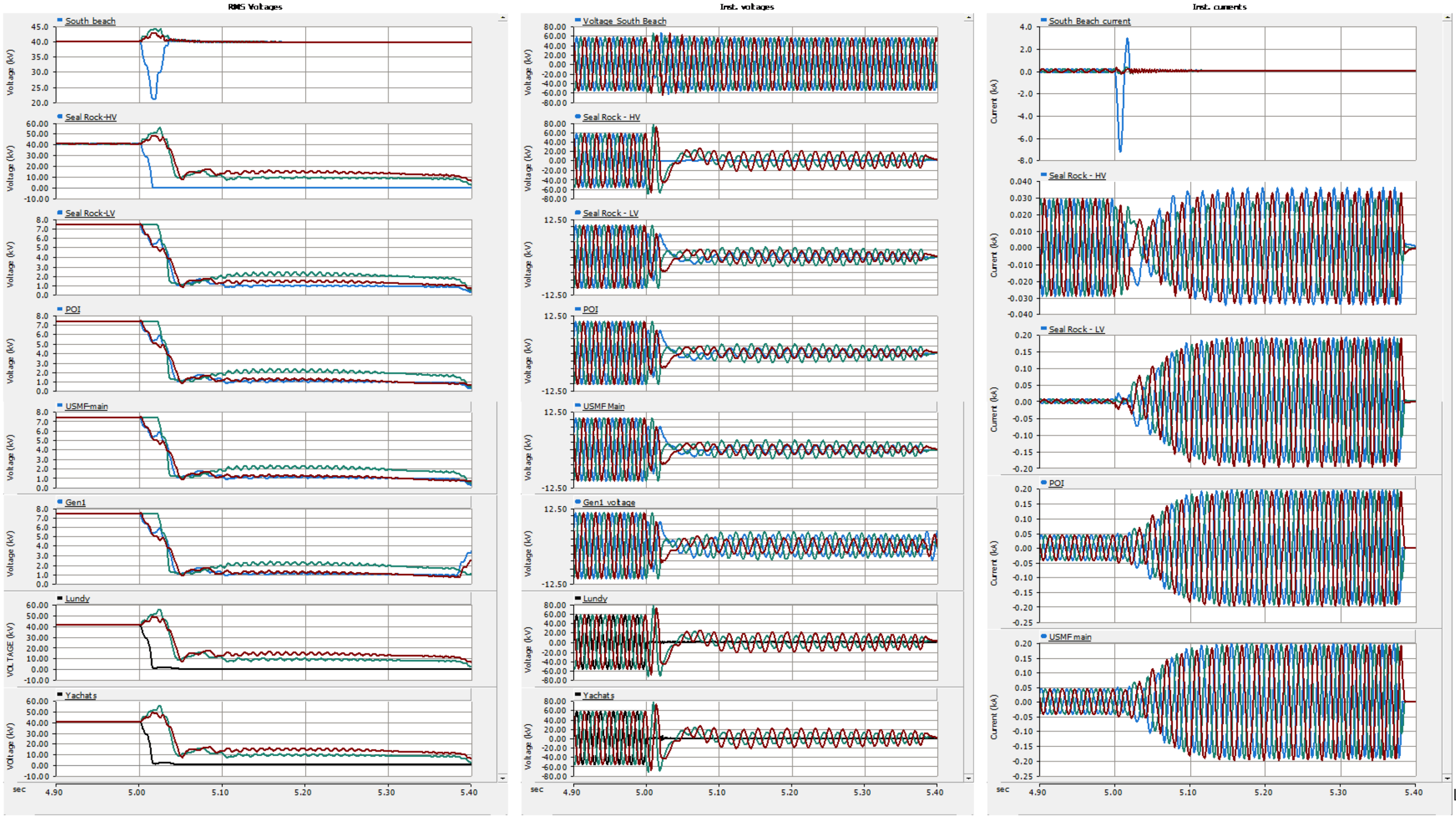




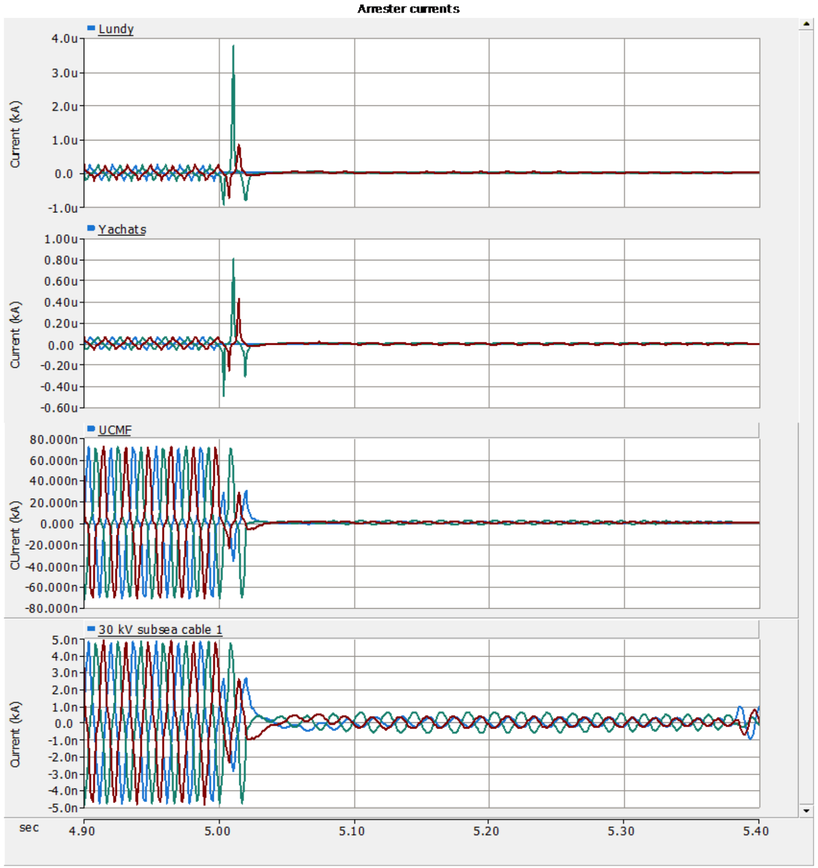
LROV 2: Seal Rock 69 kV breaker opens at T=5s 10 MW generation

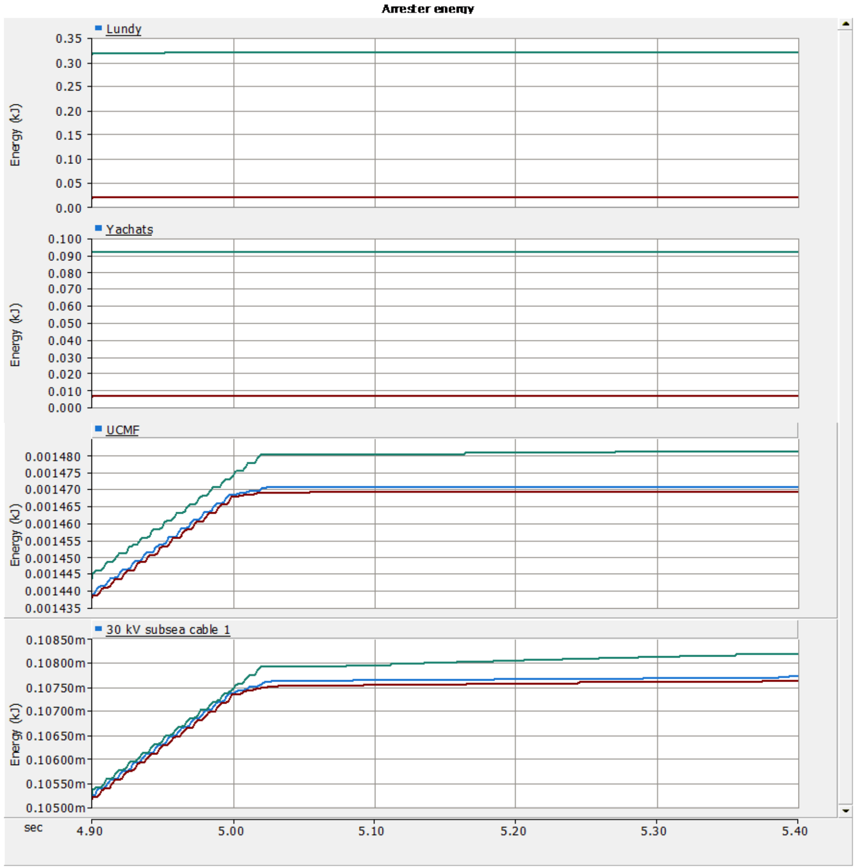


GFOV 2: Fault at SR HV bus, SR 69 kV breaker opens at T=5.016s 10 MW gen

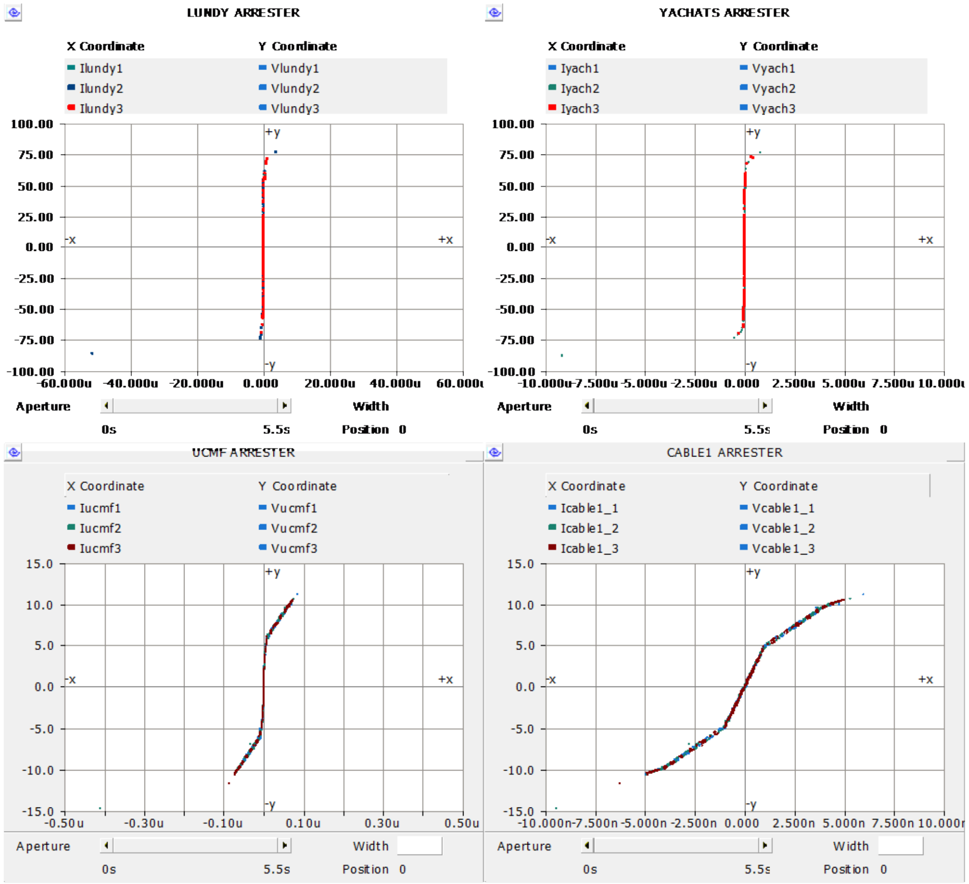


GFOV 2: Fault at SR HV bus, SR 69 kV breaker opens at T=5.016s 10 MW gen

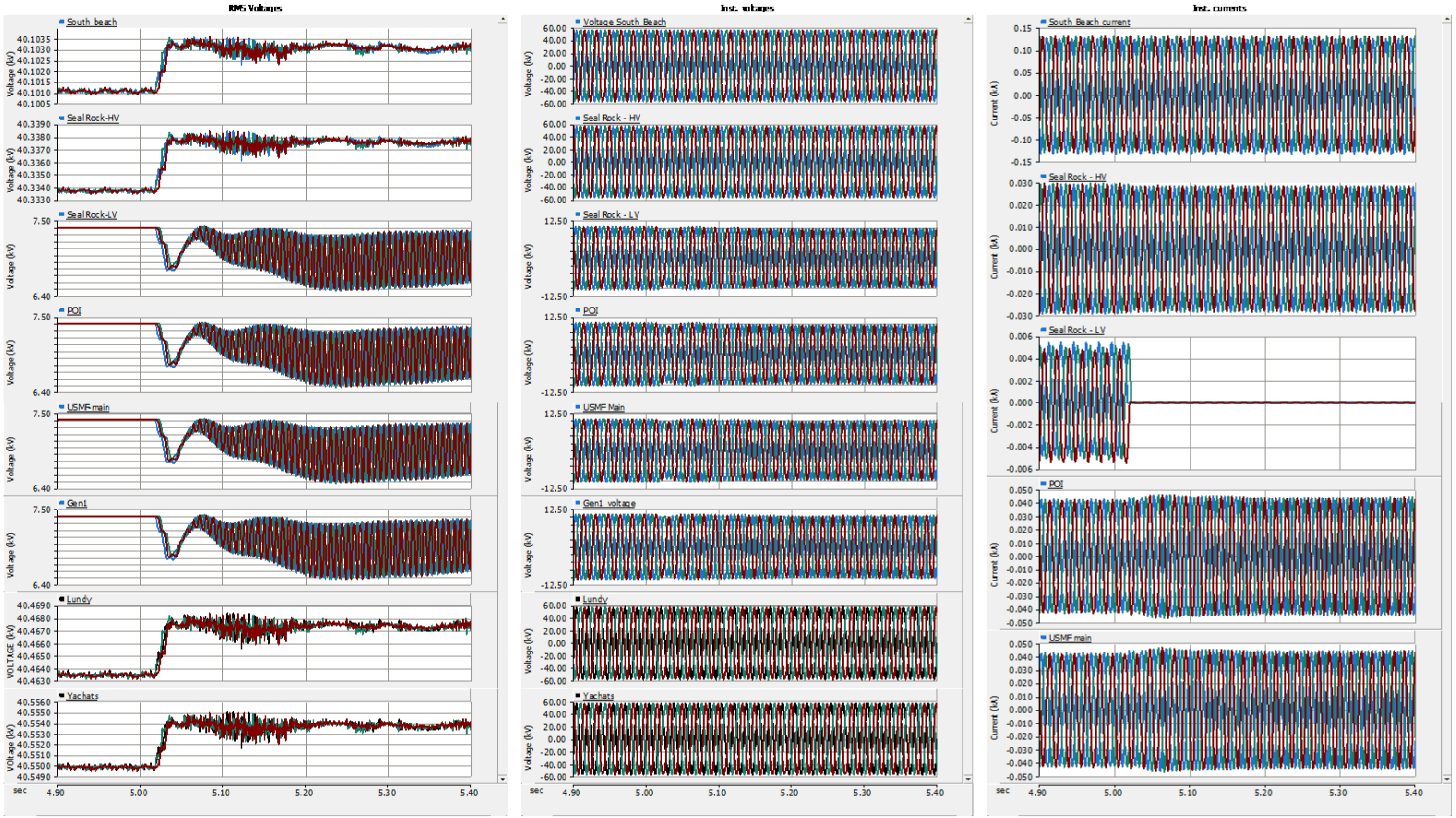




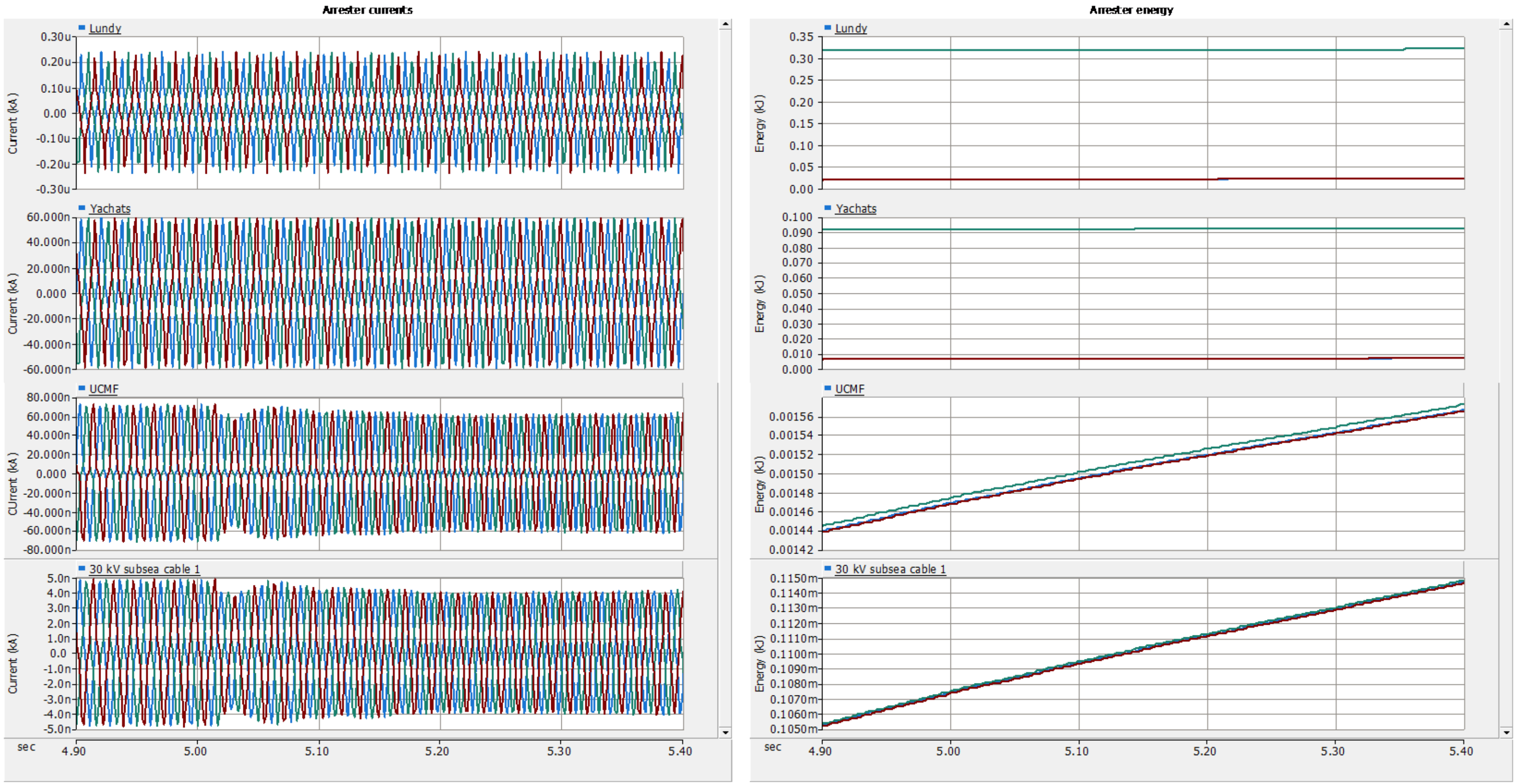
GFOV 2: Fault at SR HV bus, SR 69 kV breaker opens at T=5.016s 10 MW gen



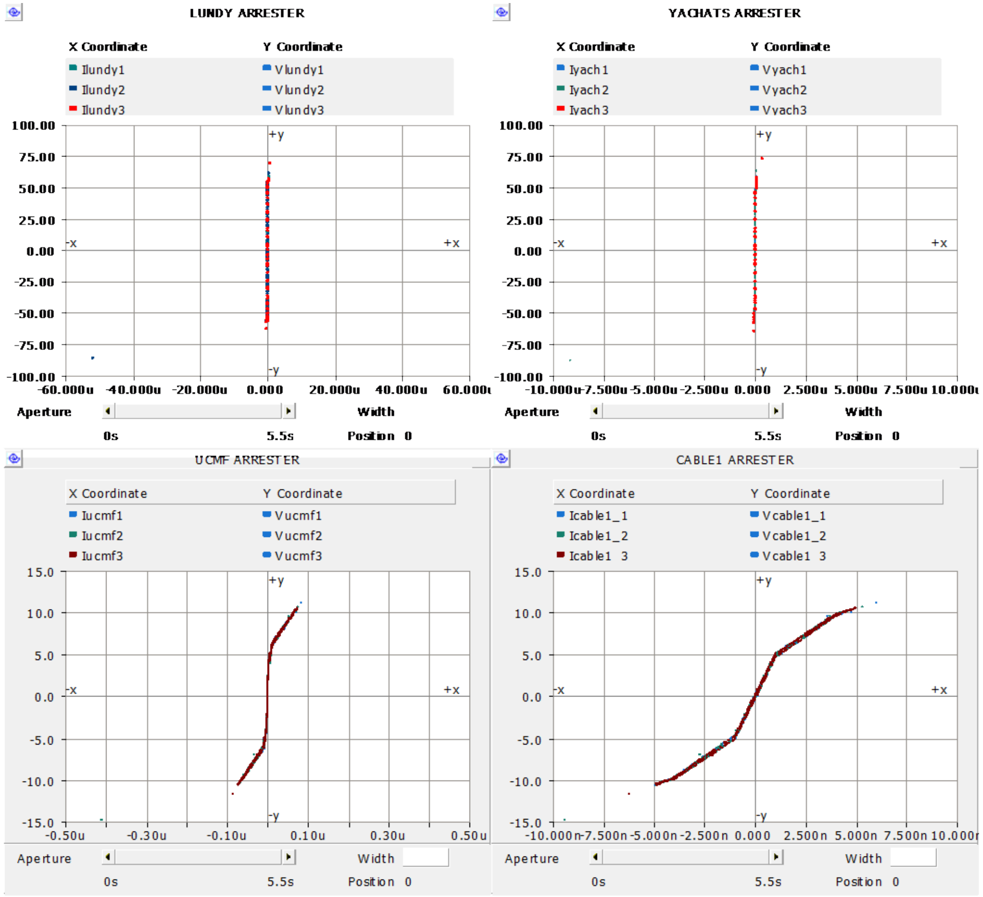
LROV 3: Seal Rock 12. 47 kV breaker opens at T=5s 10 MW generation



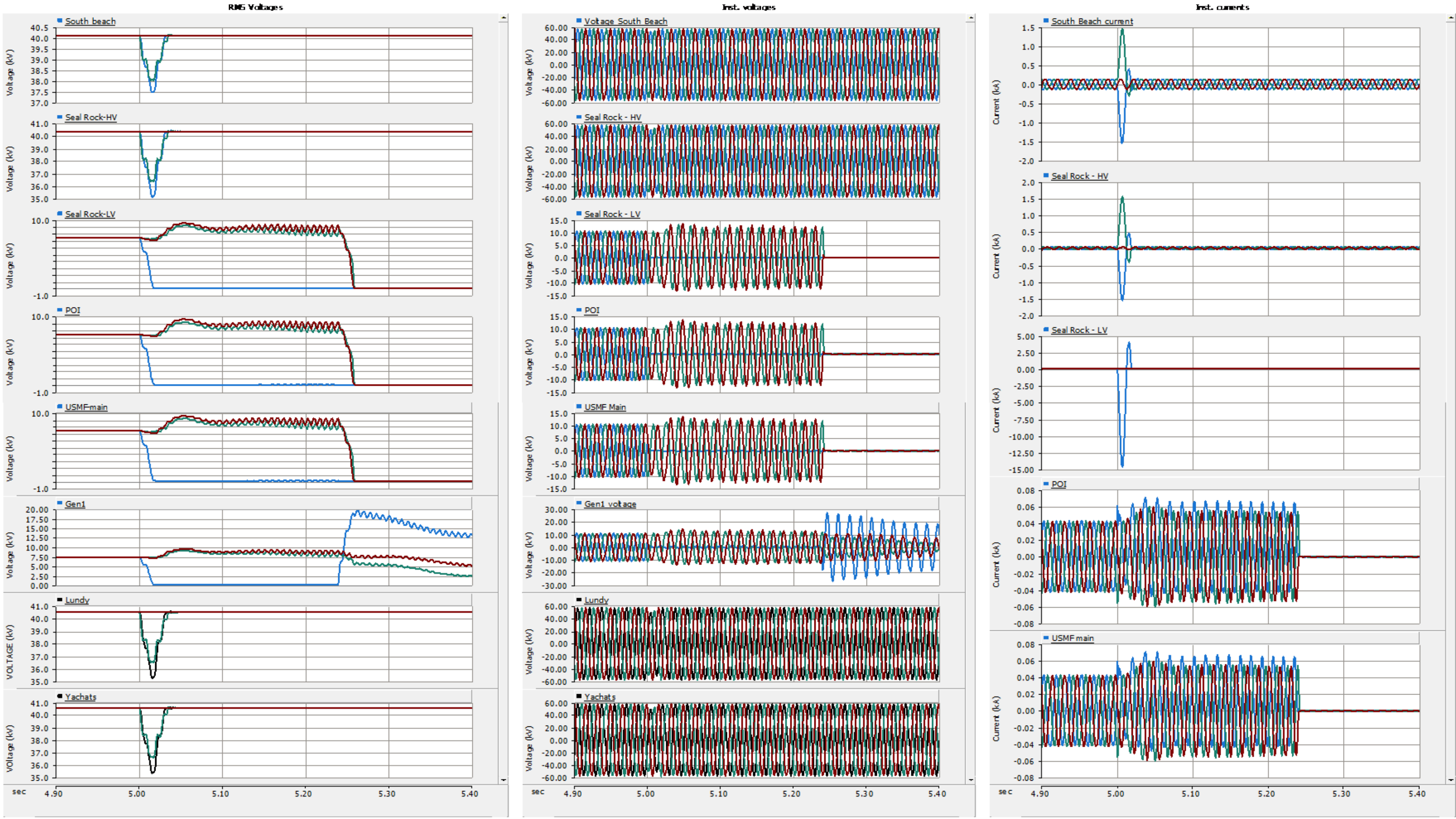
LROV 3: Seal Rock 12. 47 kV breaker opens at T=5s 10 MW generation



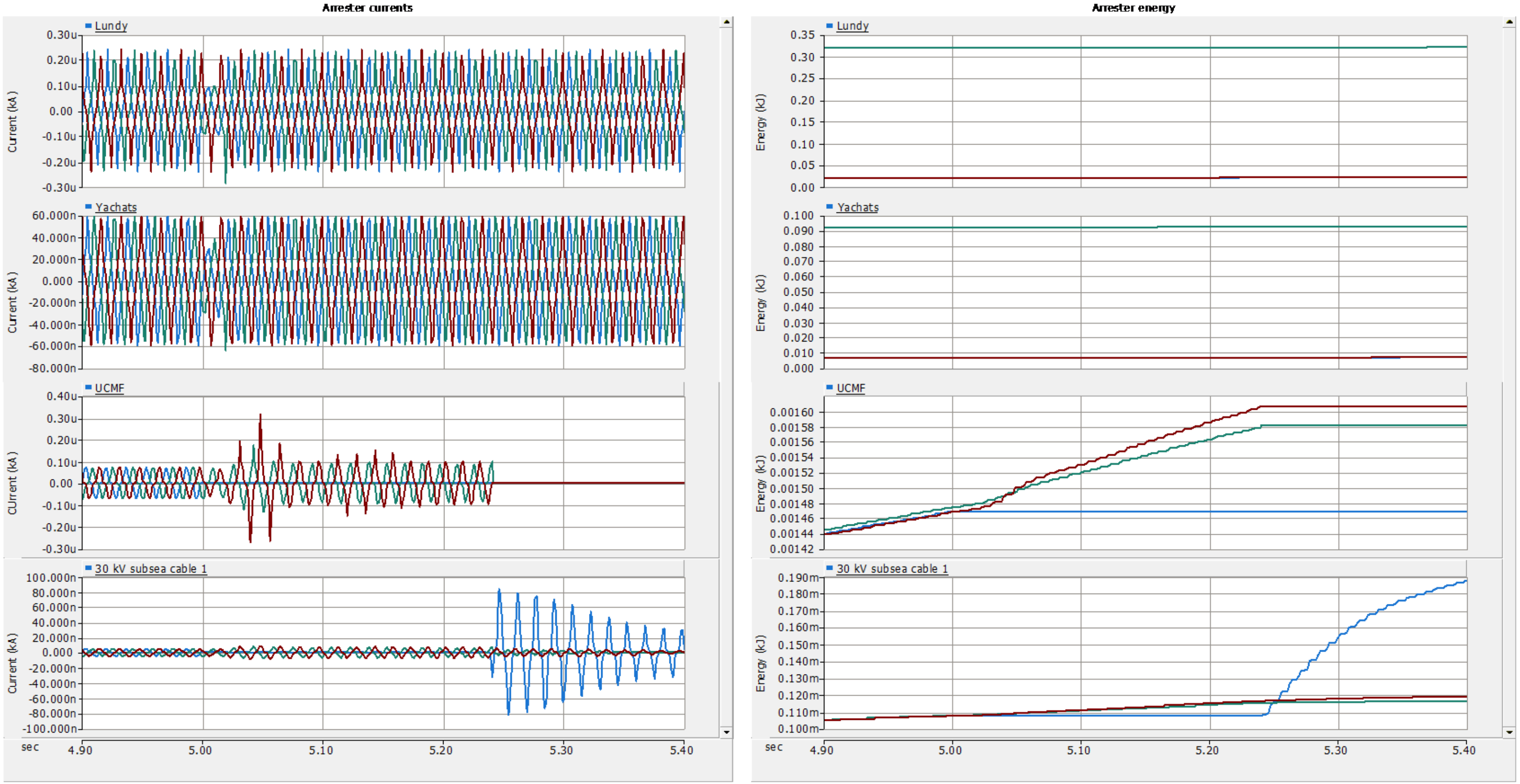
LROV 3: Seal Rock 12. 47 kV breaker opens at T=5s 10 MW generation



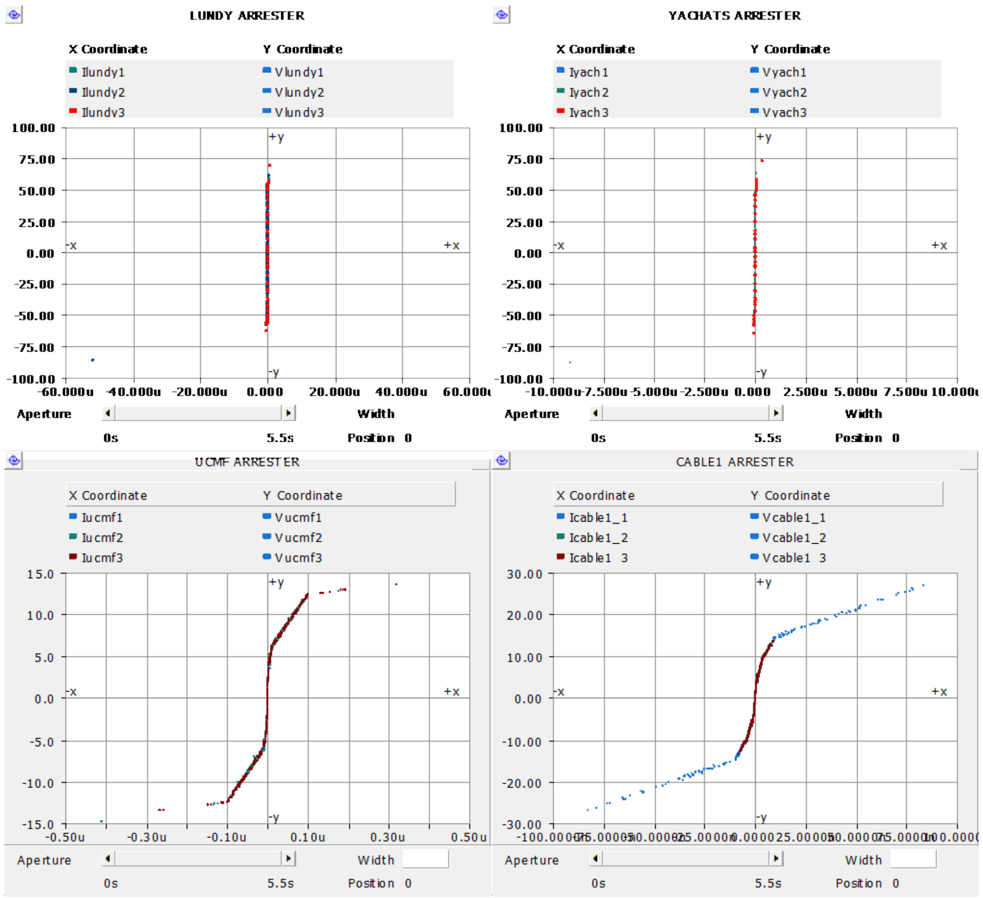
GFOV 3: Fault at SR feeder, SR 12.47 kV breaker opens at T=5.016s 10 MW generation



GFOV 3: Fault at SR feeder, SR 12.47 kV breaker opens at T=5.016s 10 MW generation



GFOV 3: Fault at SR feeder, SR 12.47 kV breaker opens at T=5.016s 10 MW generation



Appendix C. PacWave Interconnection Study Results

PacWave Technical Design Review

August 27, 2019

PacWave Interconnection Study

Vahan Gevorgian, NREL
Terry Lettenmaier, Williwaw Engineering
August 27, 2019

Method

- ➢ Select hypothetical PacWave generation scenarios to study.
- ➢ Preliminary review per IEEE 1547.7:
  - Is there potential to adversely affect the local distribution system?
  - Determine specific studies that are necessary.
- ➢ Perform studies (analysis and simulation) recommended by IEEE 1547.7.
- ➢ Develop mitigation strategies if necessary.

IEEE 1547.7: *IEEE Guide for Conducting Distribution Impact Studies for Distributed Resource Interconnection*

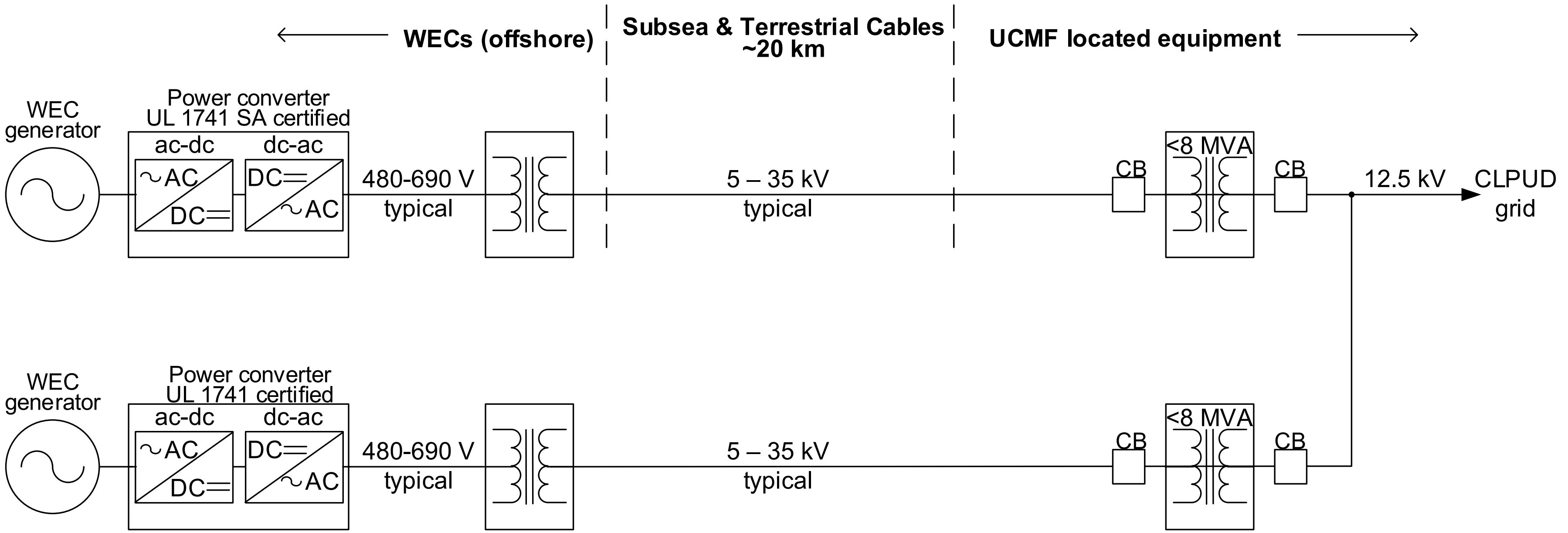
Generation Scenarios and IEEE 1547.7 Preliminary Review

PacWave Generation Scenarios Studied

The following PacWave generation scenarios were decided on for the interconnection study during an October 26, 2017, phone call including PacWave team members from Pacific Energy Ventures (PEV), Oregon State University (OSU), the U.S. Department of Energy (DOE), the National Renewable Energy Laboratory (NREL), 3U, and Williwaw Engineering:

- Two identical point absorber wave energy converters (WECs) were deployed at two test berths.
- Each WEC has 5-MW peak output power.
- Use Sandia/NREL Reference Model 3 WEC with output power scaled.
    1. PTO with energy storage and power limiting
    2. No energy storage or power limiting (direct drive output power).
- Assume perfect correlation between the two devices (combined peak output 10 MW).
- Assume both WECs interconnected with UL 1741 SA certified inverters.

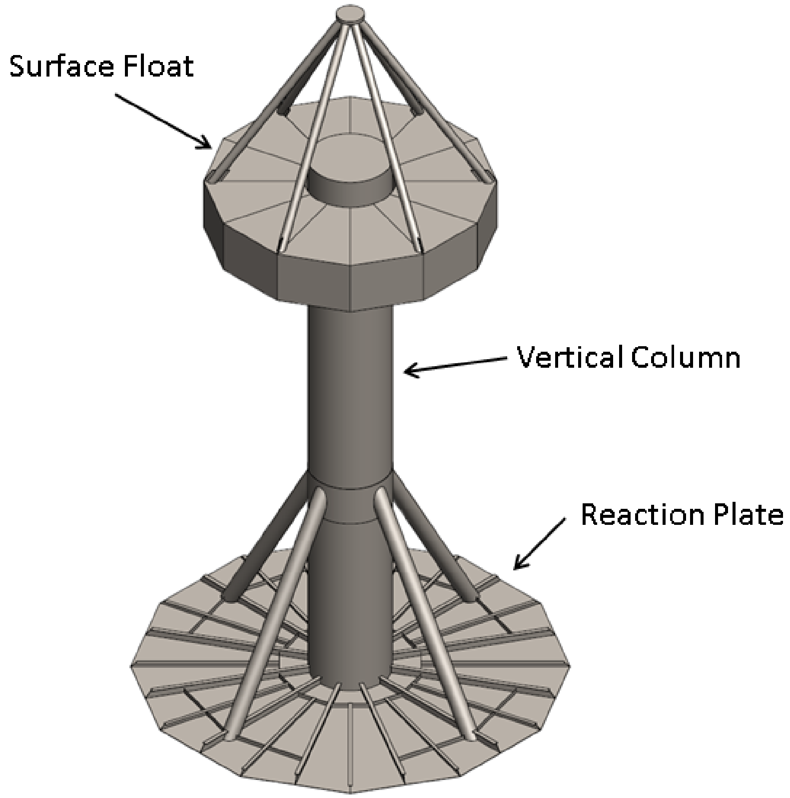
Typical Point Absorber Electrical Connection

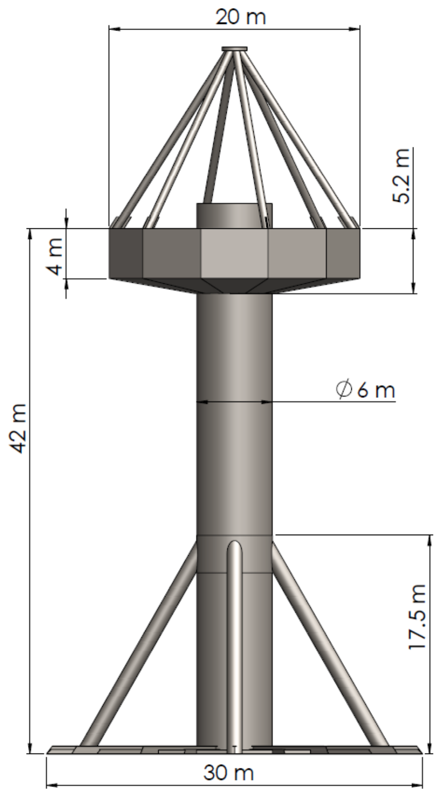


PMEC test berths #1 and 2 shown above. Test berths #3 and #4 unused for grid interconnection scenarios

Reference Model 3 Point Absorber

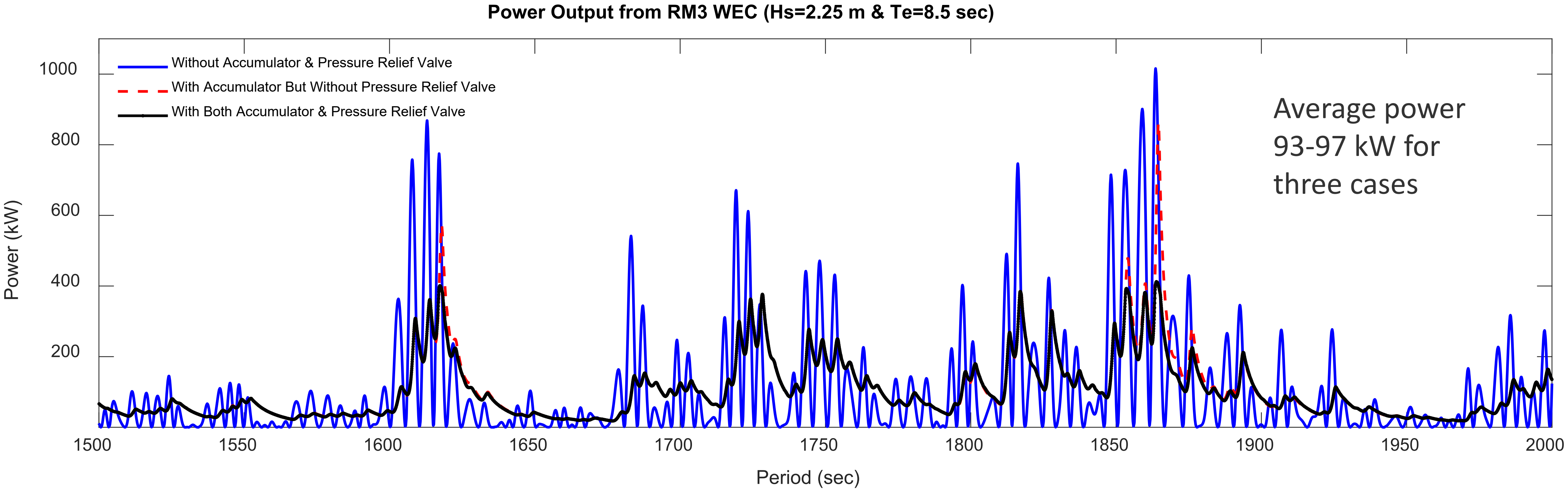
- Developed by Sandia and NREL
- DOE Reference Model Project
- Open-source design.





Reference Model 3 Point Absorber

From NREL hydrodynamic simulations of Reference Model 3



Average power 93-97 kW for three cases

IEEE 1547.7 Preliminary Review

Clause	Preliminary Review Criteria	Critera Met?	Analysis needed
7.2	Use of certified DR equipment	Yes	
7.3	Potential for unintended islands	Yes	
7.4	Impact on EPS equipment loading under all steady state conditions	Yes	
7.5	Impacts on system protection, fault conditions, and arc flash rating	No	C2 - System protection studies
7.6	Impacts on voltage regulation within the EPS under steady state conditions	No	C1 - Steady state simulation Possibly depending on steady-state simulation results: S1 - Quasi-static simulation S2 - Dynamic simulation S3 - Electromagnetic transient simulation
7.7	Impacts on EPS power quality	No	C1 - Steady state simulation S4.4 - Flicker Possibly depending on steady-state simulation results: S2 - Dynamic simulation S3 - Electromagnetic transient simulation

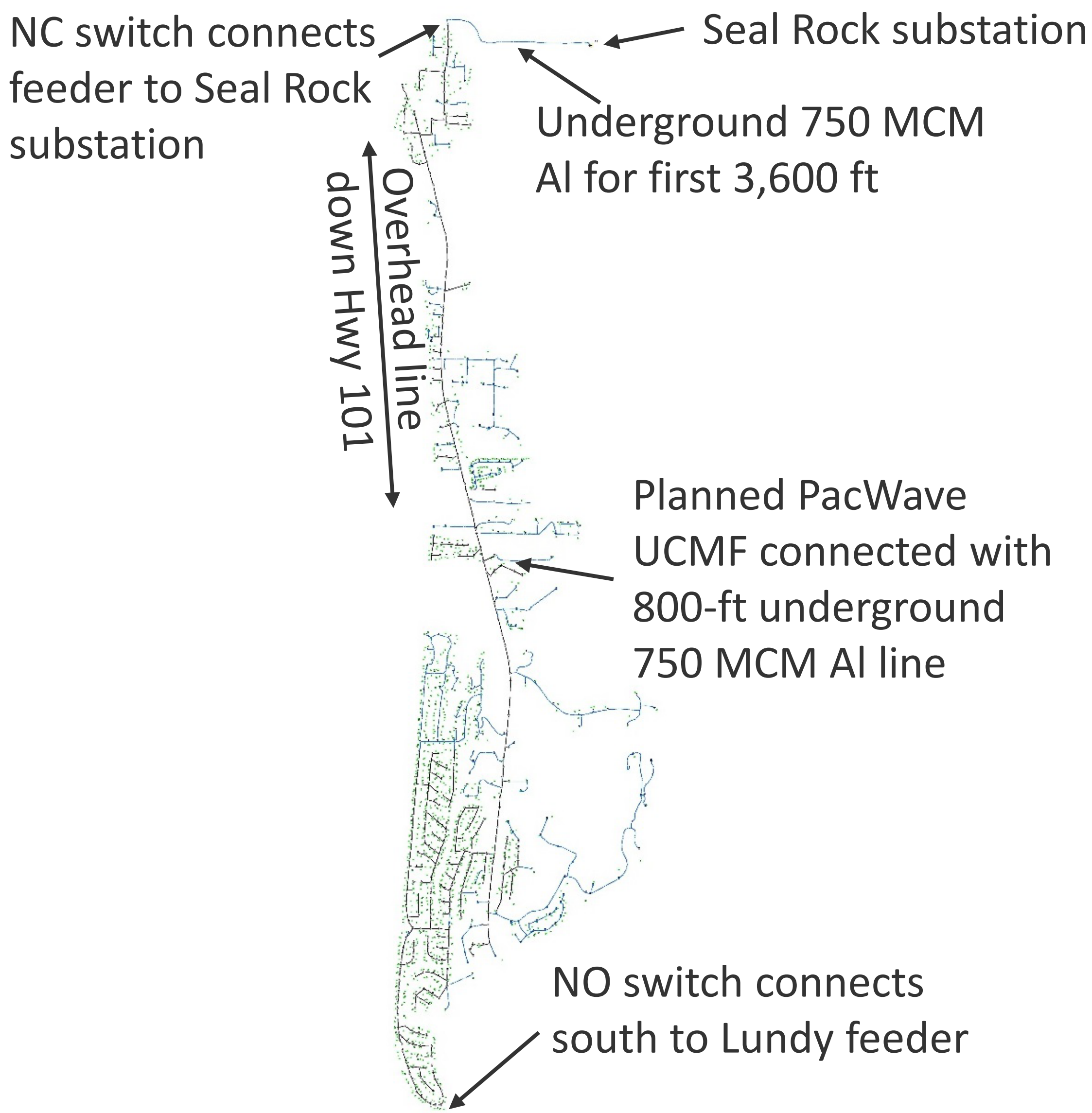
- Dynamic simulations using PSCAD were used in place of steady-state and quasi-static simulations for this study.
- System protection studies will be completed by TriAxis Engineering as part of the Utility Connection and Monitoring Facility (UCMF) detailed design.
- Flicker studies require information specific to detailed designs of WECs being deployed at PacWave, so they will not be done until deployments of specific WECs are being planned.
- Electromagnetic transient simulations were not done for this study.

Development of PSCAD Model

CLPUD Distribution Line Modeling

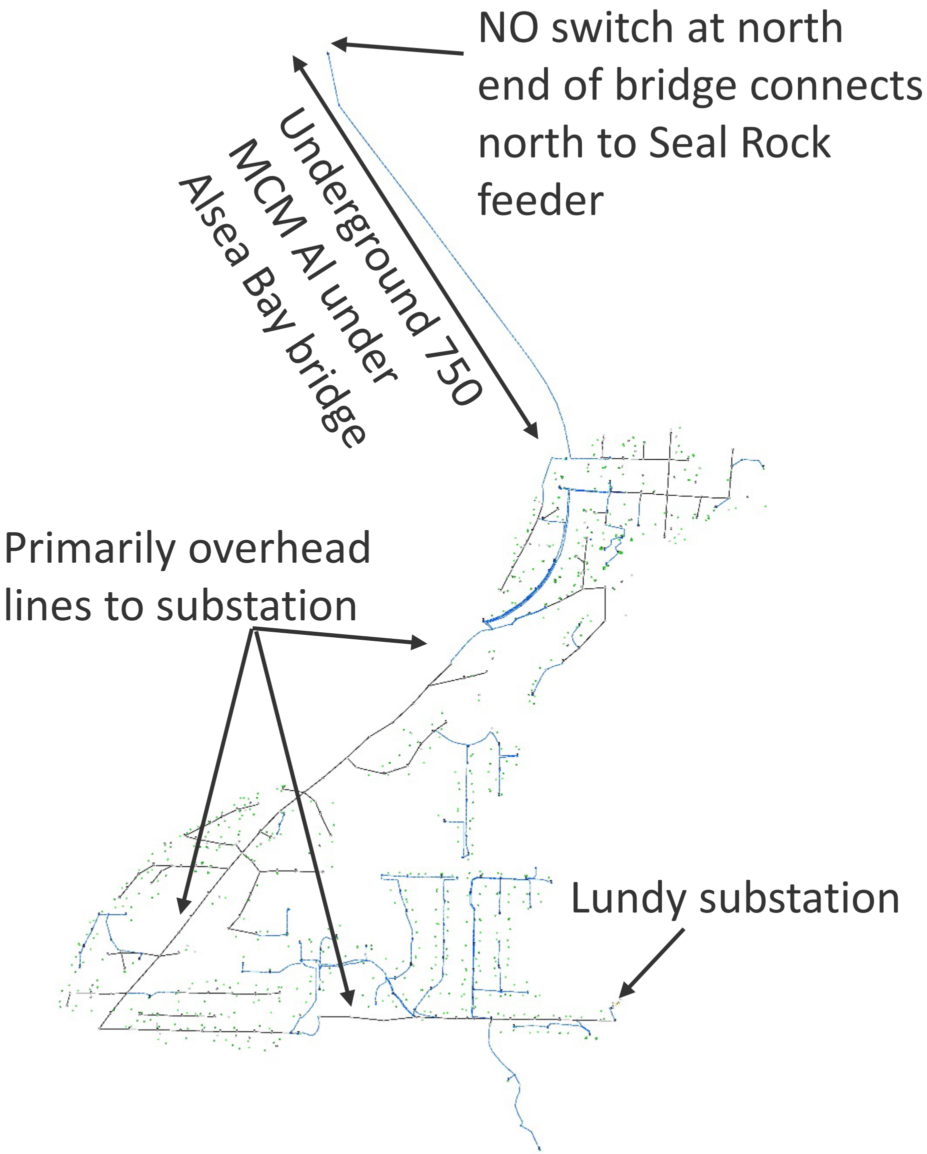
- PacWave is connected to Central Lincoln People's Utility District's (CLPUD's) SS162 F12 feeder that is normally connected to CLPUD's Seal Rock substation.
- An alternate connection of this feeder to CLPUD's Lundy substation via Lundy feeder SS163 F12 is used when maintenance is being done at Seal Rock.
- Both the Seal Rock and Lundy connections were modeled for this study.
- The following data were provided by CLPUD for each feeder:
  - Substation source impedance and transformer parameters
  - Substation transformer high- and low-voltage tap changer details
  - Overhead and underground distribution line details
  - Geographic information system maps showing distribution line and service locations
  - Global Positioning System coordinates for all services
  - 15-minute power data for all services during months of July and December 2018
  - Substation power factor data.
- The CLPUD data were used to develop simple aggregate load models for the two CLPUD feeders that were used for PSCAD modeling.

CLPUD Seal Rock Feeder SS162 F12



- Substation transformer has five-position de-energized tap changer on the high-side winding, set at 65.2 kV.
- Substation transformer has 33-position, ±10% load tap changer on the low-voltage side, controlled to 123.5 V with 3-V bandwidth (120-V basis).
- No capacitors on the line.
- There is a tie-in to the Lundy substation at the south end of this feeder that is normally only used for maintenance.
- When connection is made to Lundy, Seal Rock substation is disconnected (except for very short transition period).

Alternate Lundy Substation Connection via Feeder SS163 F12



- This line extends to the north across the Alsea Bay bridge, where there is a tie-in to the south end of the Seal Rock feeder that is normally only used during maintenance at Seal Rock.
- This feeder primarily serves residential loads in the small town of Waldport.
- Substation transformer has same five-position de-energized tap changer on the high-side winding as at Seal Rock, set at 65.2 kV.
- Substation transformer has an identical load tap changer and control as used at Seal Rock.
- No capacitors on the line.

Line Parameters Used for PSCAD Modeling

Subsea cables: parameters for an Oceaneering 50-mm^2 subsea cable were used:

R = 0.375 Ω/km   C = 0.13 μF/km   L = 0.504 mHy/km

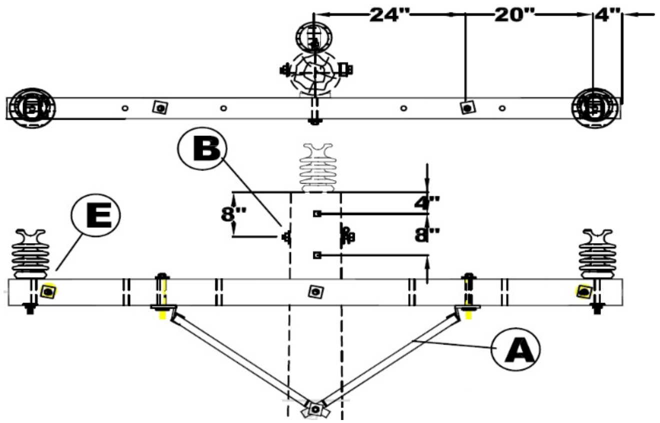
PacWave terrestrial cables: triangular arrangement of 4/0 Type MV-105 cable with 4.75-in. separation. Parameters calculated per ABB land cable systems handbook:

R = 0.261 Ω/km   C = 0.178 μF/km   L = 0.68 mHy/km

CLPUD underground lines: flat arrangement of 750 MCM aluminum conductors with 220-mil insulation and 4.5-in. separation. Parameters calculated per ABB land cable systems handbook:

R = 0.761 Ω/km   C = 0.43 μF/km   L = 0.54 mHy/km

CLPUD overhead lines:



- Neutral 8 ft below crossarm through bolt
- 394AAAC "Canton" conductor. Used data from Southwire website: diameter = 0.721 in.; Rac = .061 Ω/kft
- Symmetrical line parameters calculated in OpenDSS:
  Z = 0.2992 + j 0.6361 Ω/mi (pos. seq.)
  Z = 0.585 + j 1.97 Ω/mi (zero seq.)

Aggregate Distribution Load Model

- To simplify PSCAD model, 2018 CLPUD meter data were used to estimate aggregate loads for each feeder and line lengths connecting those loads. The aggregate loads are shown in the system diagram for the PSCAD model.
- 2018 annual minimum and maximum loads for both feeders occurred on July 10–11 and December 4 and 7, respectively. Data for minimum and maximum load times during those days were analyzed to determine aggregate loads.
- Aggregate loads were segregated to coincide with geographic “clumps” of loads where possible. For example, Seal Rock North 1 includes the town of Seal Rock, and Lundy North includes Waldport town center.
- Line lengths connecting aggregate loads were estimated using mean weighted (by kW) latitude of individual service loads for most aggregate loads, where service loads were mostly oriented North-South along Highway 101.

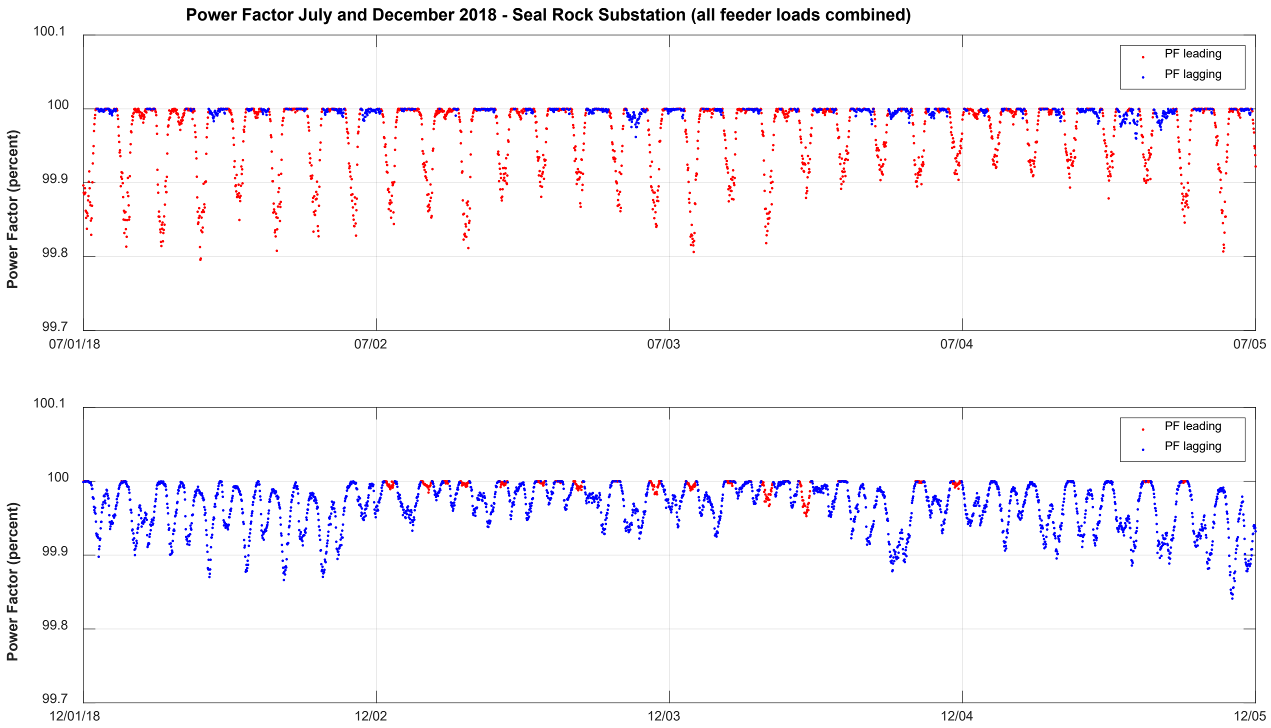
Aggregate load	Minimum load (July 10-11)		Maximum load (Dec 4 & 7)		Weighted mean latitude
	kW	Percent	kW	Percent	
Seal Rock North 1	87	11.3%	347 kW	8.1%	44.4877
Seal Rock North 2	121	15.8%	800 kW	18.7%	44.4672
Seal Rock South	559	72.9%	3137 kW	73.2%	44.4415
Seal Rock Feeder total	767	100.0%	4293 kW	100.0%	

Aggregate load	Minimum load (July 10-11)		Maximum load (Dec 4 & 7)		Weighted mean latitude
	kW	Percent	kW	Percent	
Lundy North	254	52.1%	974	43.2%	44.4251
Lundy South	233	47.8%	1280	56.7%	*
Lundy Feeder total	486	100.0%	2254	100.0%	

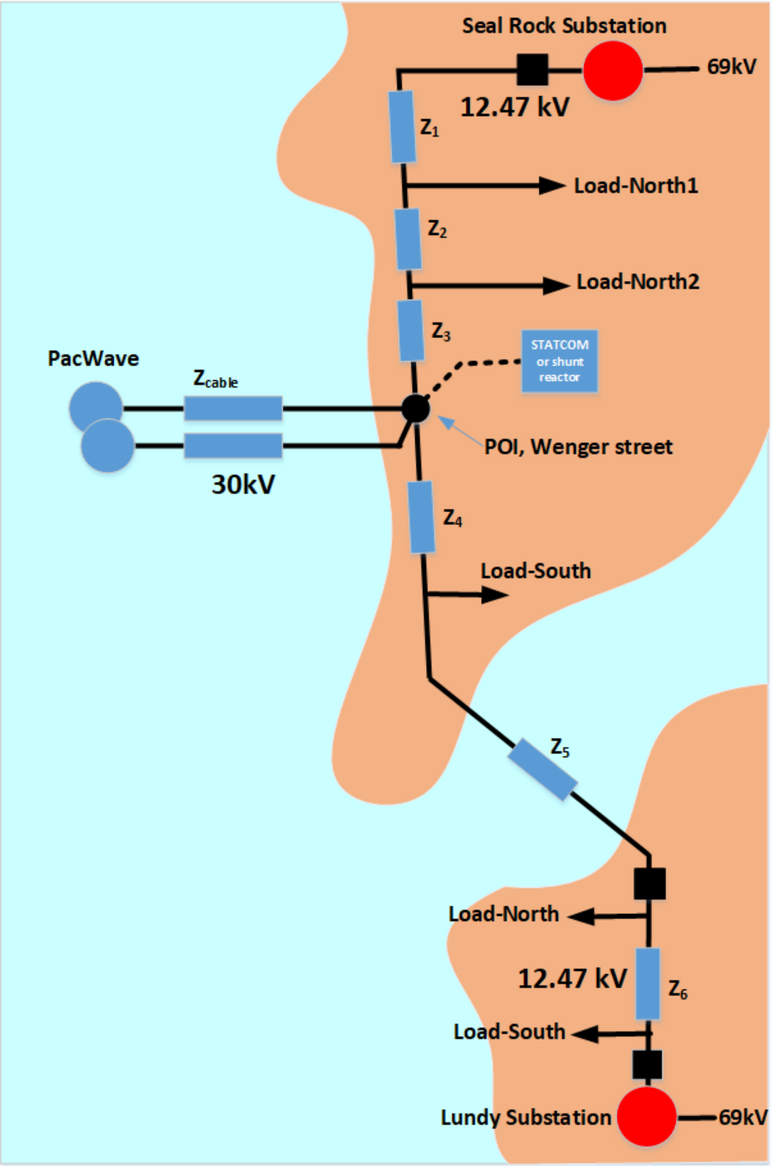
* Since Lundy South load is distributed E-W and N-W a combination of latitude and longitude were used to estimate distance

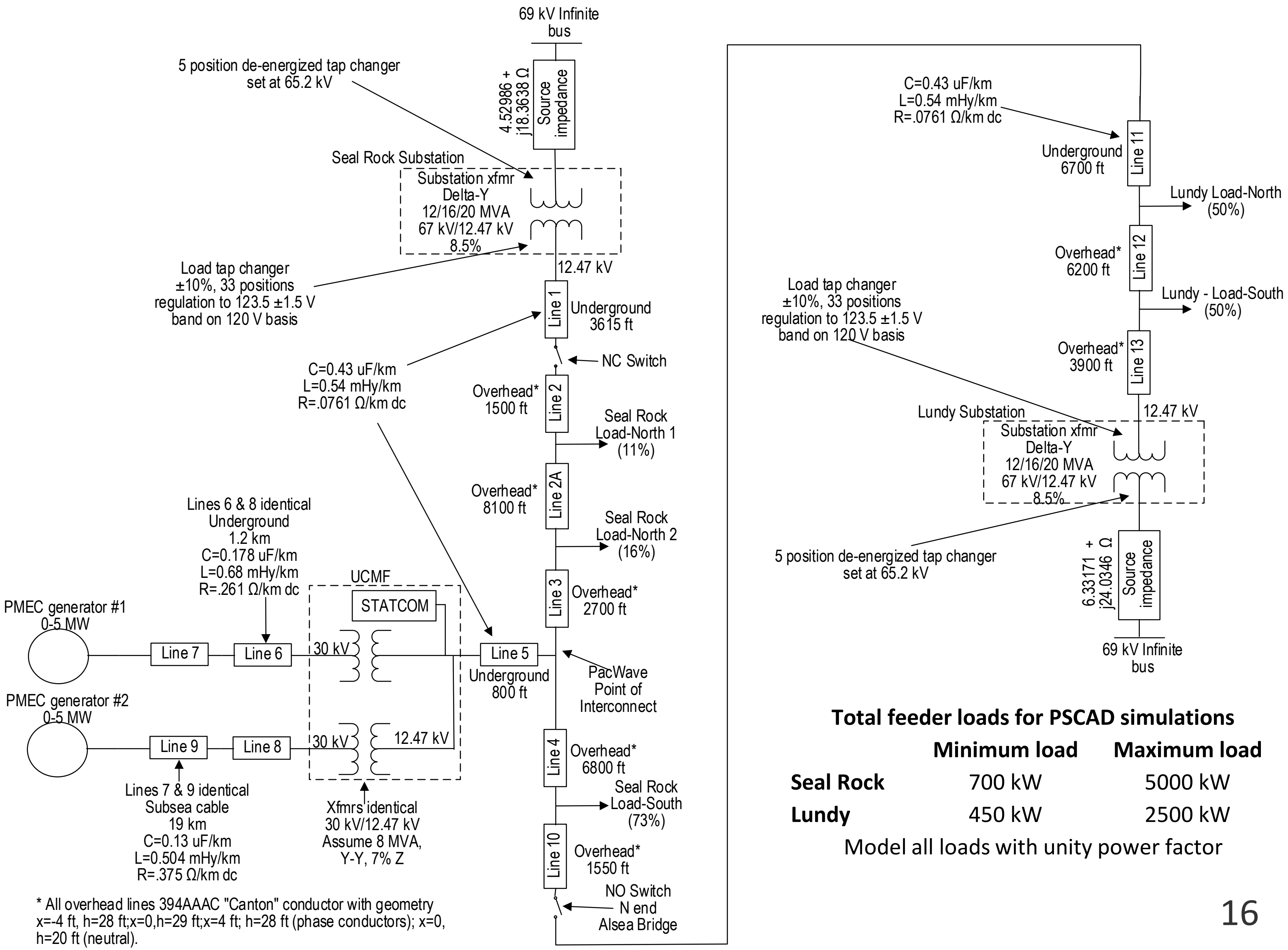
Power Factor of Distribution Loads

- Unity power factor loads were used for PSCAD modeling.
- CLPUD power factor data from Seal Rock substation (below) shows PF>99.8% during July and December 2018.
- CLPUD stated that Lundy substation power factor exceeds 99% most of the time. Lundy substation data were not requested for the study.



System Diagram for PSCAD Model





Total feeder loads for PSCAD simulations

	Minimum load	Maximum load
Seal Rock	700 kW	5000 kW
Lundy	450 kW	2500 kW

Model all loads with unity power factor

CLPUD Substation Transformer Tap Changer Control

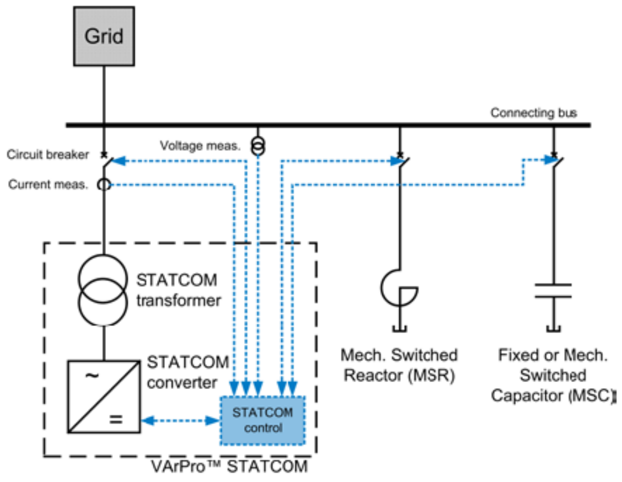
- CLPUD presently uses substation tap changer control to regulate feeder voltage. The same tap changer arrangement and controls are used at both Seal Rock and Lundy.
  - New Beckwith M-2001D controllers were recently installed at both Seal Rock and Lundy substations. The same control settings are used for both substations.
  - Controllers regulate substation 12.47-kV bus to 123.5 ± 1.5 V on a 120-V basis (1.017 p.u. to 1.042 p.u. range).
  - Tap changers have 45-second delay.
  - No line regulation is used in the existing control.
  - Existing control is not set up for reverse power flow.
- The existing tap controllers can be used to regulate feeder voltages with reverse power flow if they are reprogrammed to allow this.
- TriAxis Engineering will coordinate with CLPUD to determine the specific tap changer control settings that will be implemented for operation with PacWave.
- PSCAD simulations were done with tap changer stepped through each tap setting to show feeder voltage and STATCOM volt ampere reactive (VAR) requirements for each tap position in the control range.

STATCOM for Dynamic Reactive Power Compensation

OSU plans to install a static compensator (STATCOM) at the PacWave UCMF to control grid voltage.

General benefits of STATCOMs:

- Power factor control
- Voltage regulation
- Independent phase control
- Flicker compensation
- Active harmonic filtering (application specific)
- Multiple system parallel control
- High- and low-voltage ride through
- Modular inverter blocks for simple long-term maintenance
- Flexible transformer integration for optimal footprint and low installation costs
- Optional overload capacity up to 300% possible.

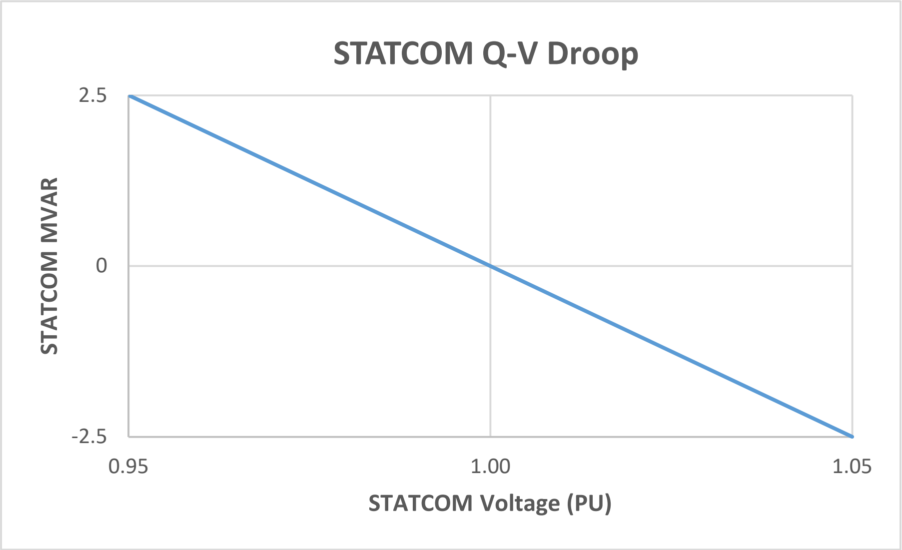


STATCOM Operation with Q-V Droop

STATCOM voltage droop is defined as:

$$\frac{1}{droop} = -\frac{\frac{\Delta Q}{Q_{nom}}}{\frac{\Delta V}{12.47\ kV}} * 100\% \quad Q_{nom} = \text{STATCOM rating in MVAR}$$

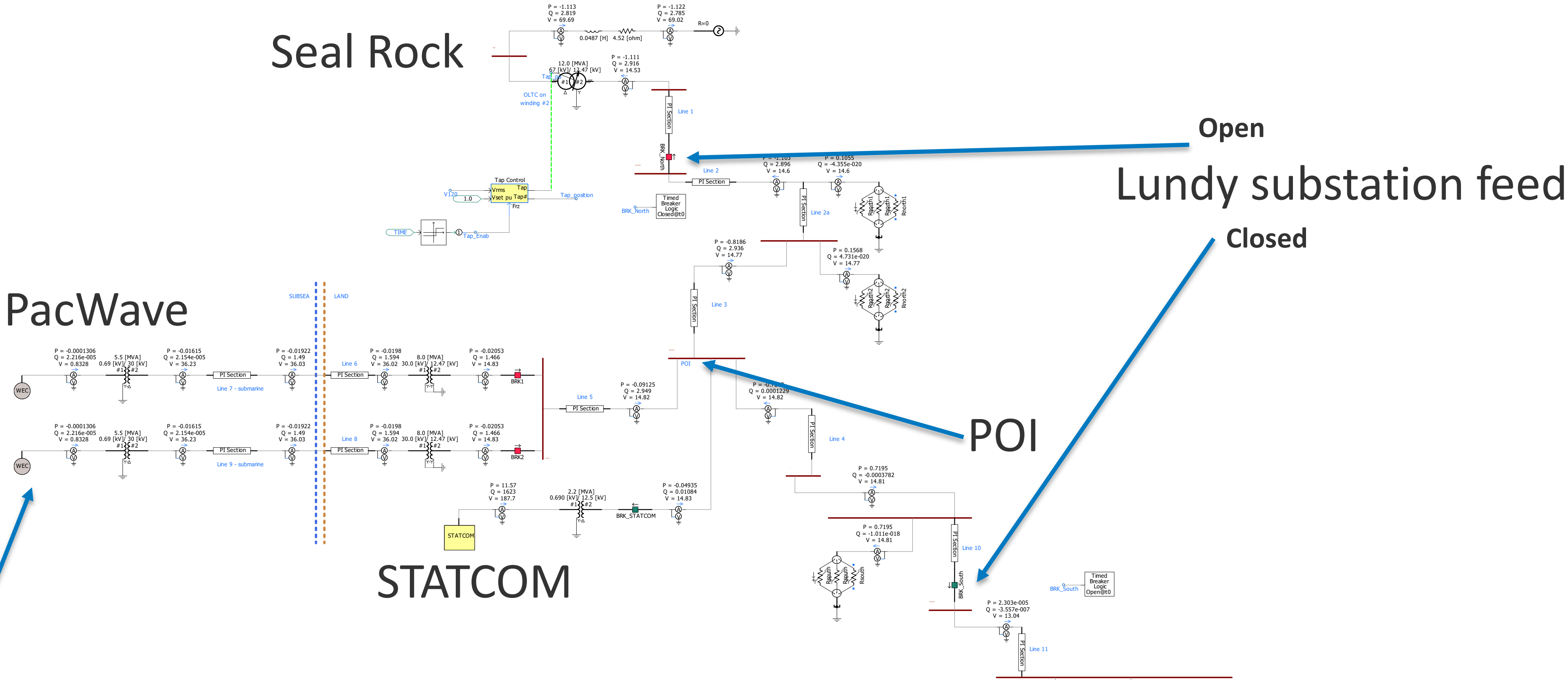
The example below shows 5% droop for a 2.5-MVAR STATCOM:

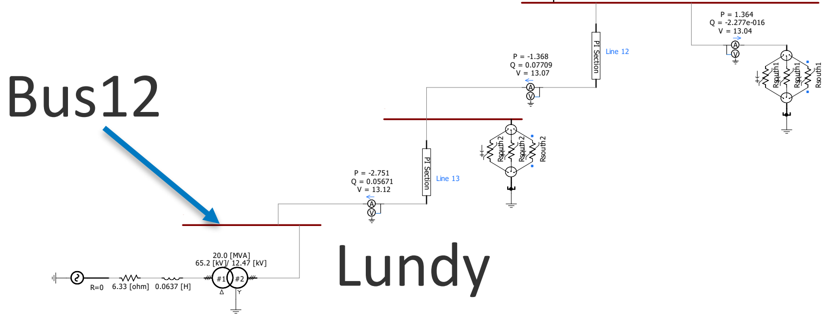


Voltage variations at the point of interconnection (POI) depend on active (ΔP) and reactive power variations (ΔQ) and feeder parameters (R and X):

$$\Delta V \approx \frac{\Delta P \cdot R - \Delta Q \cdot X}{V}$$

PSCAD Model





WEC generator modeled as P-Q source (operated with unity power factor for these simulations)

PSCAD Results

Overview

- Results show the PacWave POI voltage when the 12.47-kV substation bus is within the CLPUD tap changer control window (1.017 p.u. to 1.042 p.u.) for a wide range of conditions.
- Initial analysis used static simulations to show PacWave POI voltage for the full range of substation tap positions.
  - The results for PacWave disconnected are the baseline case for the CLPUD system as is.
  - The results show that feeder voltage violations will occur at the PacWave POI when PacWave is connected without STATCOM. Voltage exceeds 1.05 p.u. with both zero and 10-MW PacWave generation. The zero-generation voltage rise is due to the PacWave subsea cable capacitance.
  - Results with STATCOM added show that the voltage violations can be mitigated with the connection of STATCOM.
- Dynamic results are presented for PacWave sinusoidal 0–10-MW power fluctuation and for Reference 3 model WEC power output time series. The POI and substation voltages at discrete times in the dynamic results are consistent with voltages shown for the static results under similar conditions.
- Results are shown first for the Seal Rock substation connection and then repeated for the Lundy substation connection.

Static Simulations Matrix
Seal Rock Feed

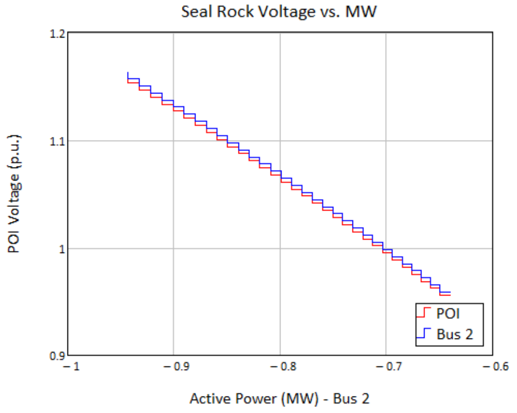
Case #	Seal Rock Feed
1	PacWave disconnected
2	PacWave connected, zero PacWave generation, no STATCOM
3	PacWave connected, zero PacWave generation, 2.5-MVAR STATCOM
4	PacWave with 10 MW generation, no STATCOM
5	PacWave with 10 MW generation, 2.5-MVAR STATCOM

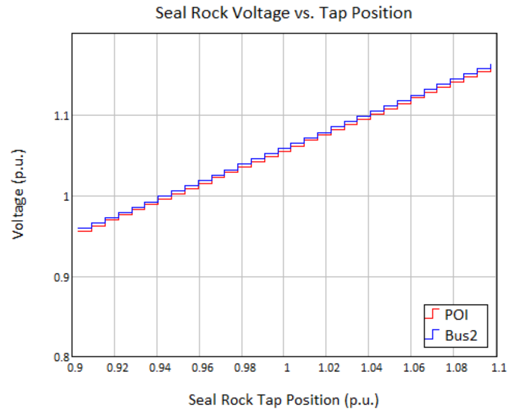
Note: Results are shown for light and heavy feeder loads on each slide:

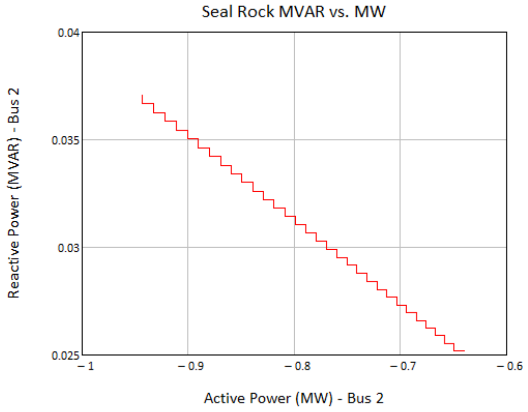
- Light load: 700 kW for Seal Rock feeder
- Heavy load: 5,000 kW for Seal Rock feeder

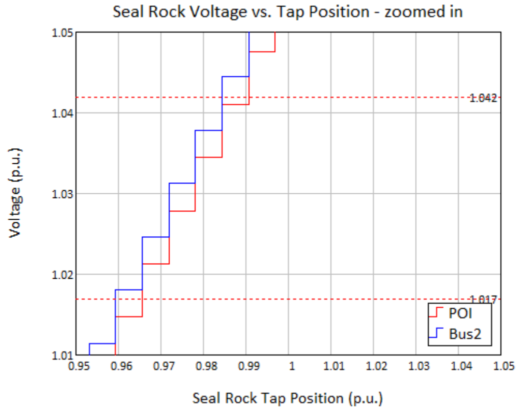
Seal Rock Feed, No PacWave

Light Load

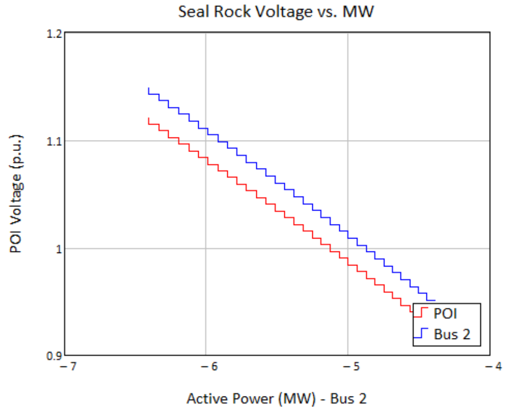


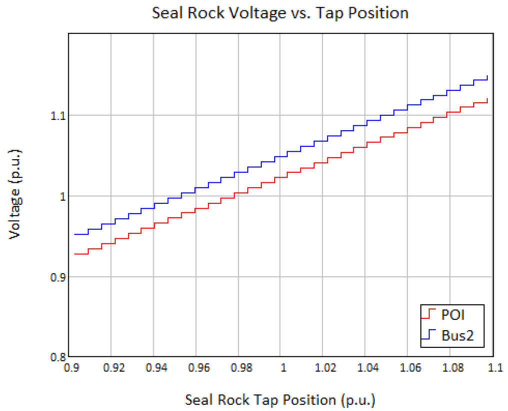


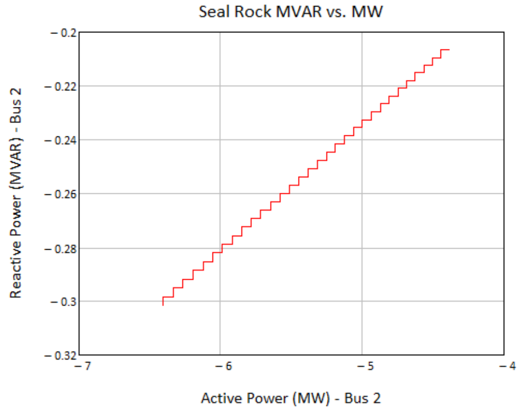


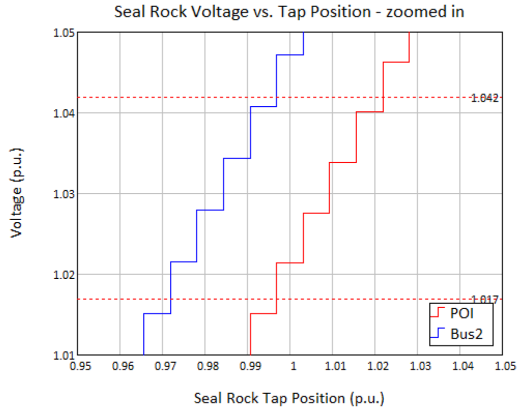


Heavy Load



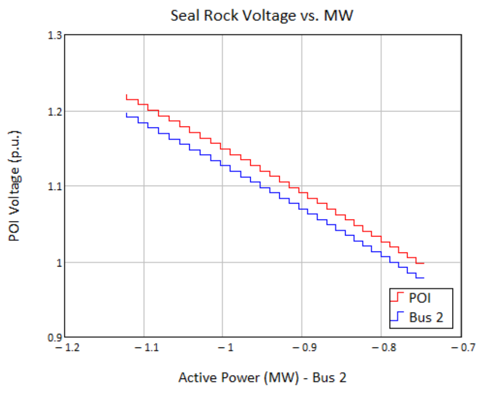


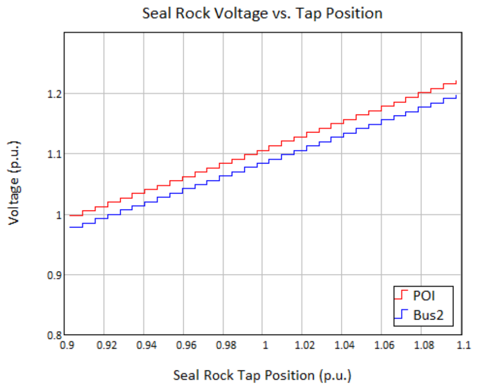


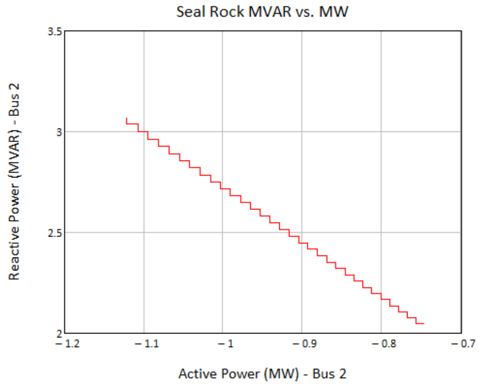


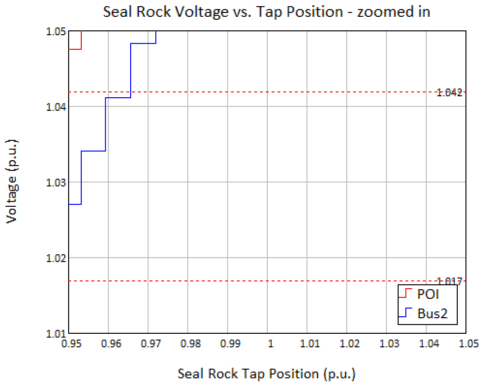
Seal Rock Feed, PacWave Cable Energized

Light Load

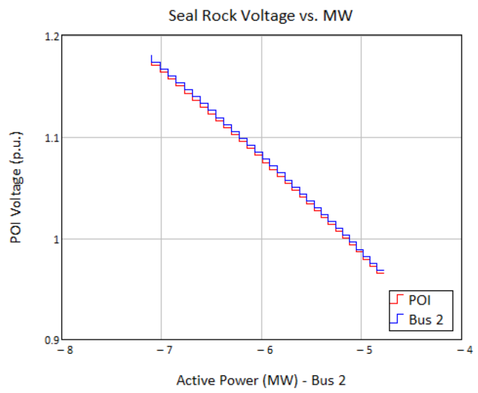


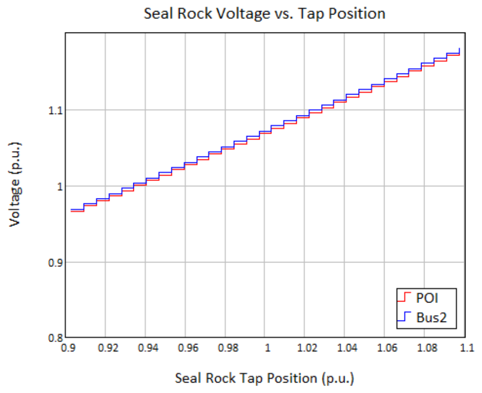


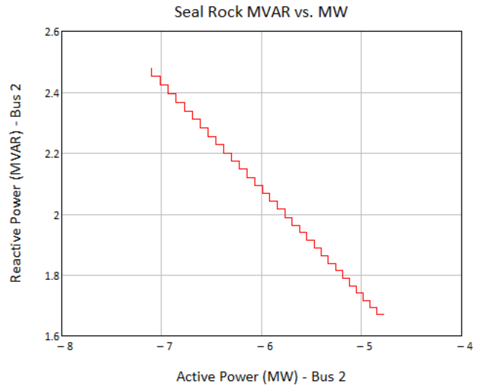


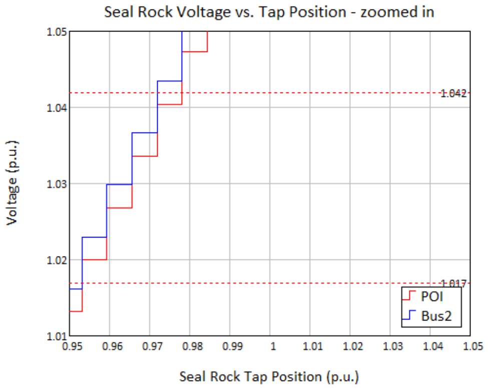


Heavy Load



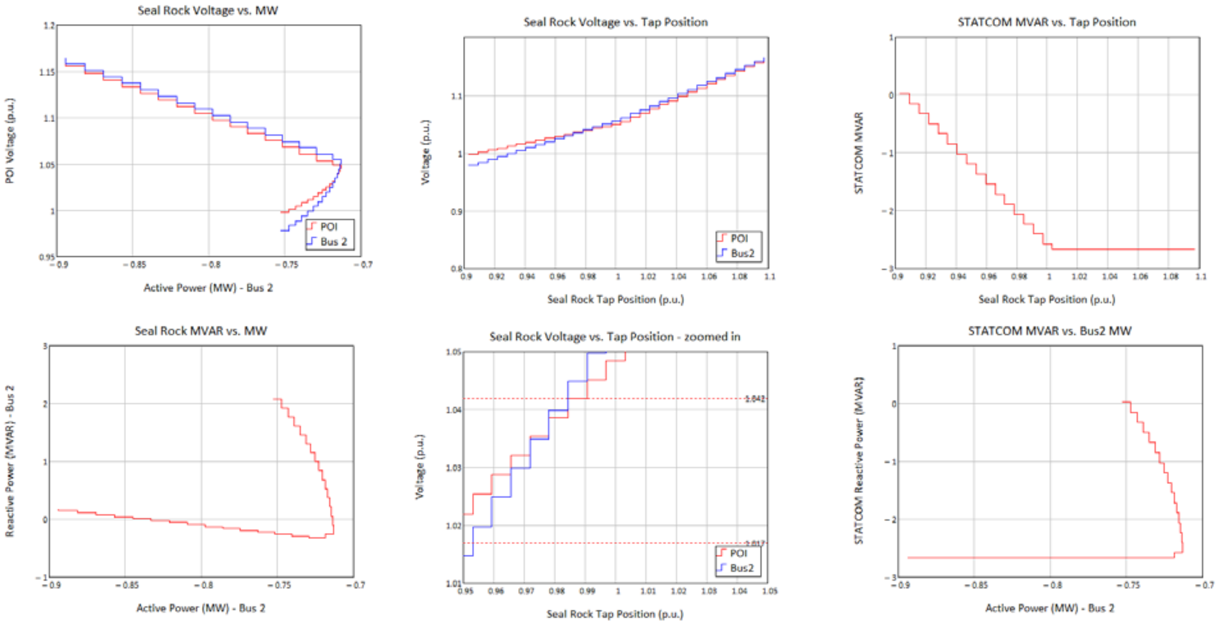




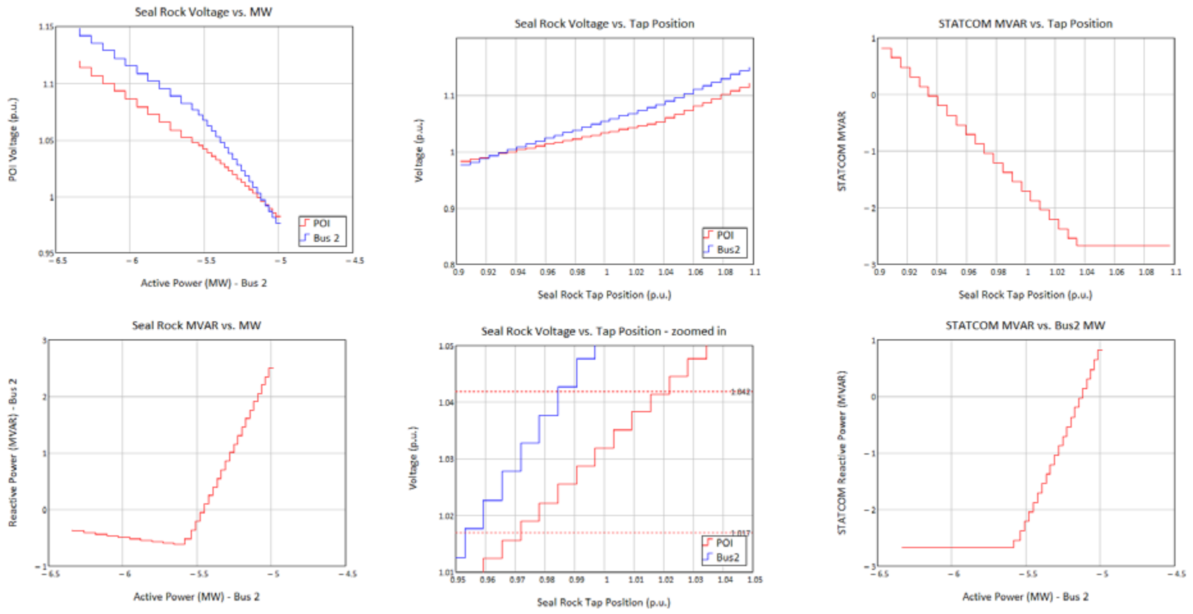


Seal Rock Feed, Cables Energized, 2.5-MVAR STATCOM

Light Load

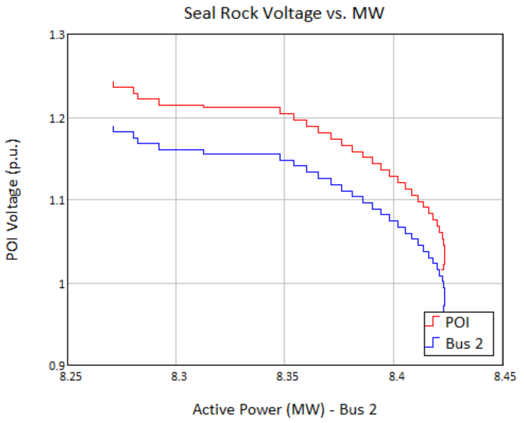


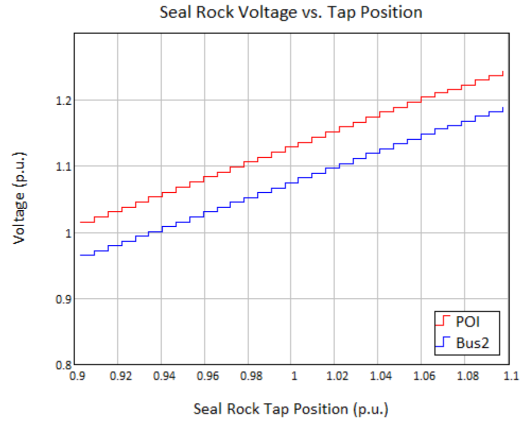
Heavy Load

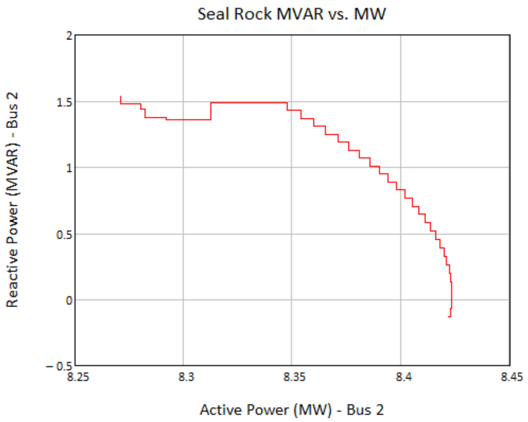


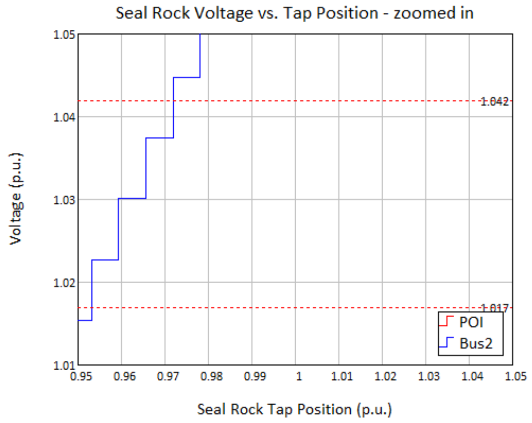
Seal Rock Feed, No STATCOM, PacWave Operating at 10 MW

Light Load

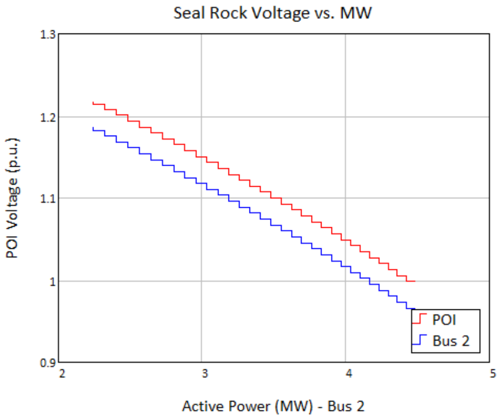


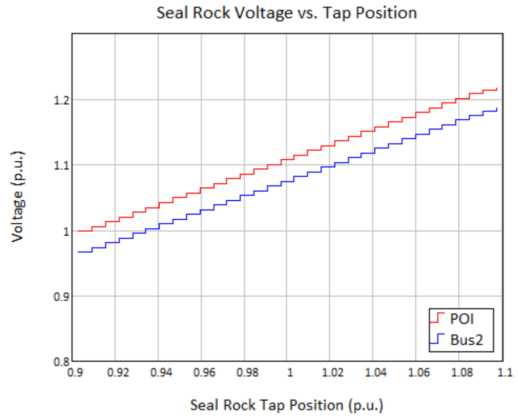


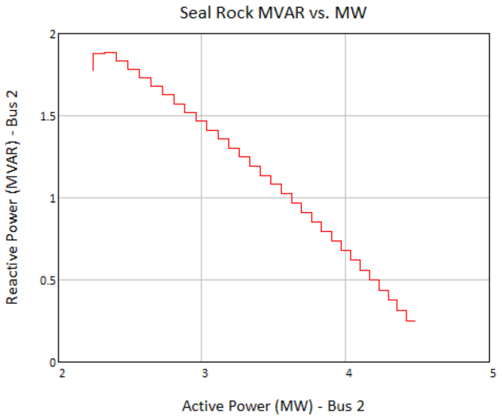


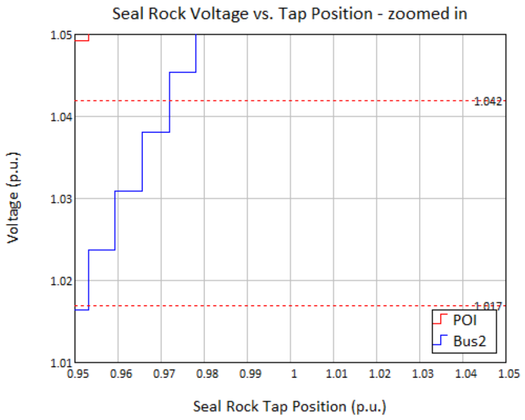


Heavy Load



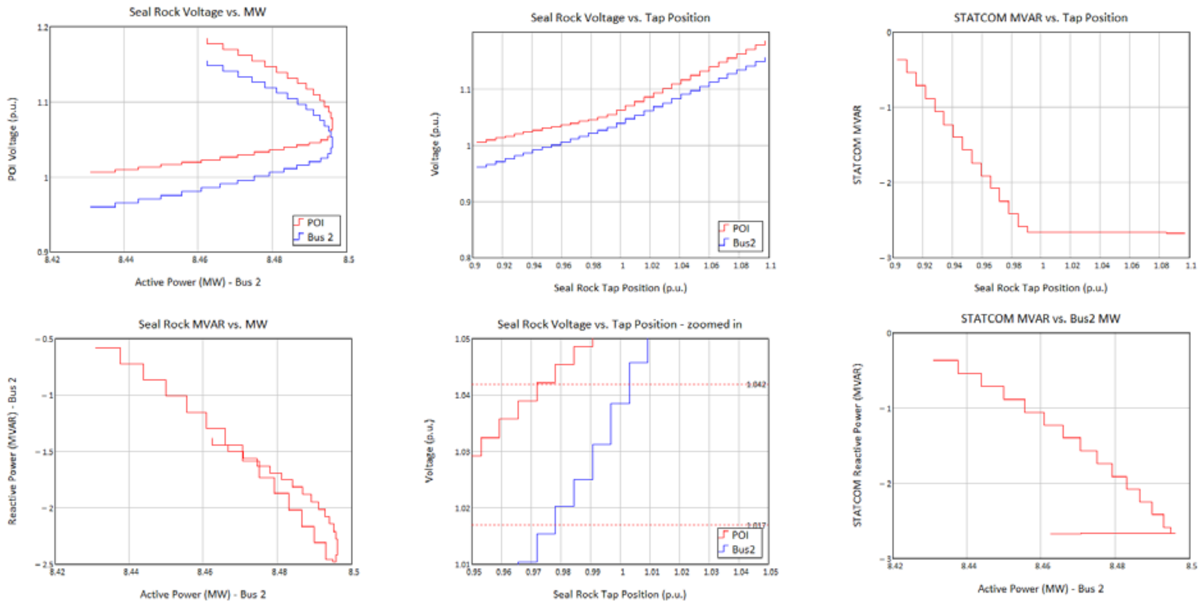




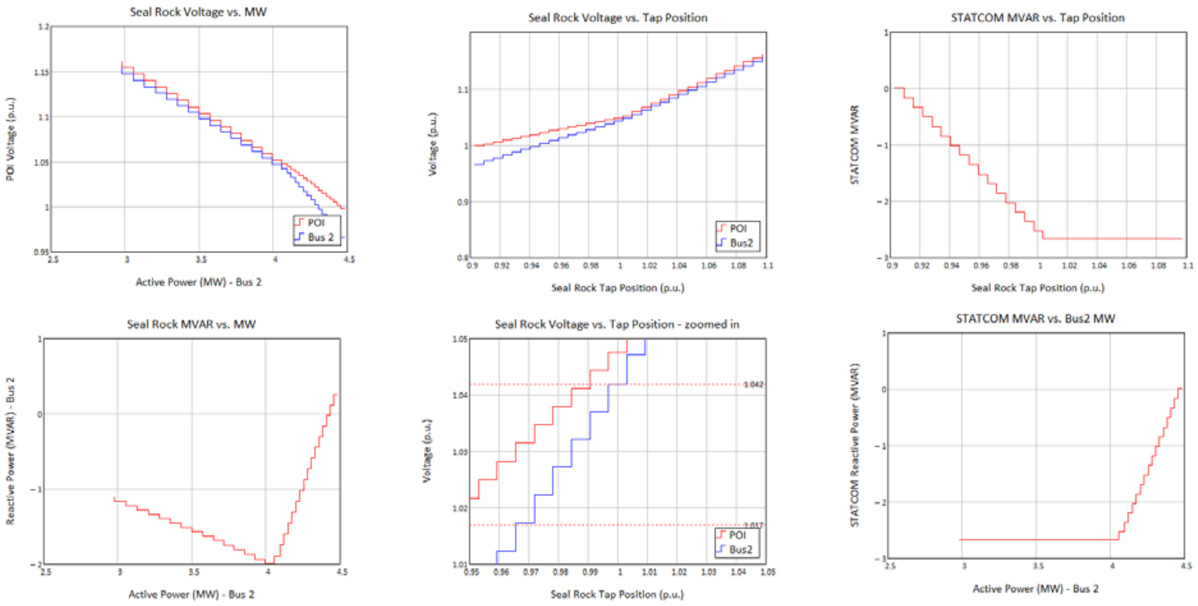


Seal Rock Feed, 2.5-MVAR STATCOM, PacWave Operating at 10 MW

Light Load



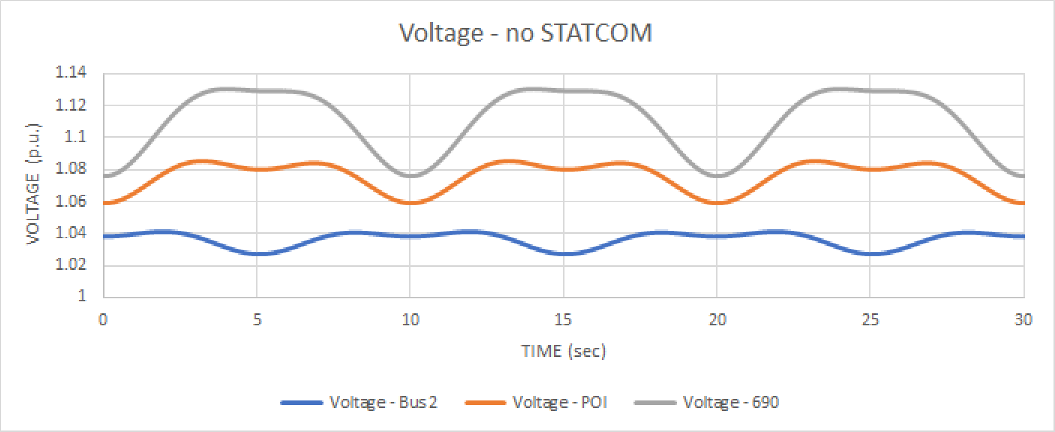
Heavy Load

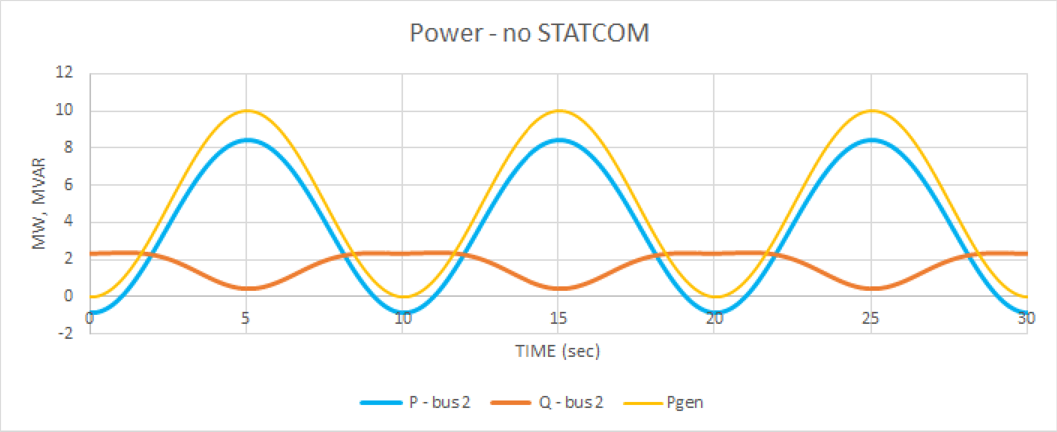


Seal Rock Feed—0–10-MW Sinusoidal Power Injection by PacWave Generators

Fixed tap position in Seal Rock transformer

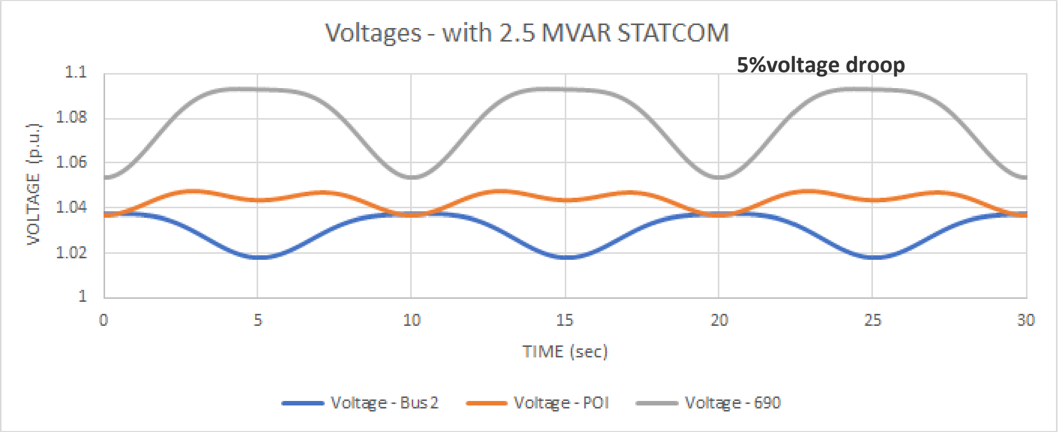
Per-unit tap position = 0.9625

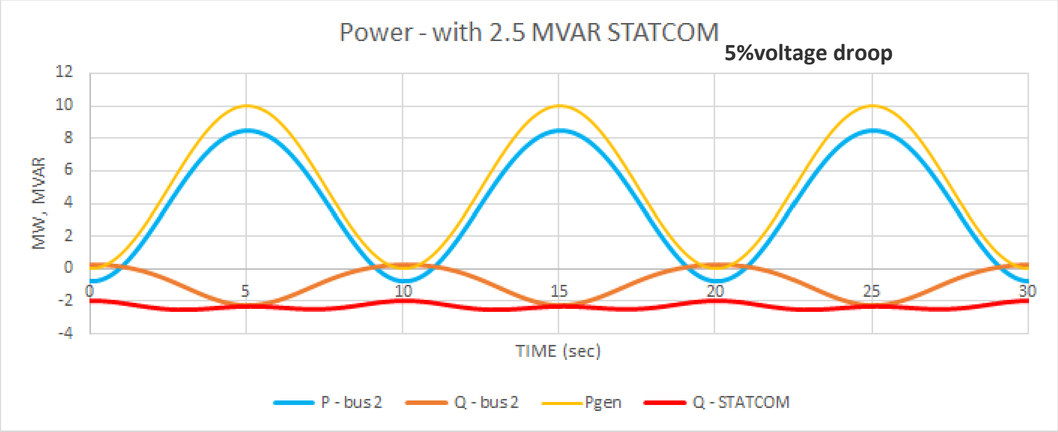




- Light feeder load (700 kW)

Per-unit tap position = 0.975



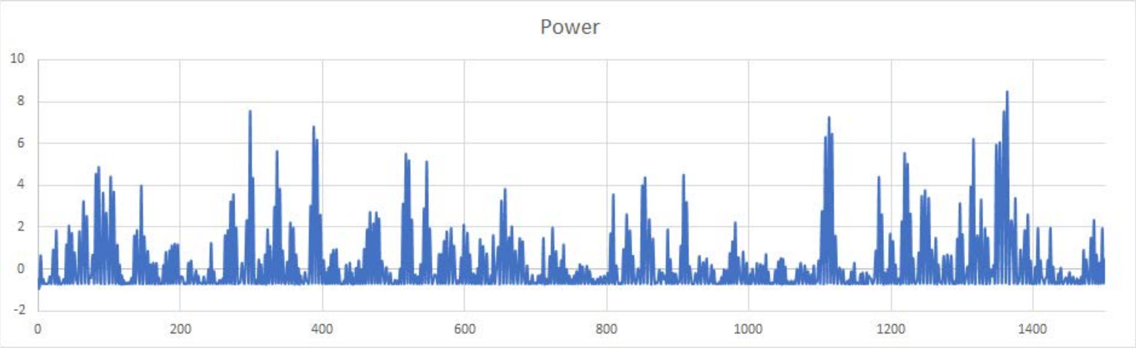


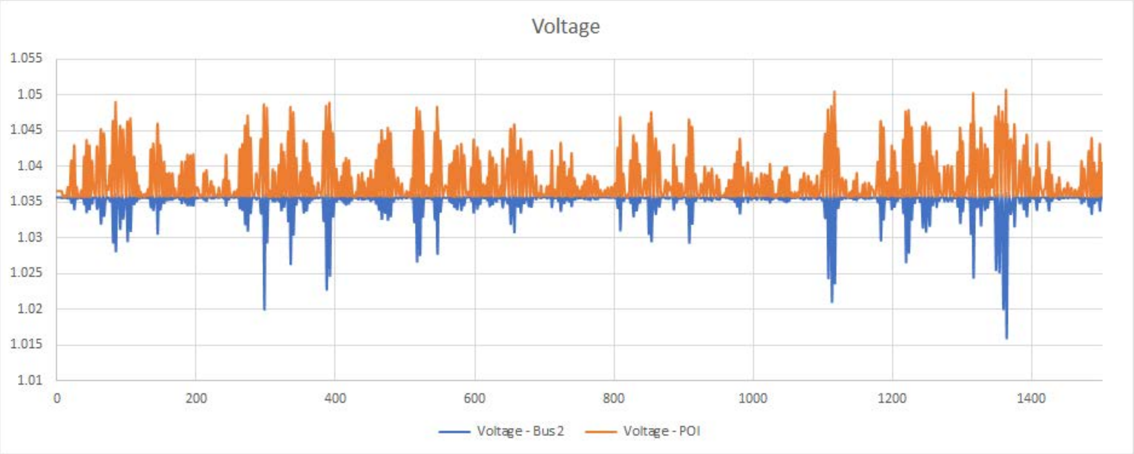
- This is the most severe case (both WEC systems operate in phase).
- Voltage at 690-V terminal of WEC generators increases up to ~1.1 p.u. because they operate at PF = 1.
- This needs to be considered in cable specifications, offshore transformer ratings, and protection settings.

Reference Model 3 WEC Simulations
Seal Rock Feed

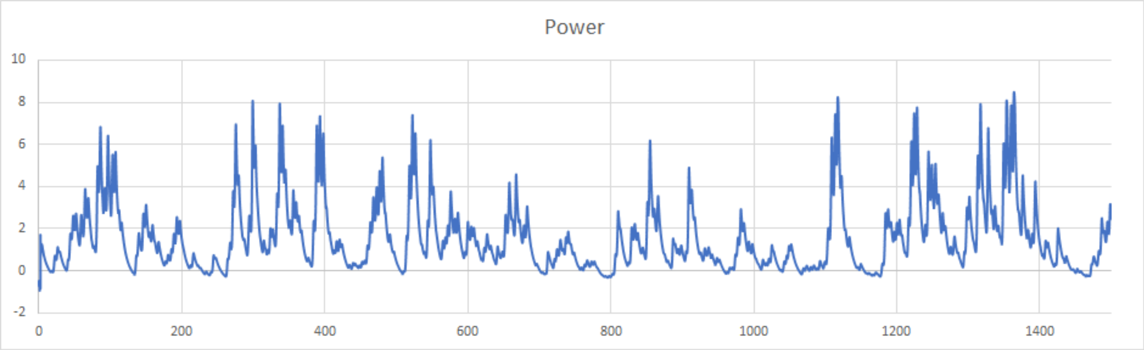
2.5-MVAR STATCOM operating with 5% droop
Light feeder load (700 kW)

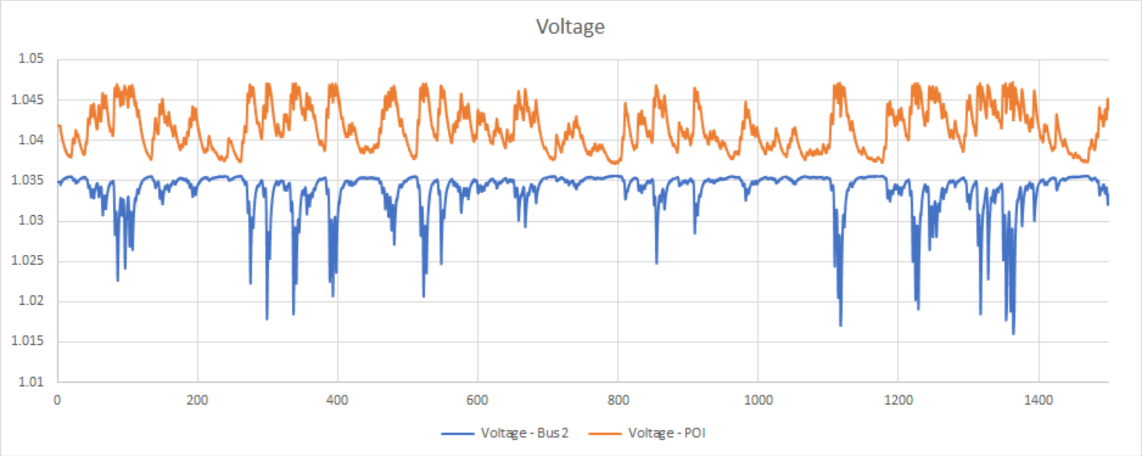
No accumulator and pressure release valve





With accumulator and pressure release valve





Static Simulations Matrix
Lundy Feed

Case #	Lundy Feed
1	PacWave disconnected
2	PacWave connected, zero PacWave generation, no STATCOM
3	PacWave connected, zero PacWave generation, 4-MVAR STATCOM
4	PacWave with 10 MW generation, no STATCOM
5	PacWave with 10 MW generation, 4-MVAR STATCOM

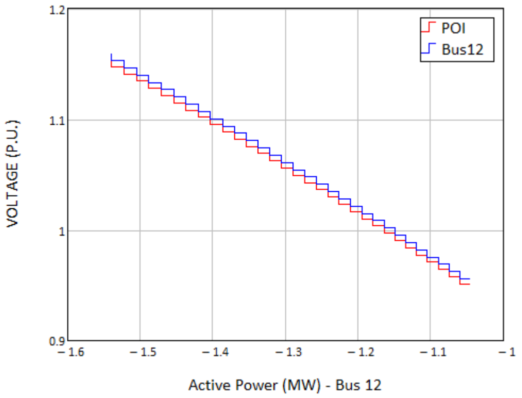
Note: Results are shown for light and heavy feeder loads on each slide:

- Light load:
  - 700 kW for Seal Rock feeder
  - 450 kW for Lundy feeder
- Heavy load:
  - 5,000 kW for Seal Rock feeder
  - 2500 kW for Lundy feeder

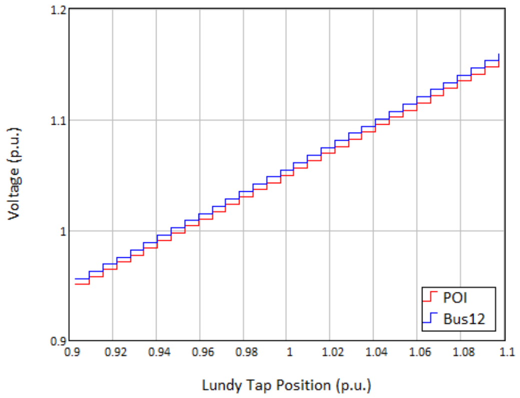
Lundy Feed, No PacWave

Light Load

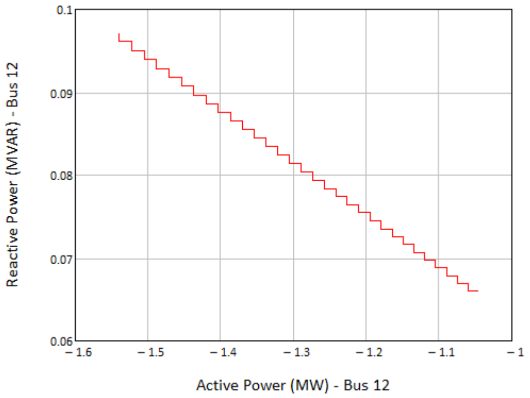
Lundy Voltage vs. MW



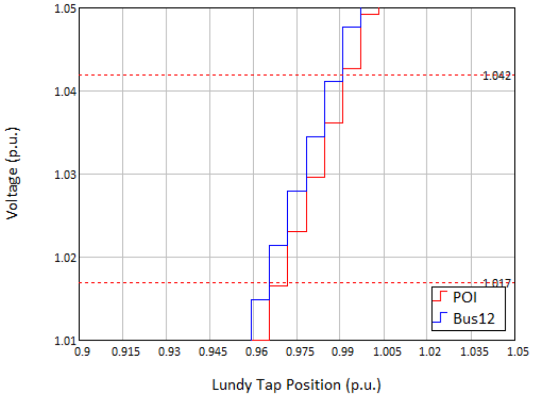
Lundy Voltage vs. Tap Position



Lundy MVAR vs. MW

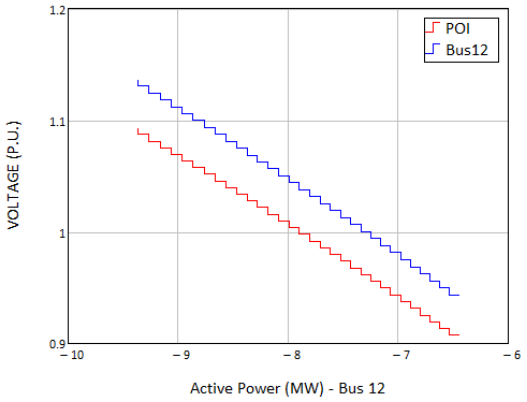


Lundy Voltage vs. Tap Position - zoomed in

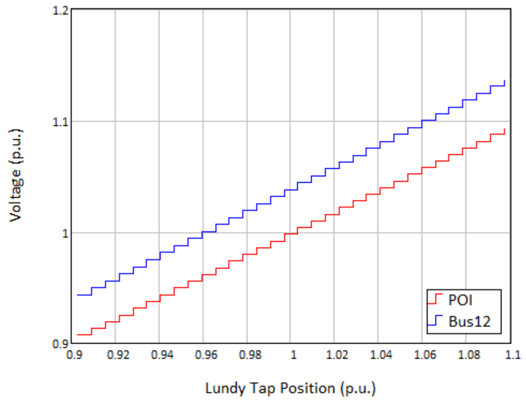


Heavy Load

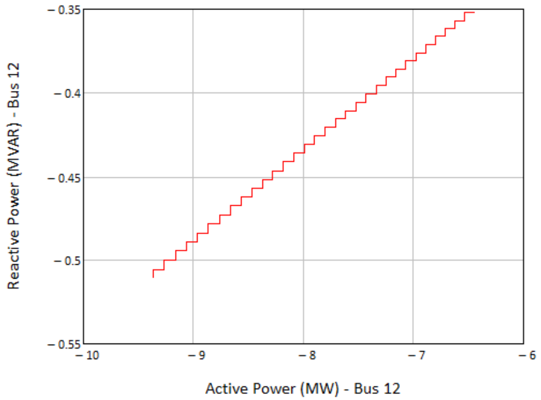
Lundy Voltage vs. MW



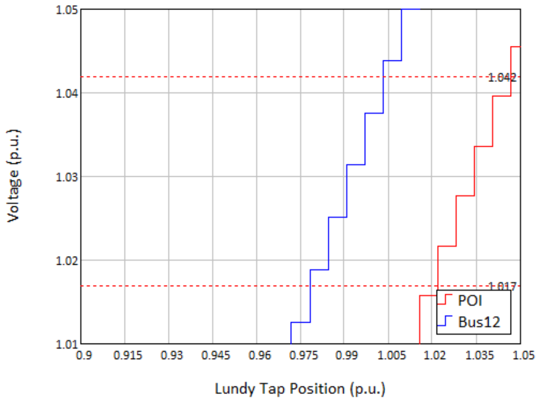
Lundy Voltage vs. Tap Position



Lundy MVAR vs. MW

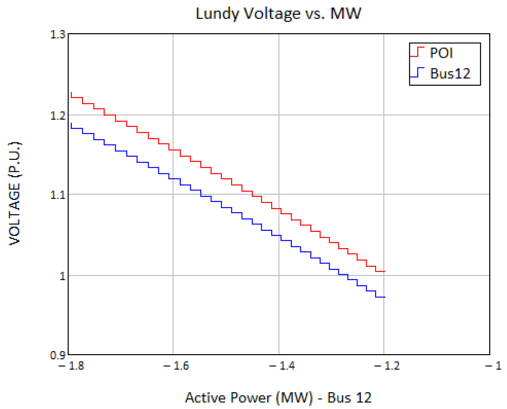


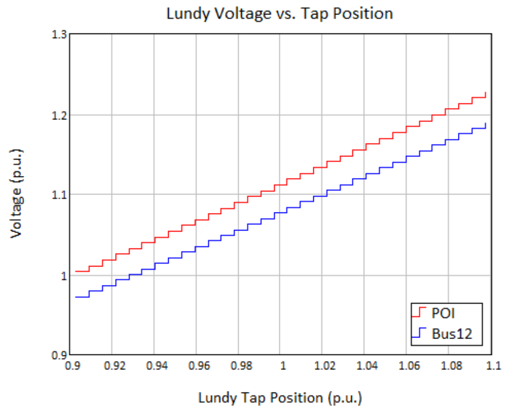
Lundy Voltage vs. Tap Position - zoomed in

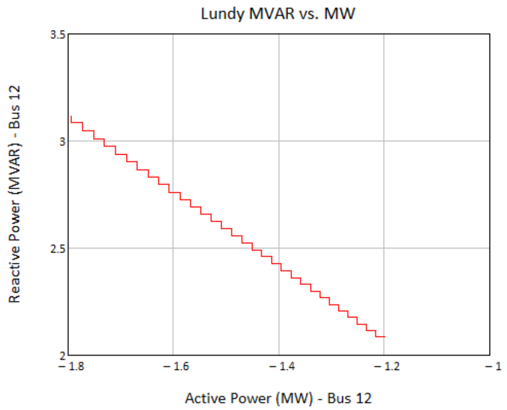


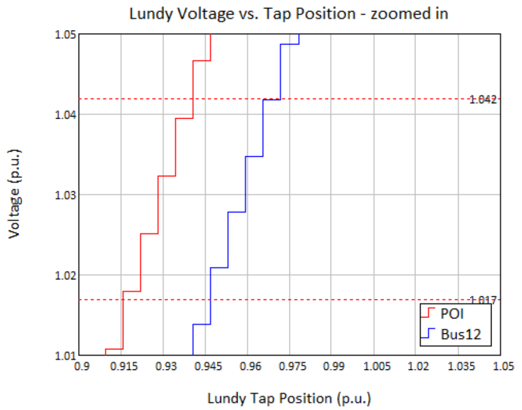
Lundy Feed, PacWave Cable Energized

Light Load

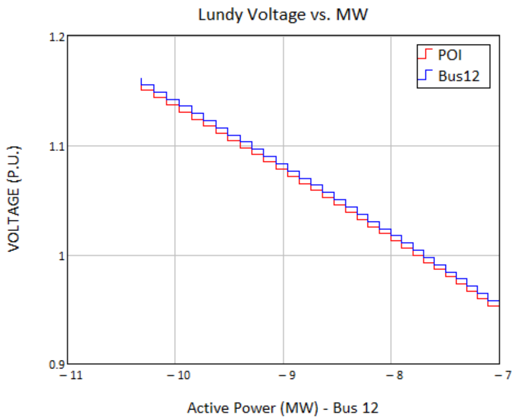


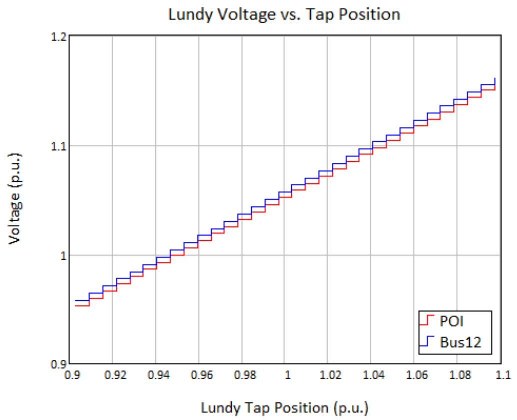


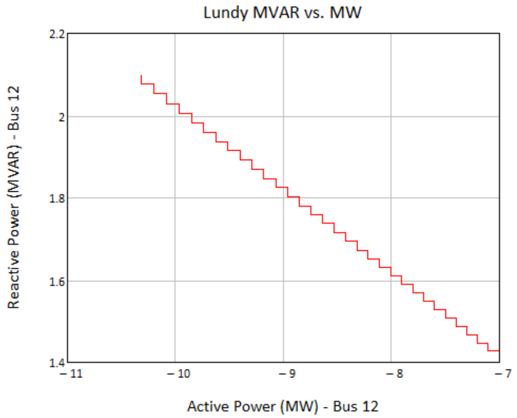


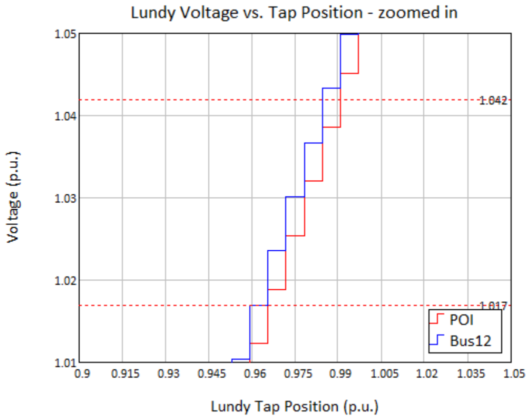


Heavy Load



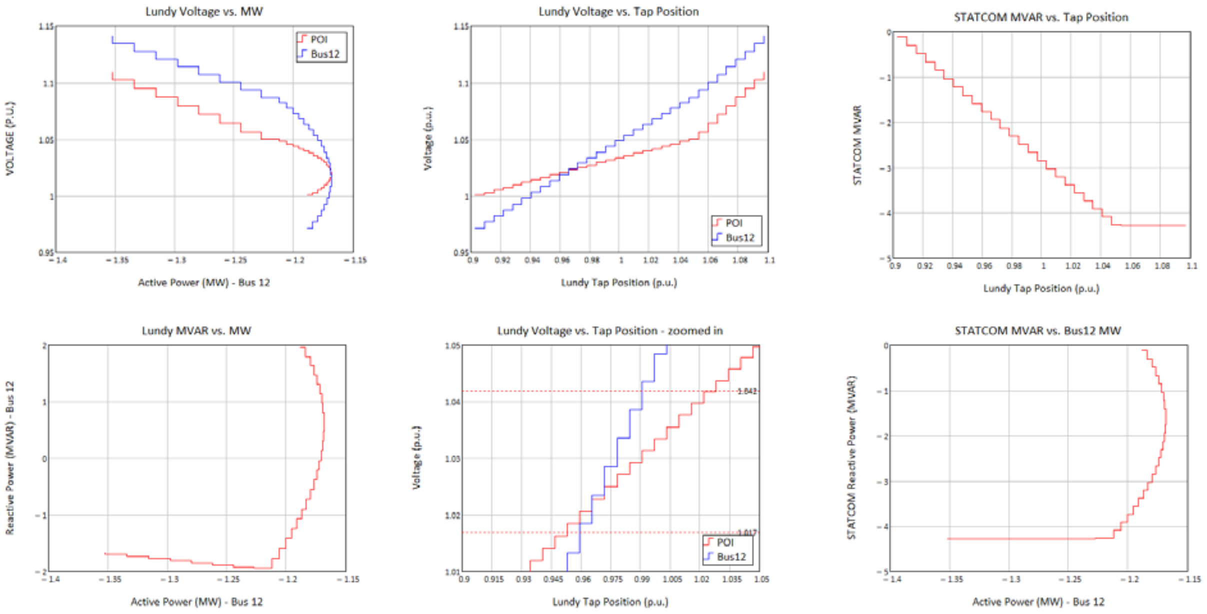




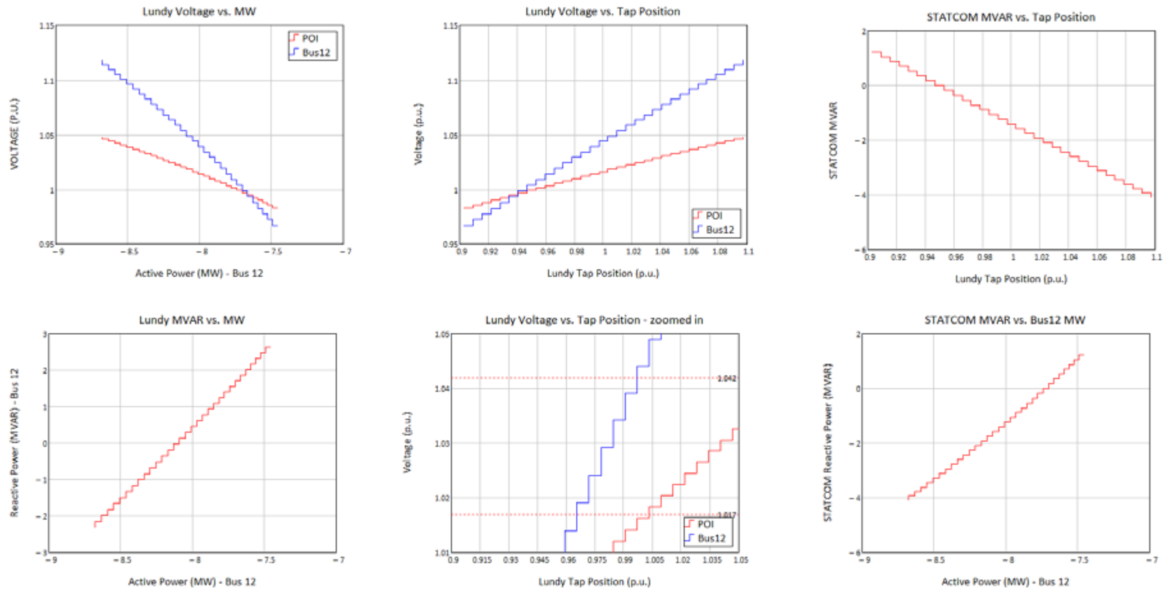


Lundy Feed, Cables Energized, 4-MVAR STATCOM

Light Load

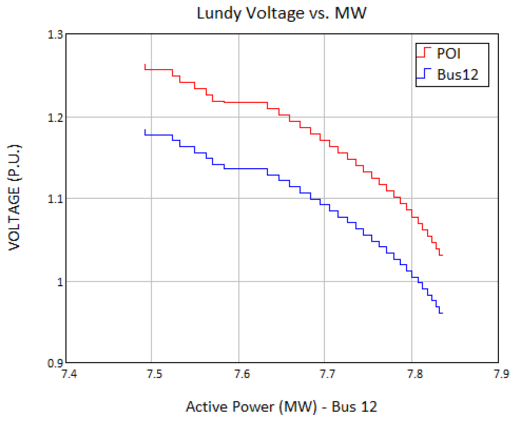


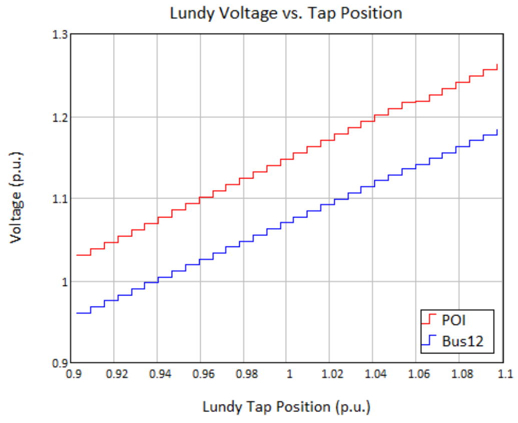
Heavy Load

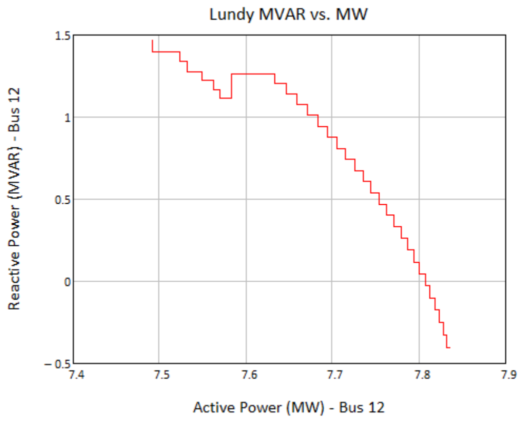


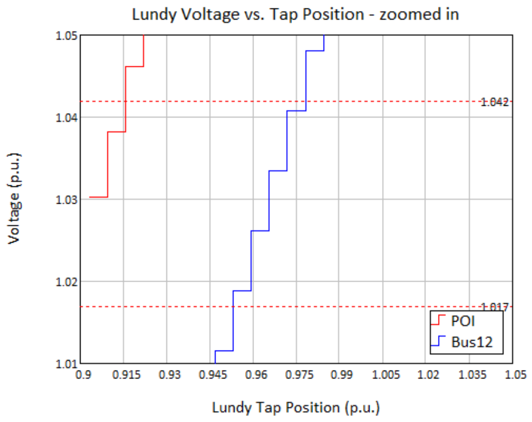
Lundy Feed, No STATCOM, PacWave Operating at 10 MW

Light Load

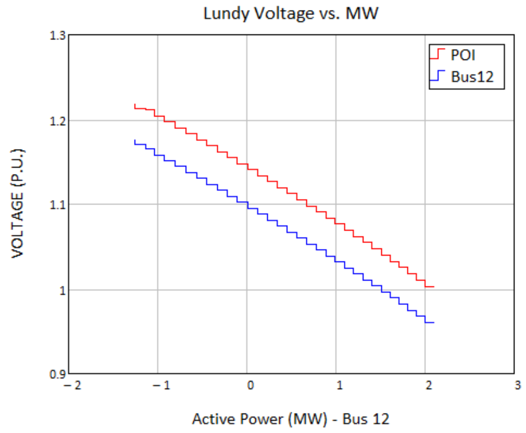


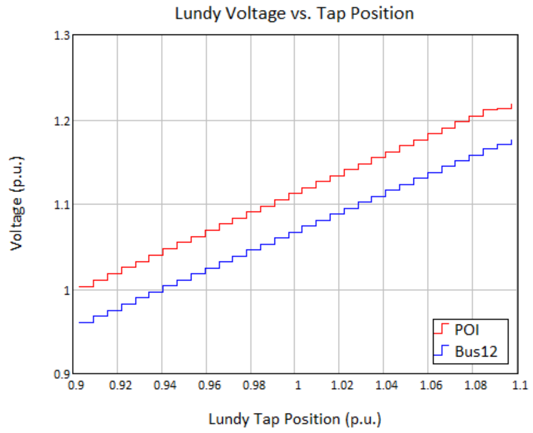


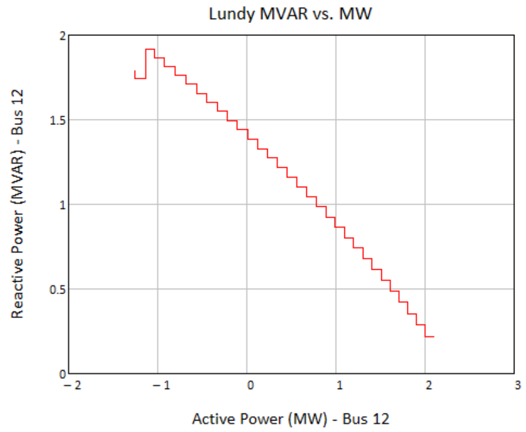


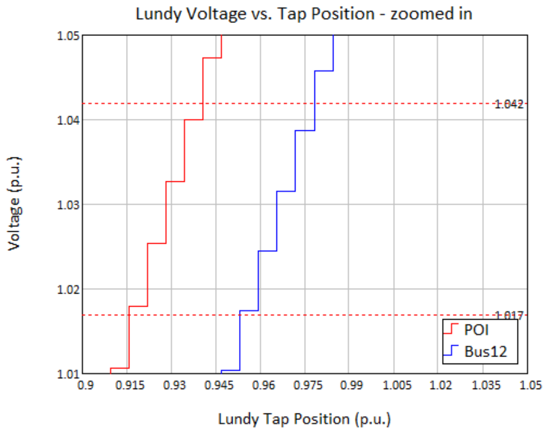


Heavy Load



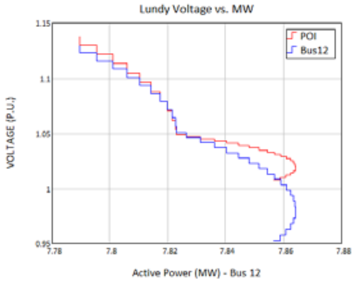


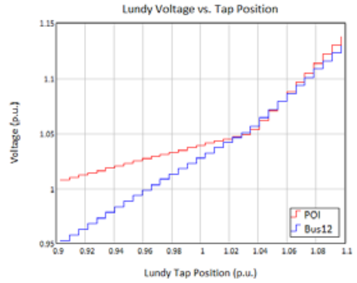


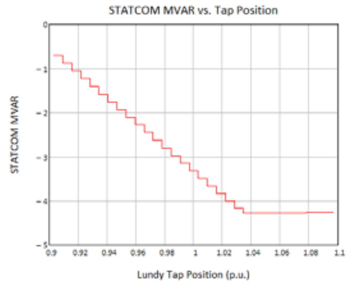


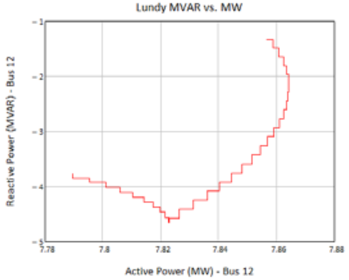
Lundy Feed, 4-MVAR STATCOM, PacWave Operating at 10 MW

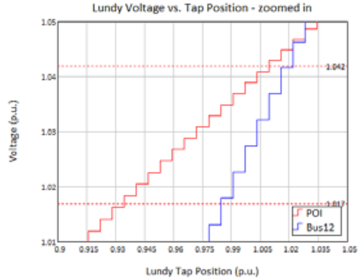
Light Load

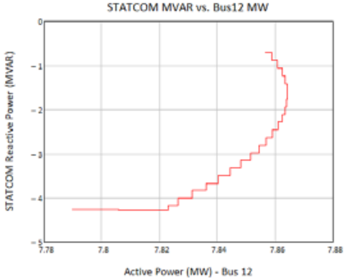




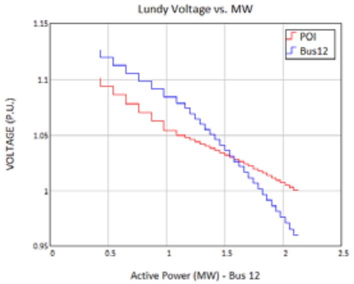


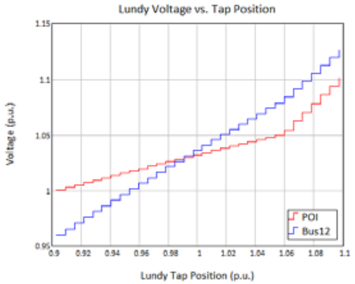


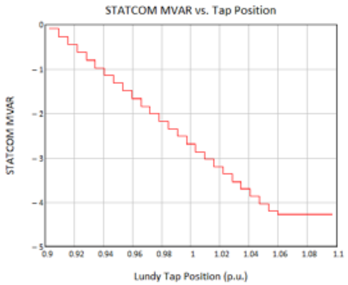


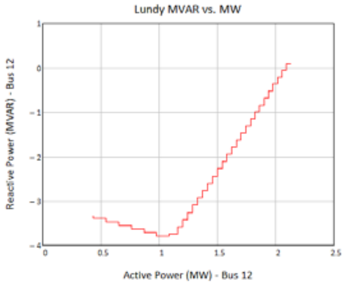


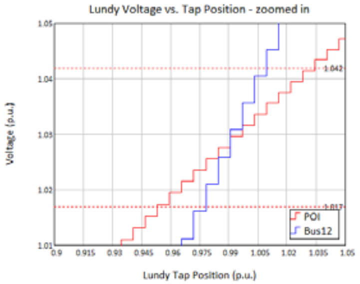
Heavy Load

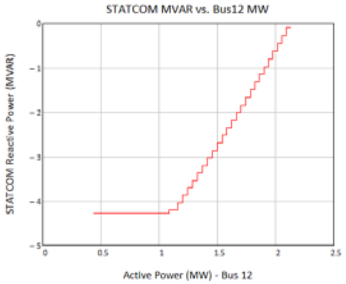








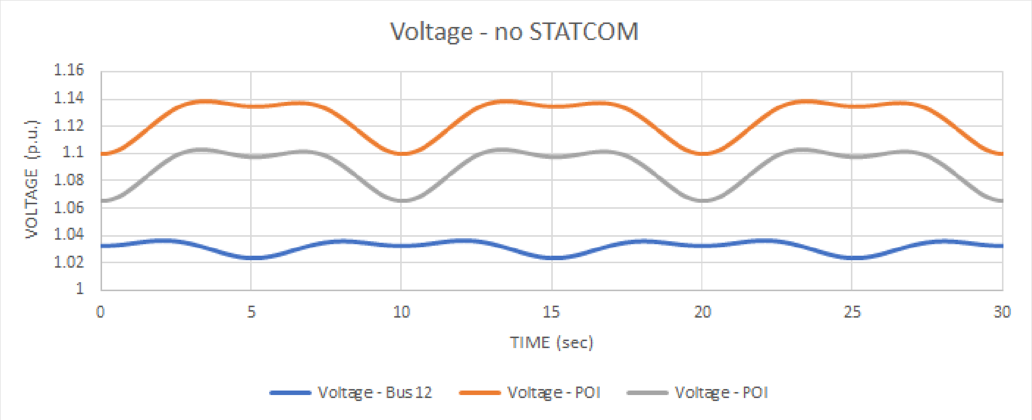


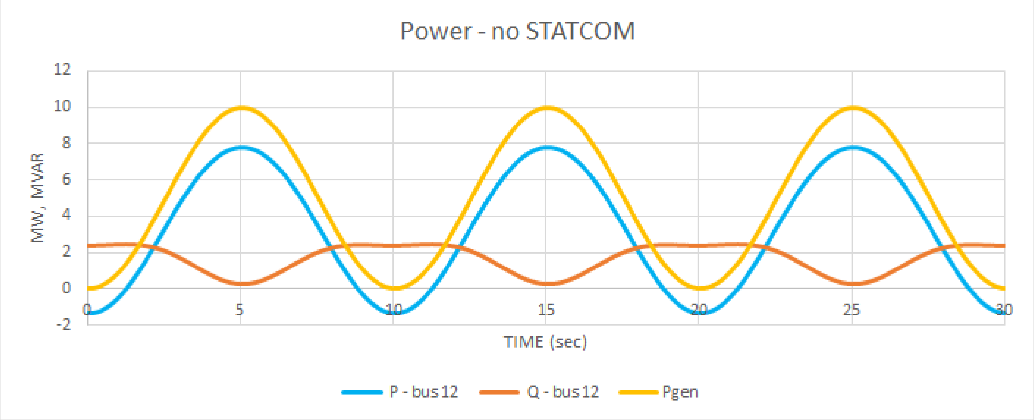


Lundy Feed—0–10-MW Sinusoidal Power Injection by PacWave Generators

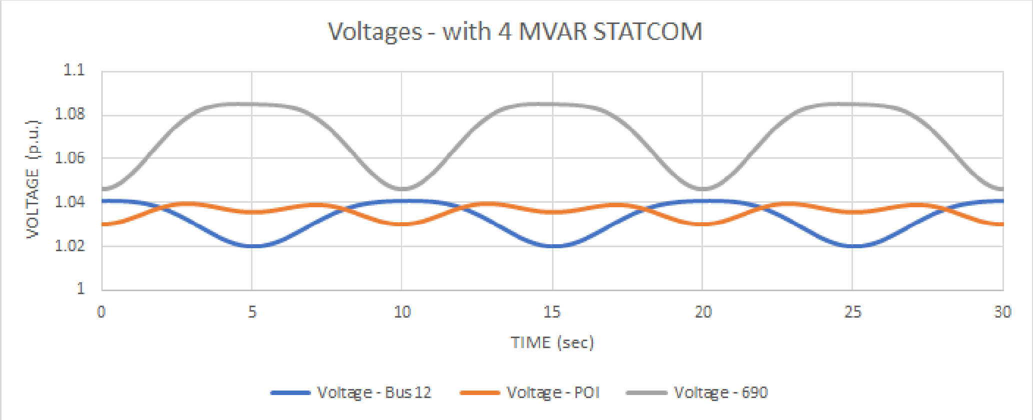
Fixed tap position in Lundy transformer

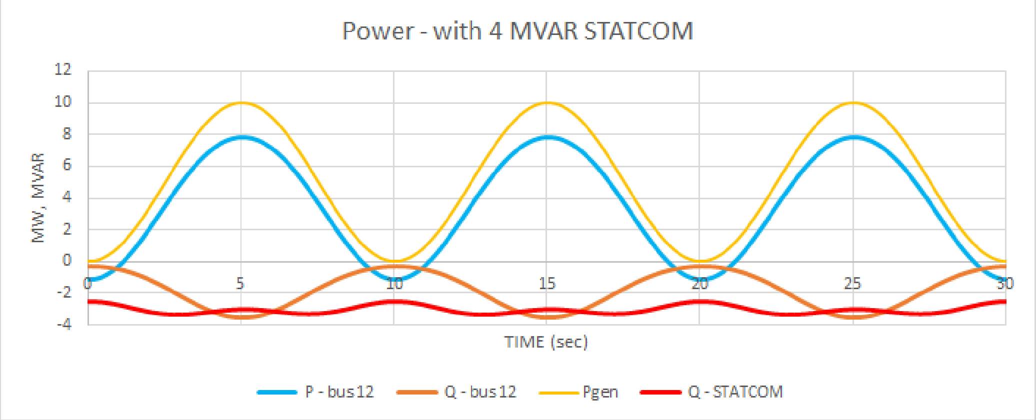
Per unit tap position = 0.9625





Per unit tap position = 0.9875





- Light feeder load (Seal Rock: 700 kW and Lundy: 450 kW)

- This is the most severe case (both WEC systems operate in phase)
- Voltage at 690-V terminal of WEC generators increases up to 1.08 p.u. because they operate at PF = 1.
- This needs to be considered in cable specifications, offshore transformer ratings, and protection settings.

Conclusions

- Voltage violations (V>1.05 p.u.) will occur on CLPUD feeders when PacWave is connected without any mitigation.
- Worse voltage violations will occur when PacWave is connected to Lundy substation (the alternate connection) than with the normal Seal Rock connection because line distances to Lundy are longer.
- Voltage violations for connection to both Seal Rock and Lundy substations can be mitigated with the addition of STATCOM at the PacWave UCMF. 2.5 MVAR is sufficient for the Seal Rock connection alone, and 4 MVAR is needed for the Lundy connection.

Recommendations

The following should be completed as part of the PacWave detailed electrical design:

- Recheck of STATCOM sizing after final PacWave cable designs are completed. A larger STATCOM might be necessary if final cable capacitances are significantly higher than those used for this study.
- STATCOM control design and reconfiguration of CLPUD substation tap changer control settings for reverse power flow.
- System protection studies.

The following might be necessary during planning for specific WEC designs to be interconnected at PacWave:

- Flicker studies.