ENERGY TRANSITIONS INITIATIVE
U.S. Department of Energy

Partnership Project

City and Borough of Sitka, Alaska - Modeling and Controls Assistance and Renewable Energy Resource Assessment

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National Renewable Energy Laboratory

November 15, 2022

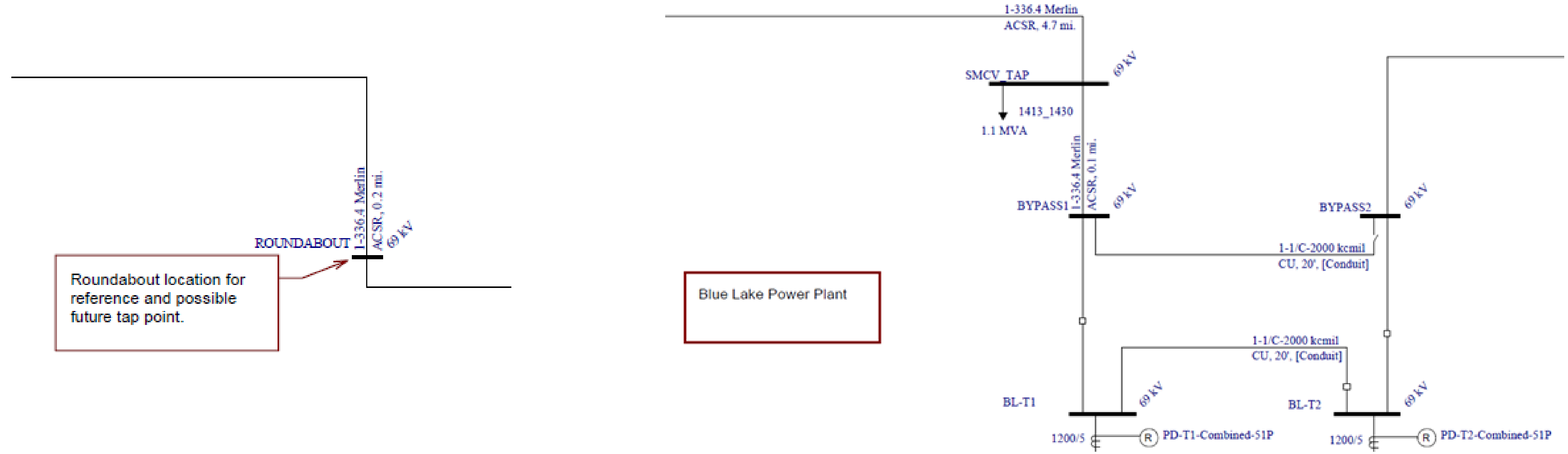
Objective

- Sizing of wind penetration in hydro-rich environment of Sitka
  - Practical Sitka grid model for dynamic analysis
  - Dynamic model of wind to assess the stability and control impacts
  - Dynamic model of Blue Lake and Green Lake synchronous machines to assess the stability and control impacts
- Analysis of efficiency of load control
- Analyze stability and grid control impacts of wind capacity expansions and locations
- Analyze wind-hydro control coordination

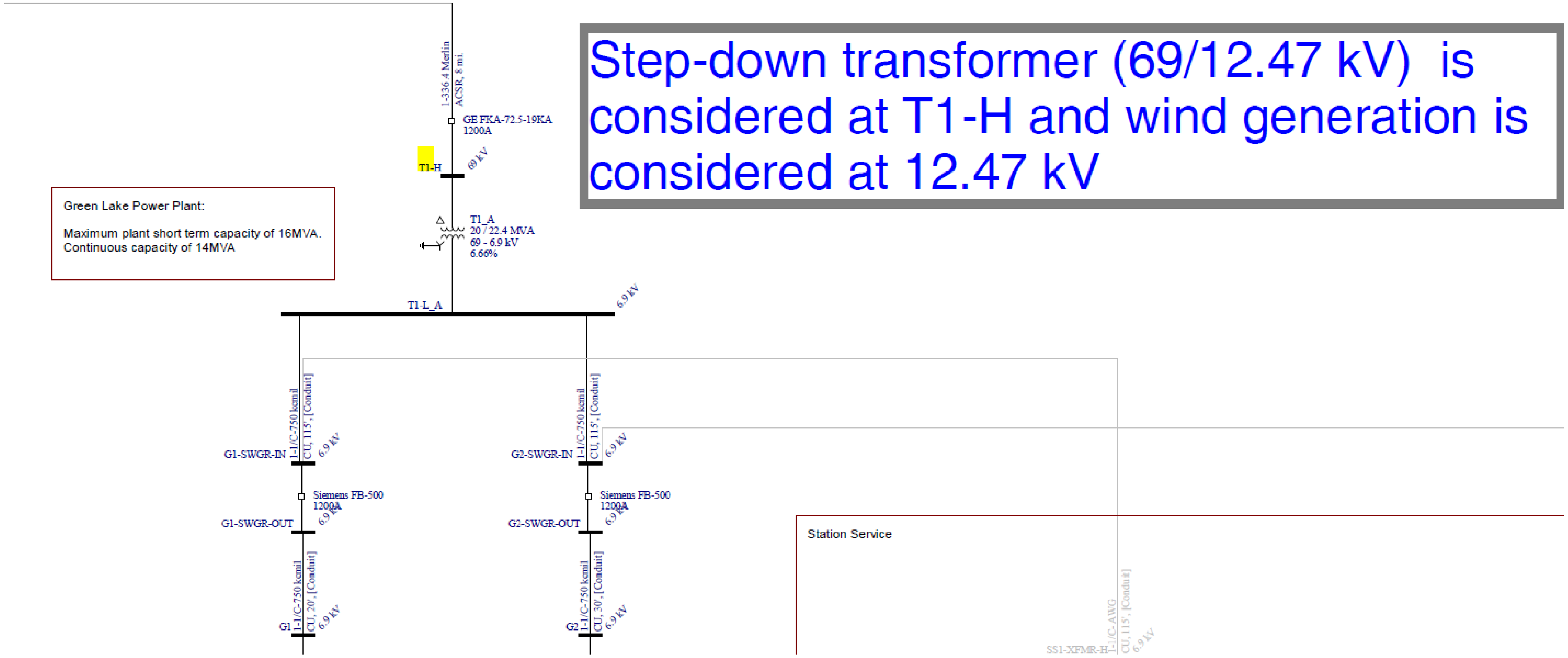
Sitka Grid Stability Analysis Using OPAL-RT

- ❑ Developed detailed dynamic Sitka OPAL-RT model to evaluate grid stability and control impacts
- ❑ Developed real-time model – Unbalanced 738-bus electric grid at 120 V, 12.5 kV, 69 kV, etc.
- ❑ Analyzed case with wind generation analysis at Beaver Lake Hump
- ❑ Analyzed case with wind generation analysis at Lucky Chance Ridge
- ❑ Analyzed case with wind generation analysis at Starrigavan Ridge
- ❑ Considered wind generation – 3 MW, 6 MW, 9 MW, 12 MW, 15 MW
- ❑ Detailed time domain dynamic models of Blue Lake and Green Lake generators
- ❑ Input data received in CSV format which was transformed to create OPAL-RT model

Wind Generation Locations (Near Roundabout and Blue Lake Station)

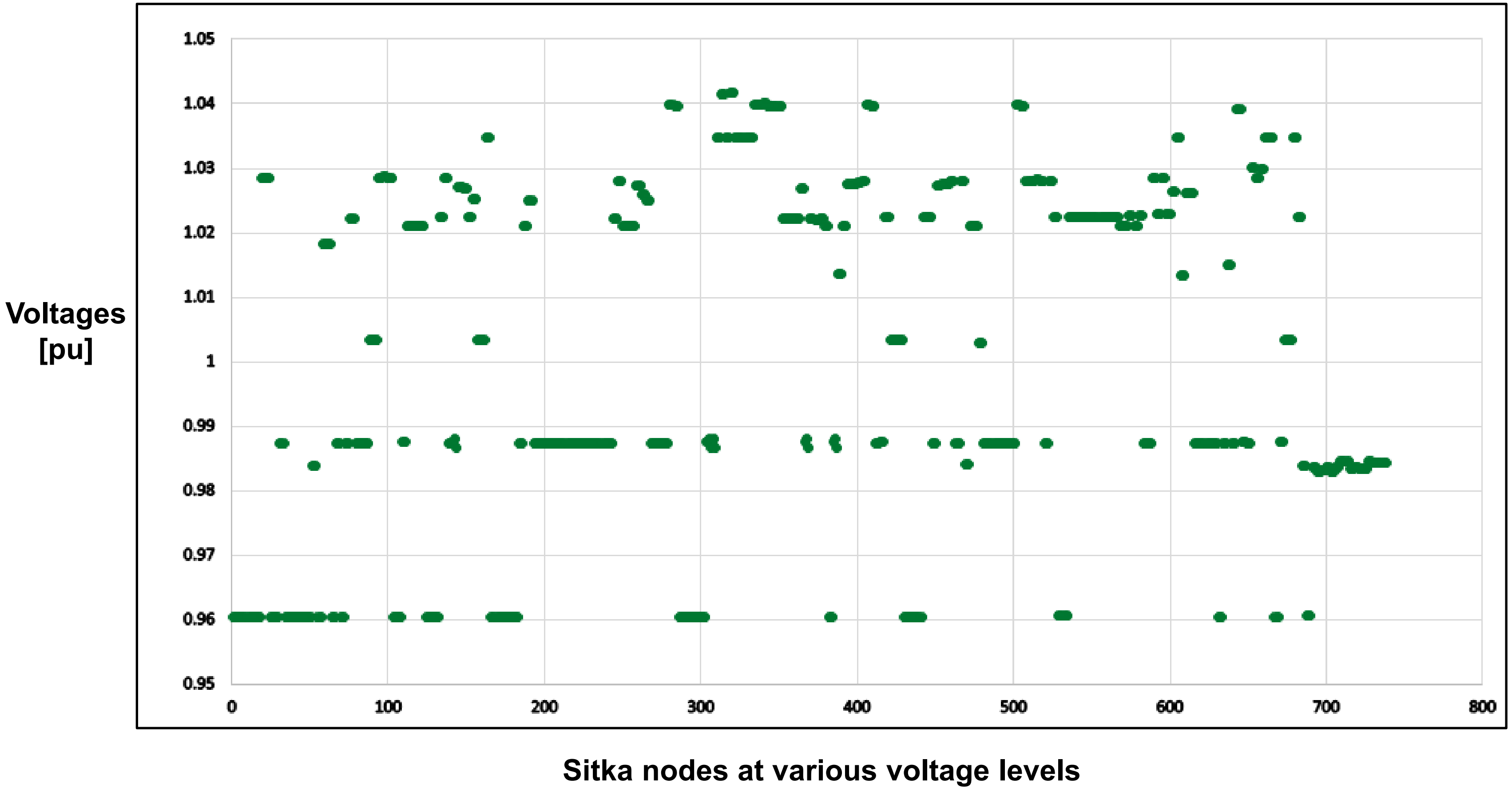


Wind Generation Locations (Green Lake Station)

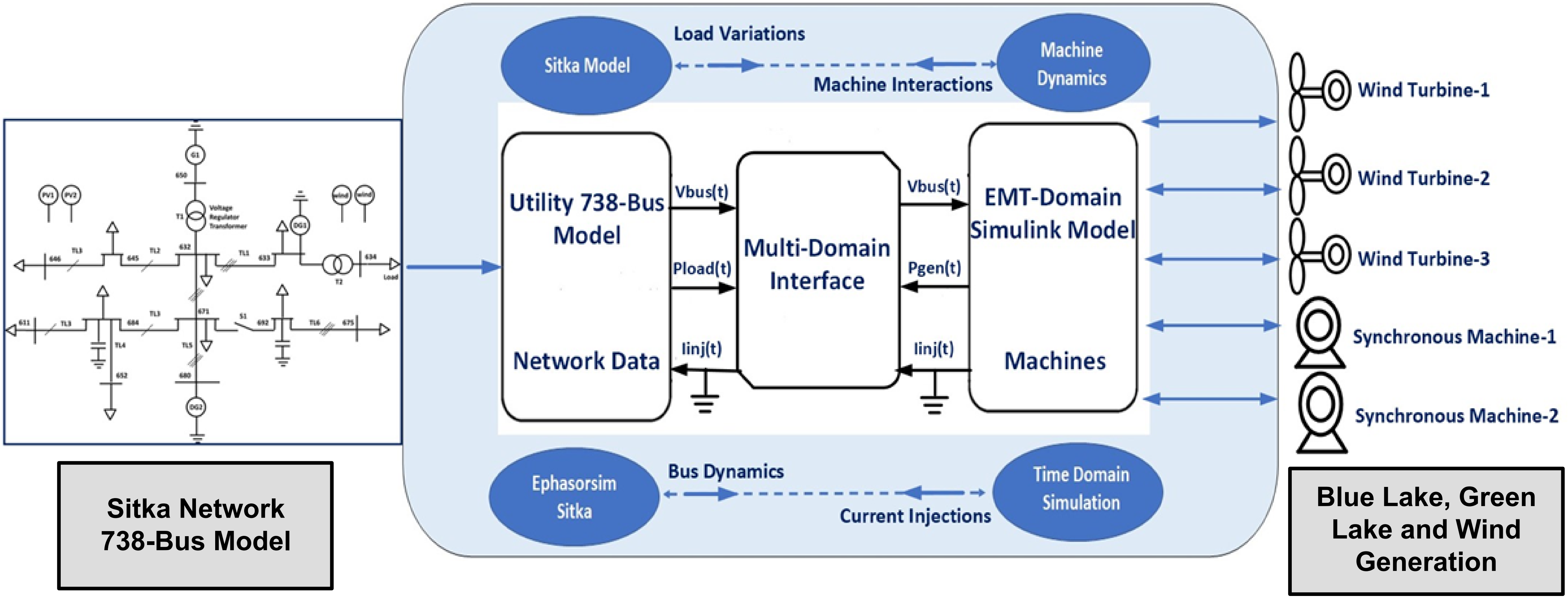


Step-down transformer (69/12.47 kV) is considered at T1-H and wind generation is considered at 12.47 kV

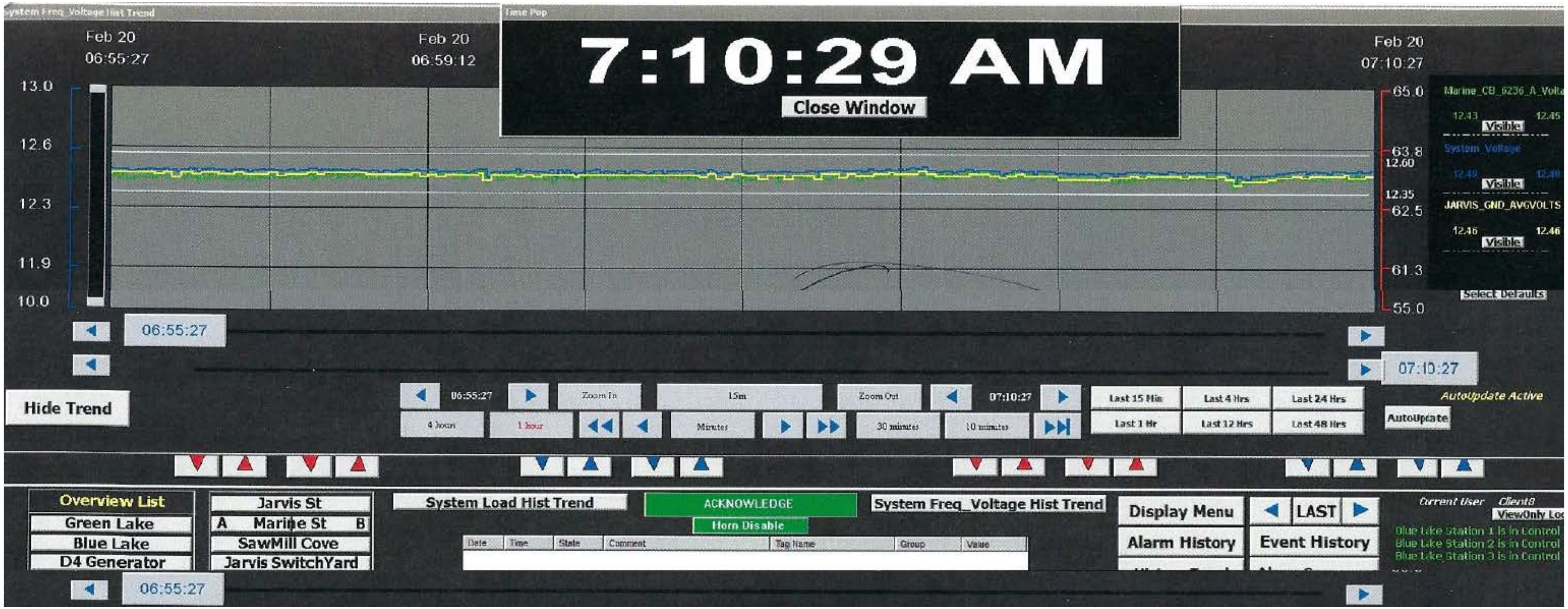
Sitka Grid Model Performance – Base Case Load Flow



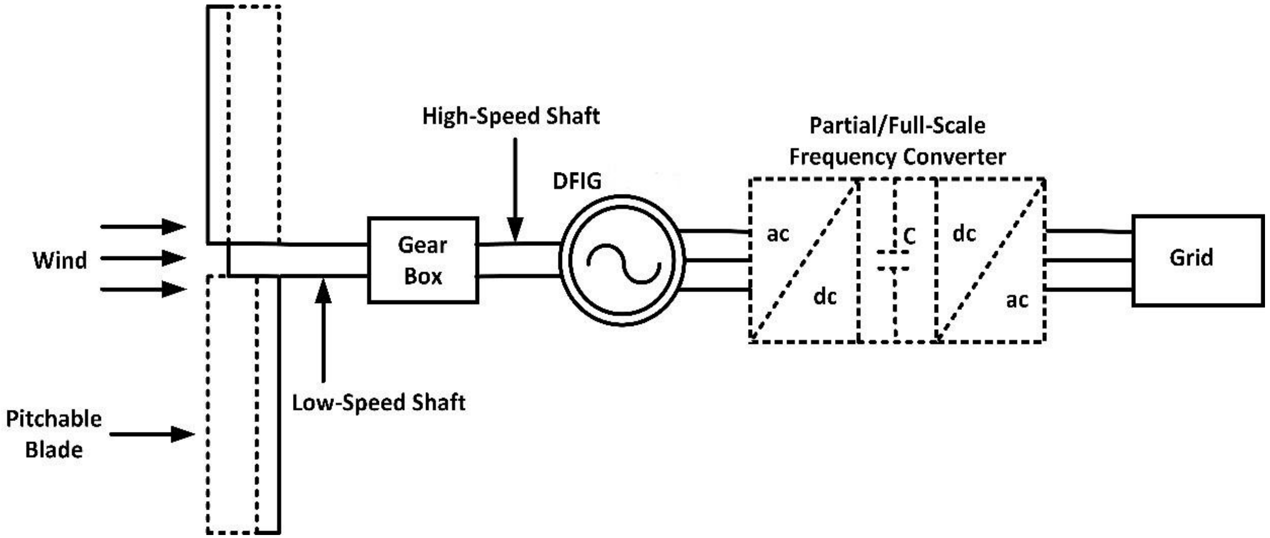
Sitka Utility Microgrid Analysis – OPAL-RT Multi-Rate Modeling for Grid Control Analysis

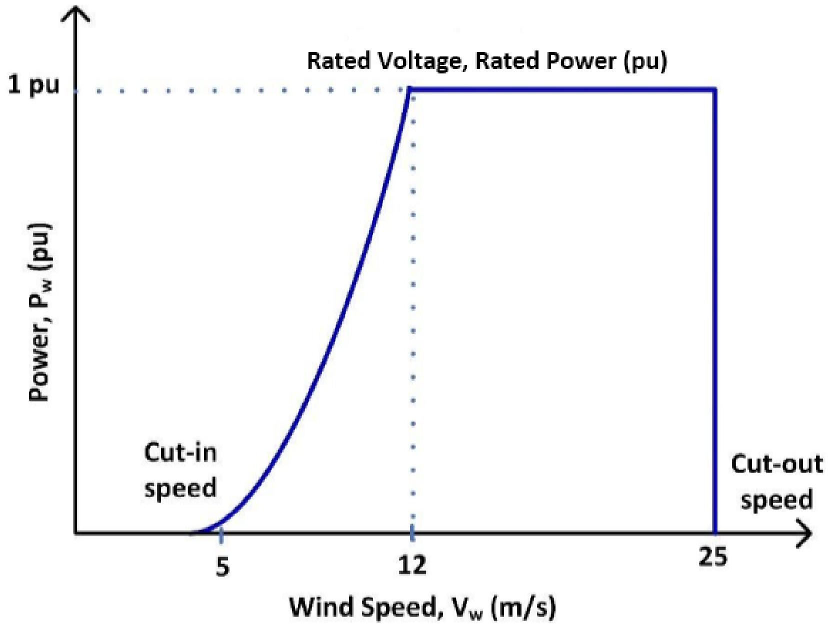


Sitka Utility Microgrid Performance Validation

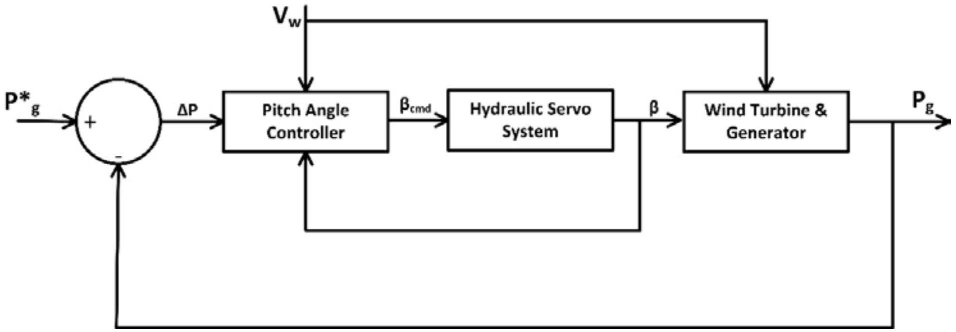


Wind Generation Model

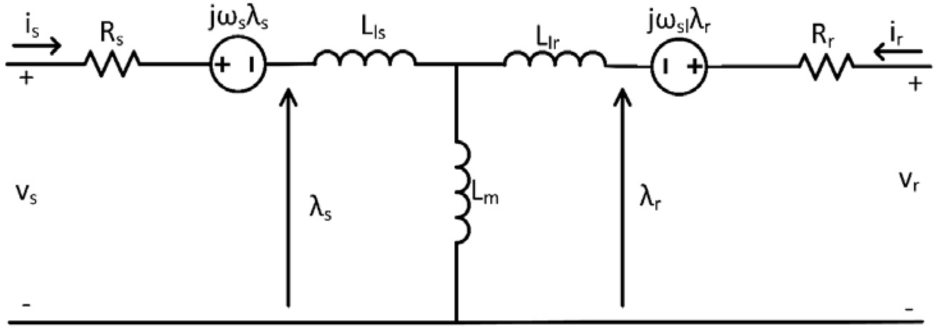




Wind Generator Model



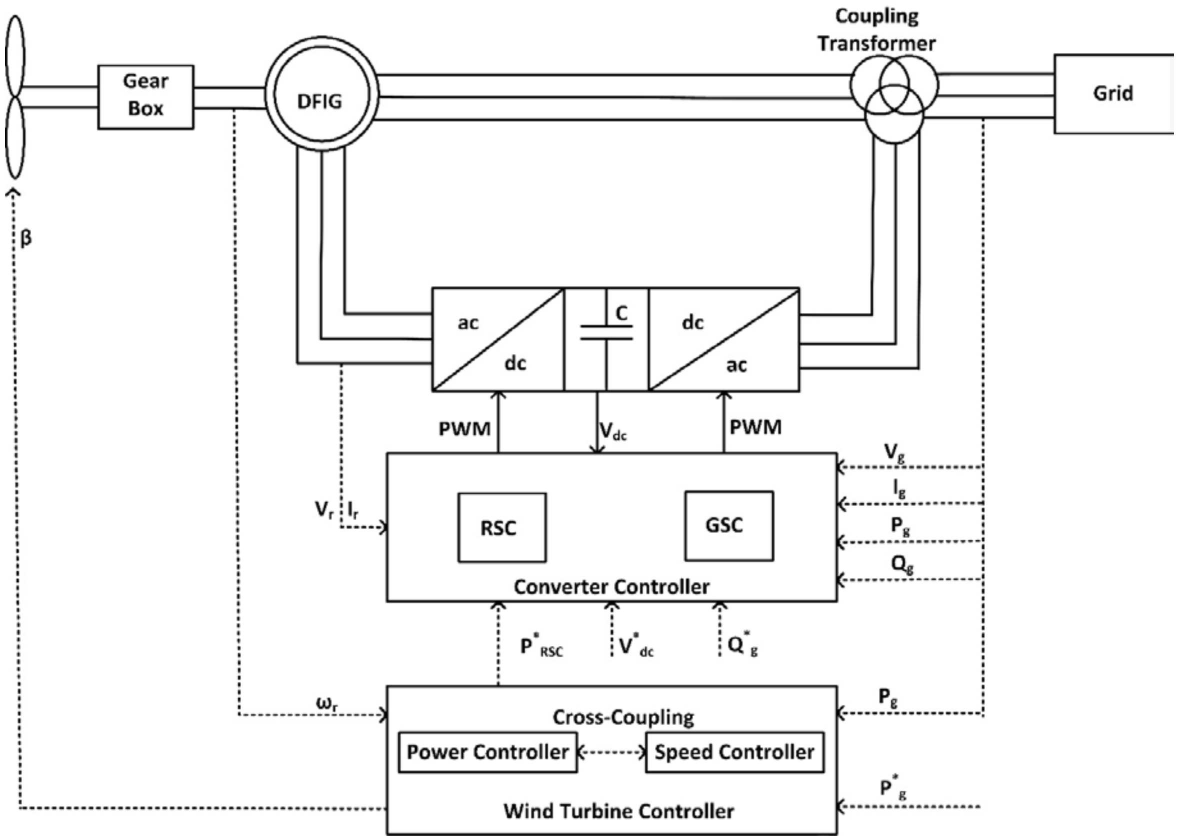
Pitch Control: Wind turbine has a pitchable blade to regulate the aerodynamic power extracted from wind and is connected to the generator through a low-speed shaft, a high-speed shaft and a mechanical gear-box.



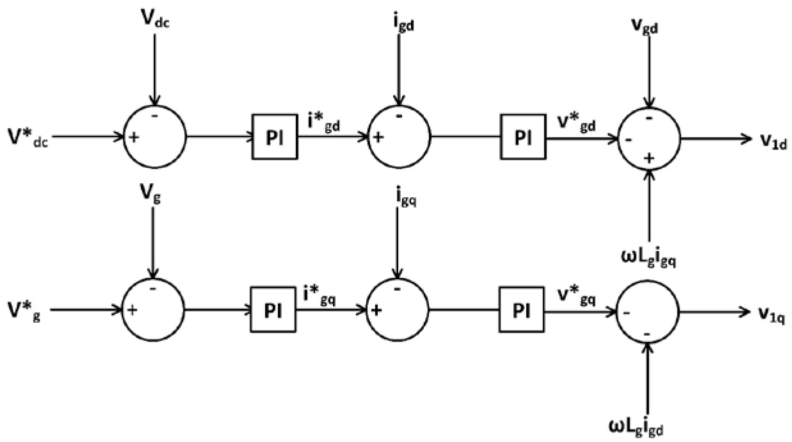
Equivalent Circuit in Synchronous Reference Frame for Controls Design

[P_g: power delivered to the grid from the generator, P^*_g: reference power, β: pitch angle, β_{cmd}: pitch angle command, V_s and V_r: stator and rotor voltage, respectively, R_s and L_{ls}: stator resistance and inductance, respectively, R_r and L_{lr}: rotor resistance and inductance, respectively, ω_s and ω_{rl}: synchronous speed and angular slip frequency, respectively, ω_r: rotor speed, λ_s and λ_r: stator and rotor flux linkage, respectively, L_m: mutual inductance]

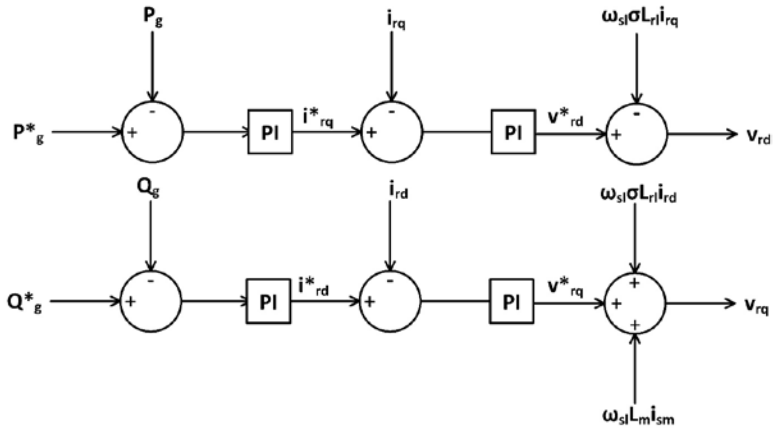
Variable-Speed Doubly-Fed Induction Generator (DFIG) Wind Energy System



DFIG Wind Energy System with Turbine Controller, Rotor Side Converter (RSC), and Grid Side Converter (GSC) Controllers [1], [2]



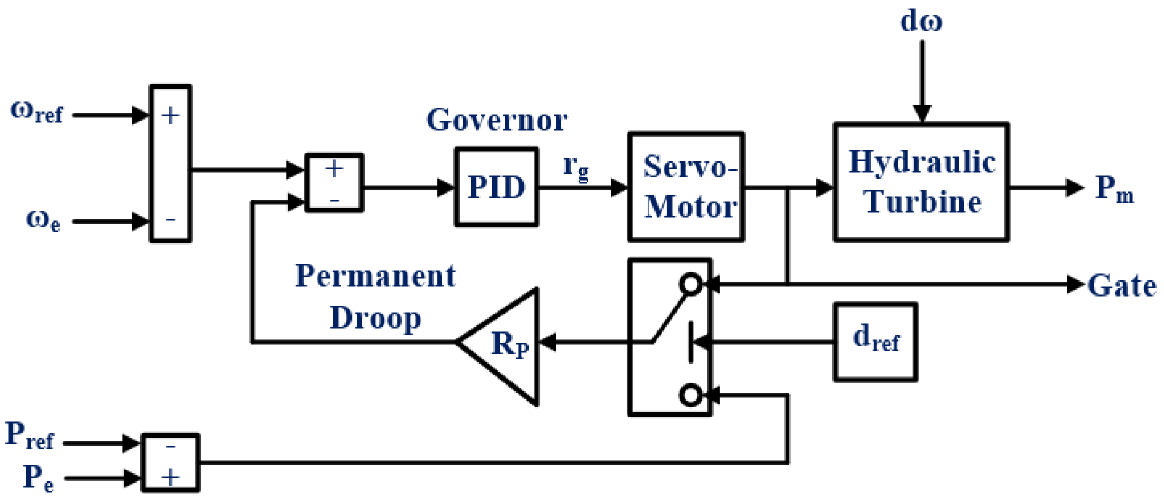
Block Diagram of GSC Controller



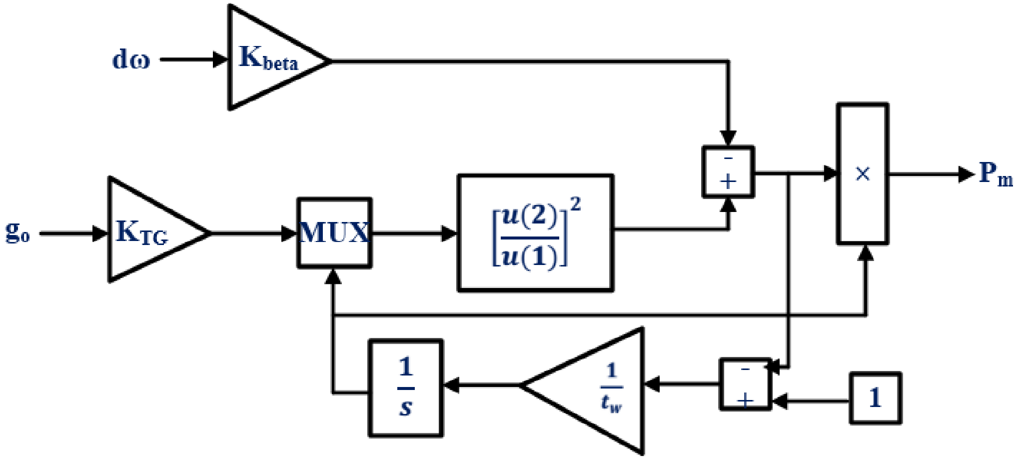
Block Diagram of RSC Controller

[Q_g: reactive power at the grid-side, Q^*_g: reference reactive power, V_{dc}: dc-link voltage, V^*_{dc}: reference dc-link voltage, V_{gd} and V_{gq}: dq components of grid-side voltage, respectively, i_{gd} and i_{gq}: dq components of grid-side current, respectively, L_g: grid-side filter inductance, V_{rd} and V_{rq}: dq components of rotor-side voltage, respectively, I_{rd} and i_{rq}: dq components of rotor-side current, respectively, σ: inductance ratio]

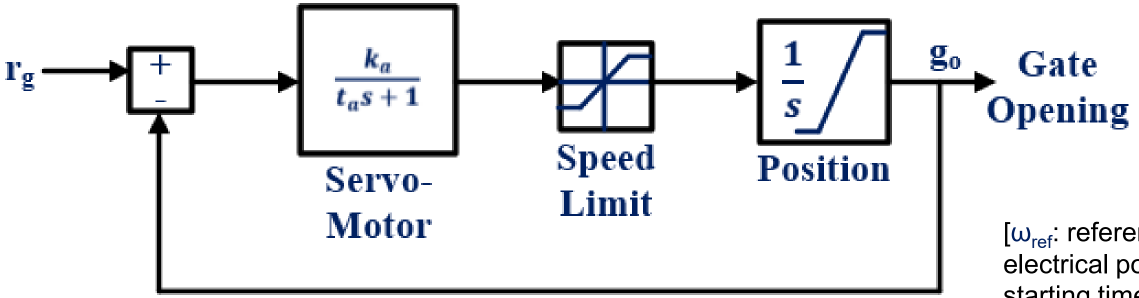
Hydraulic-Turbine-Governor (HTG) Model for Synchronous Generator



Non-Linear Hydraulic Turbine + PID Governor Model + Servo-Motor



Non-Linear Hydraulic Turbine Model



Second-Order Gate Model [3]

Synchronous Machine Model
Nominal Active Power: 7.8 MW
Terminal Voltage Control: Field Excitation System
Electrical Torque & Power Controls: HTG Model

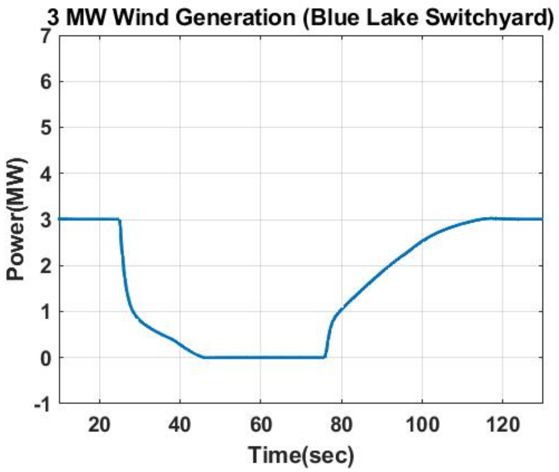
[ω_{ref}: reference speed (pu), P_{ref}: reference mechanical power (pu), ω_e: actual speed (pu), dω: speed deviation (pu), P_e: actual electrical power (pu), P_m: mechanical power for the machine block (pu), K_a: servo-motor gain, t_a: time constant in s, t_w: water starting time, R_P: permanent droop gain, K_{beta}: speed deviation damping coefficient, K_{TG}: turbine governor gain]

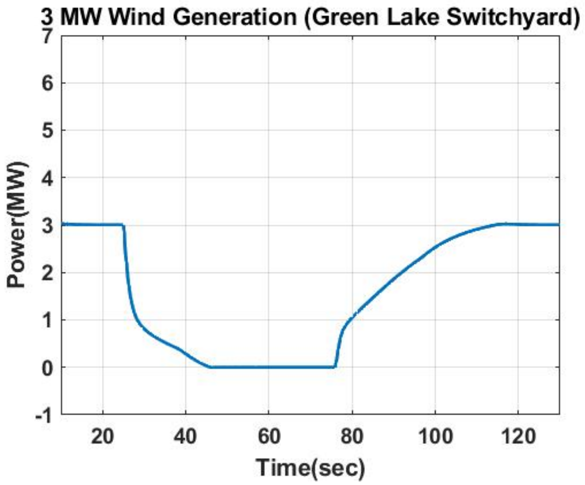
[1] J. Lee, E. Muljadi, P. Srensen and Y. C. Kang, "Releasable Kinetic Energy-Based Inertial Control of a DFIG Wind Power Plant," in *IEEE Transactions on Sustainable Energy*, vol. 7, no. 1, pp. 279-288, Jan. 2016, doi: 10.1109/TSTE.2015.2493165.

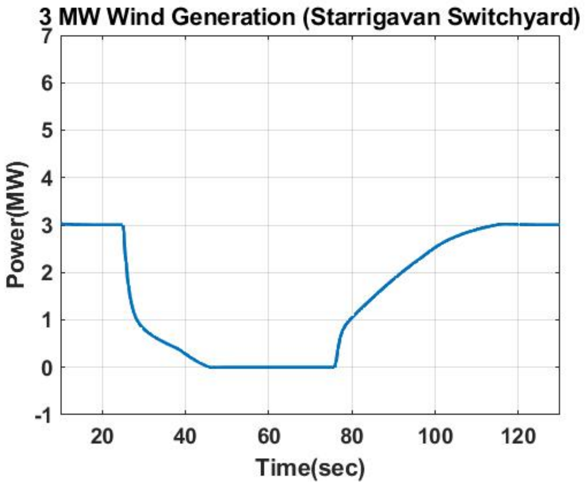
[2] R. Sakamoto, T. Senjyu, N. Urasaki, T. Funabashi, H. Fujita and H. Sekine, "Output power leveling of wind turbine generators using pitch angle control for all operating regions in wind farm," *Proceedings of the 13th International Conference on, Intelligent Systems Application to Power Systems*, Arlington, VA, 2005, pp. 1-6, doi: 10.1109/ISAP.2005.1599291.

[3] IEEE Working Group on Prime Mover and Energy Supply Models for System Dynamic Performance Studies, “Hydraulic Turbine and Turbine Control Models for Dynamic Studies,” *IEEE® Transactions on Power Systems*, Vol. 7, No. 1, February, 1992, pp. 167-179.

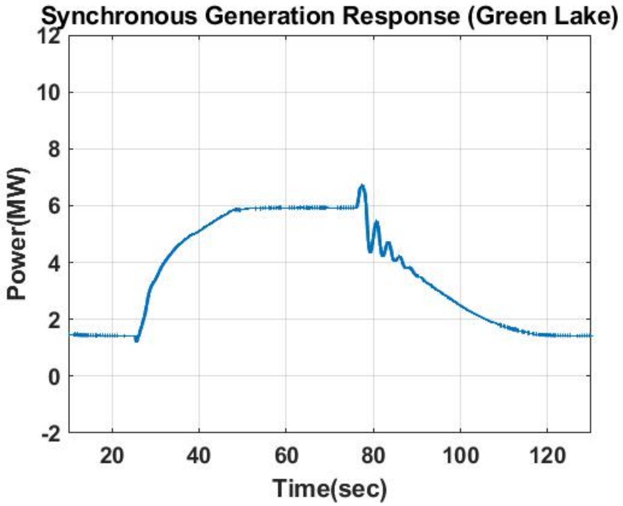
Step Change in 3+3+3 MW Wind Generation in Blue Lake, Green Lake and Starrigavan

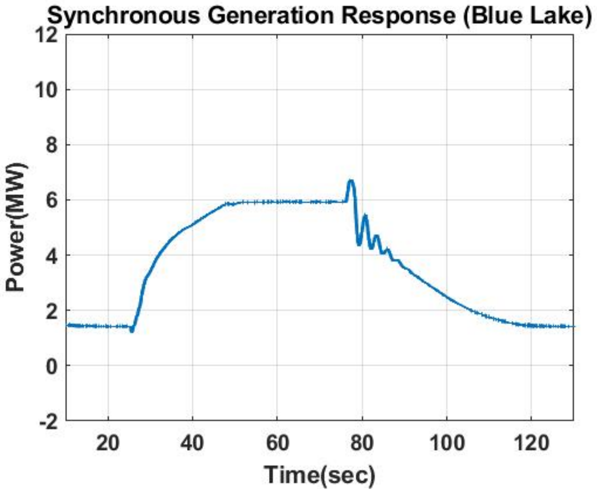




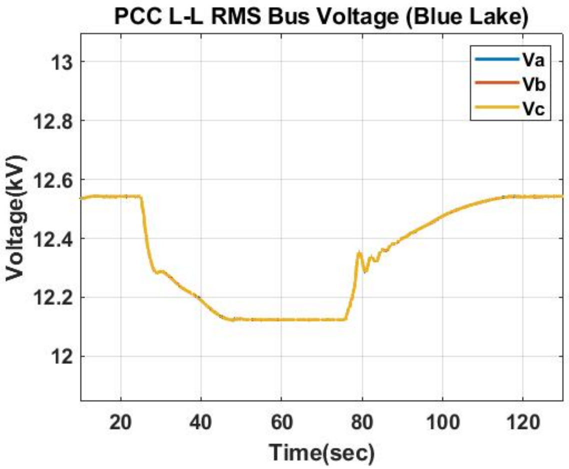


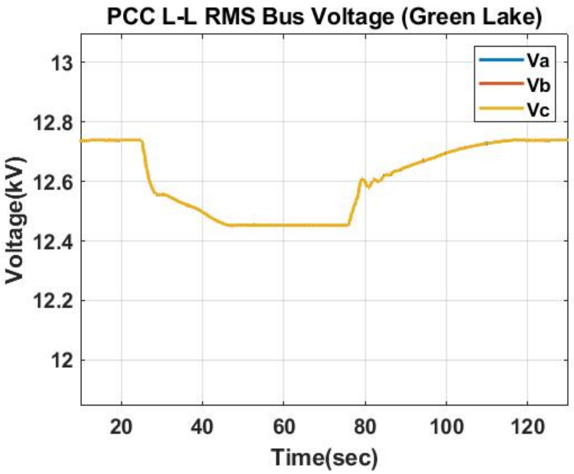
Total load is 11.85 MW.

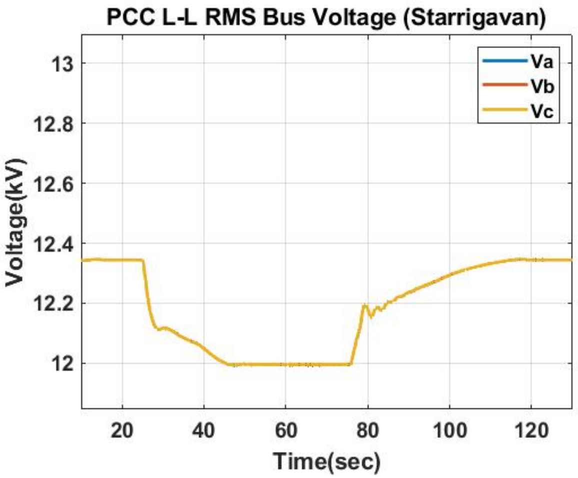




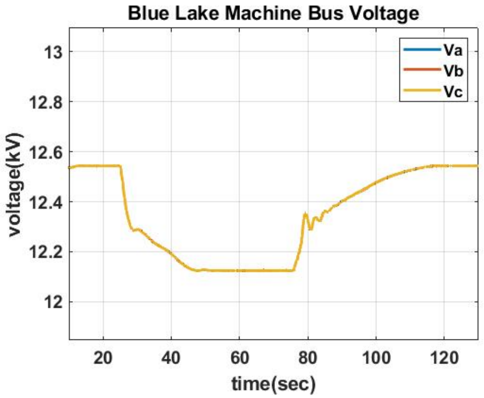
Step Change in 3+3+3 MW Wind Generation in Blue Lake, Green Lake and Starrigavan

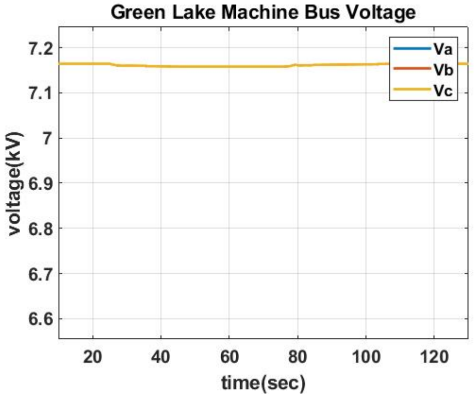


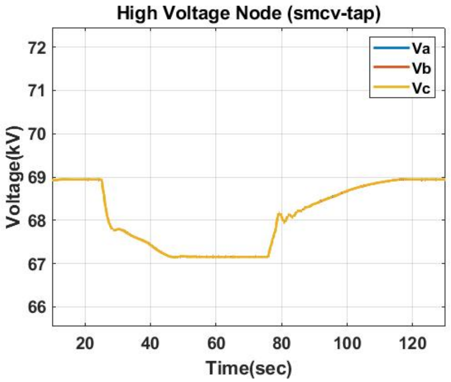


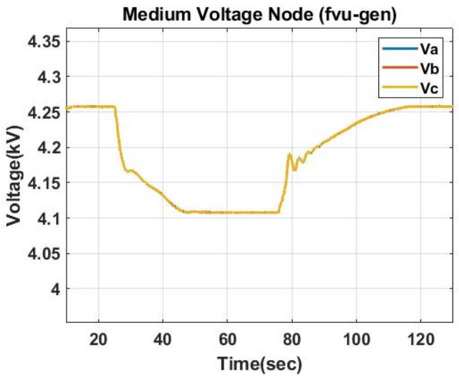


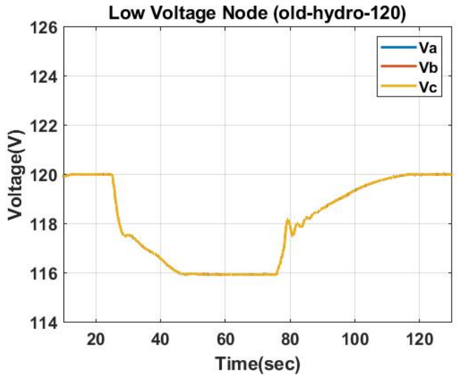
Wind Generation Buses





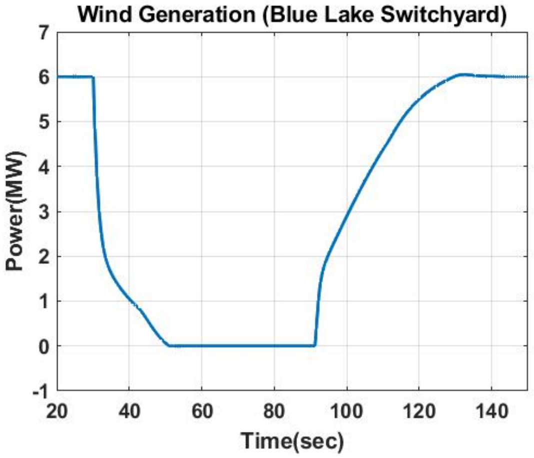


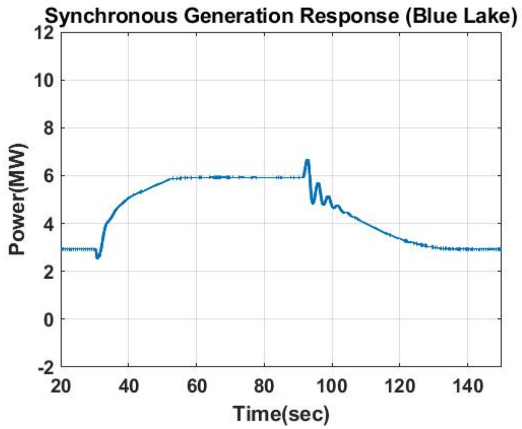


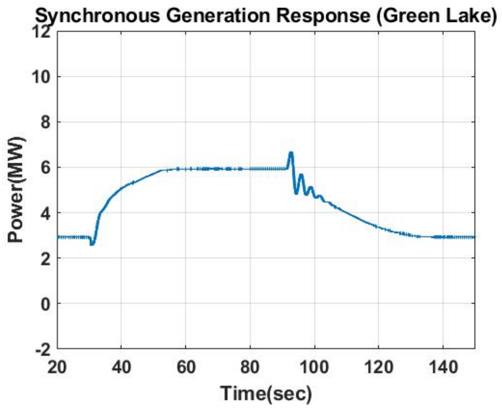


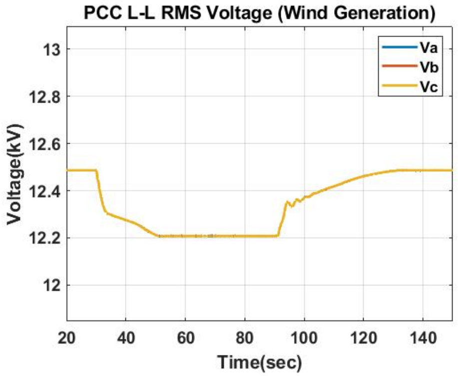
Step Change in 6 MW Wind Generation (Blue Lake)

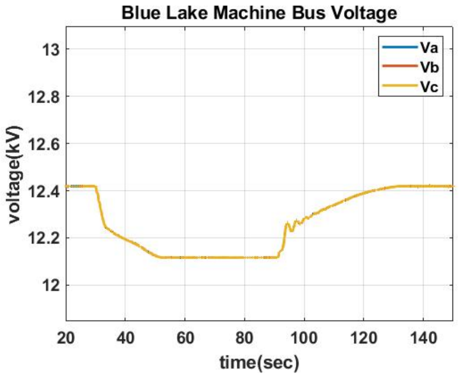
Total load is 11.85 MW.

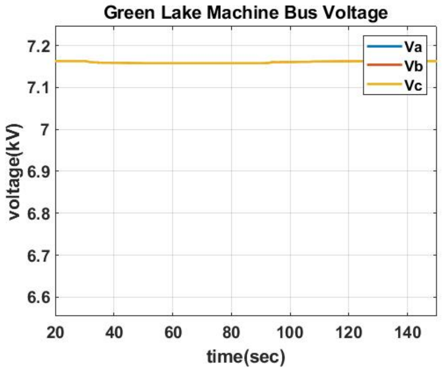


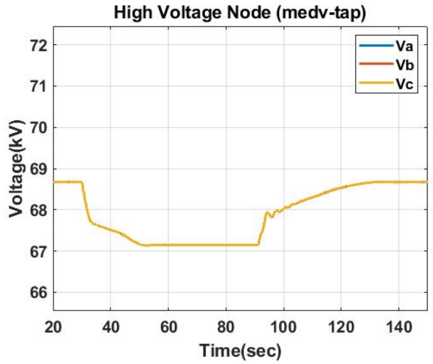


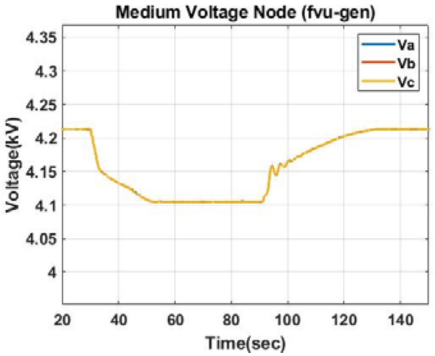


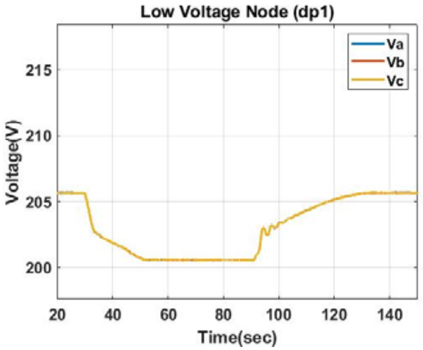






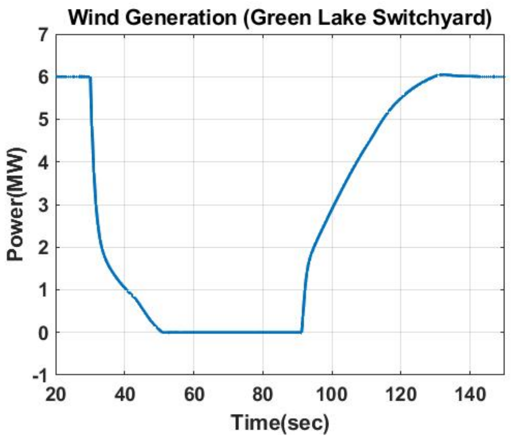


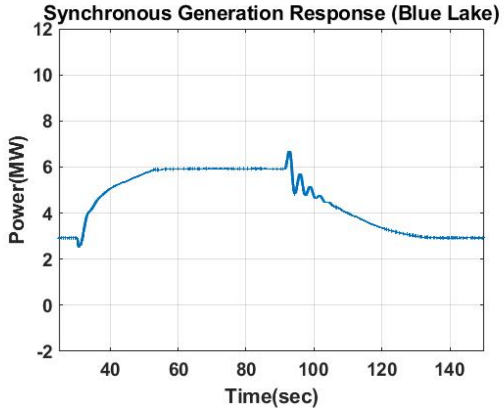


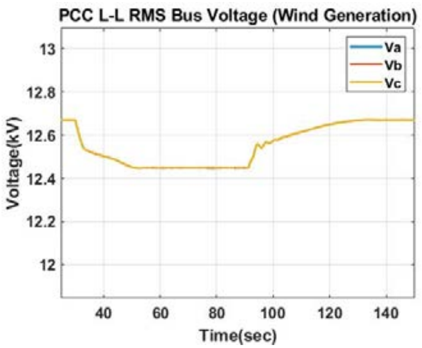


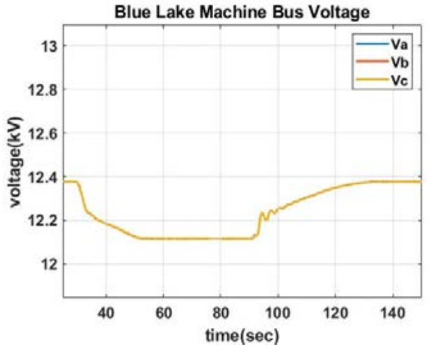
Step Change in 6 MW Wind Generation (Green Lake)

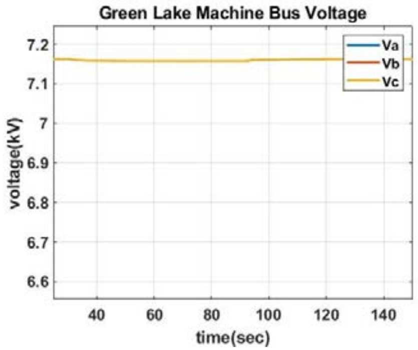
Total load is 11.85 MW.

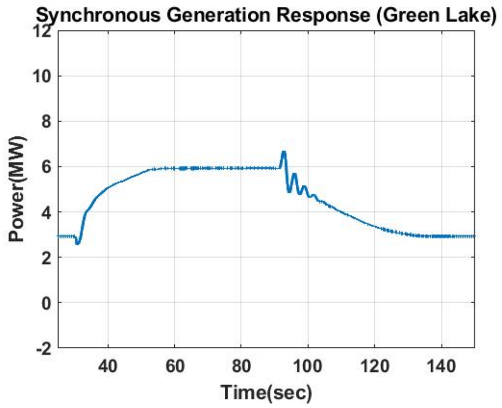


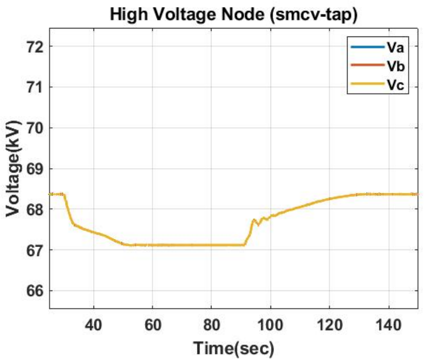


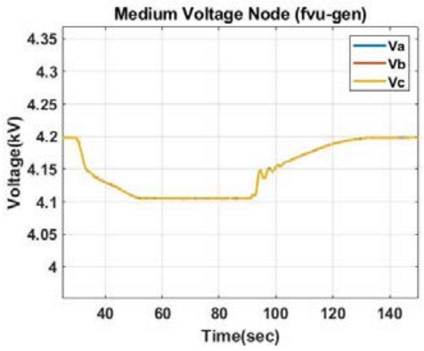


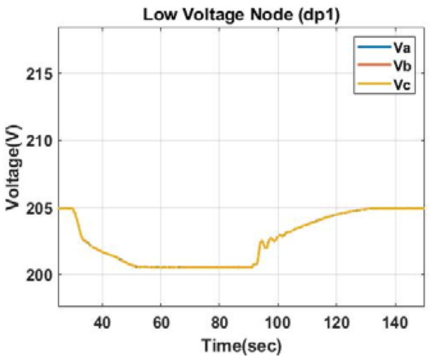




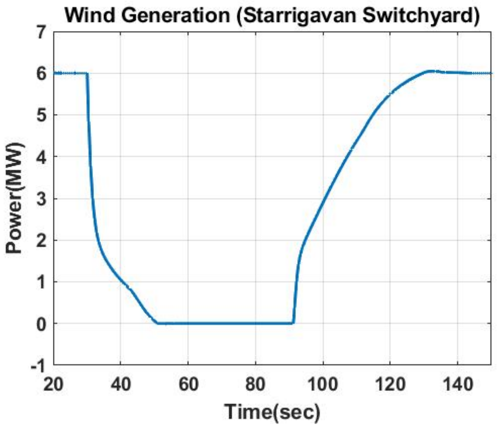


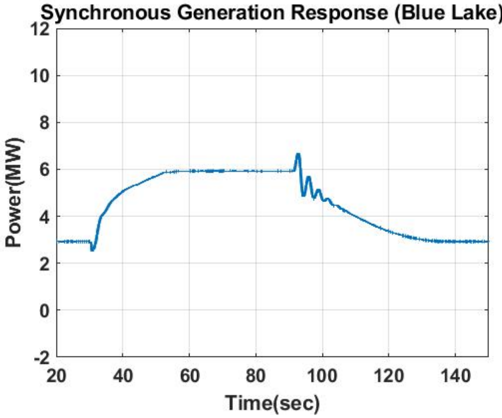


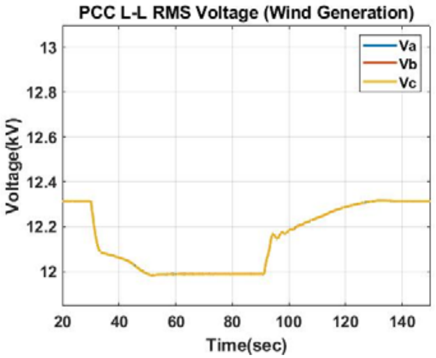


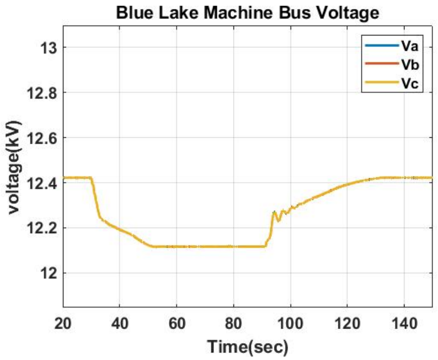


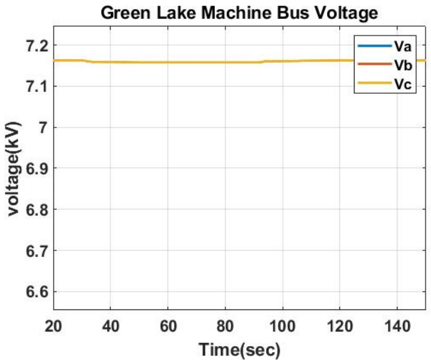
Step Change in 6 MW Wind Generation (Starrigavan)

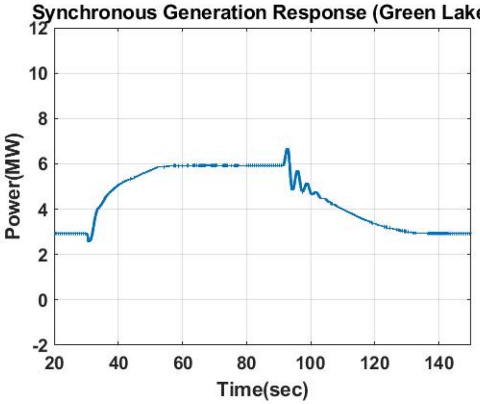


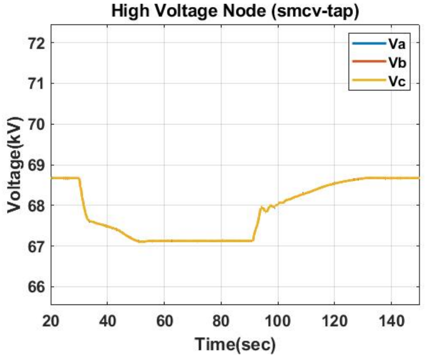


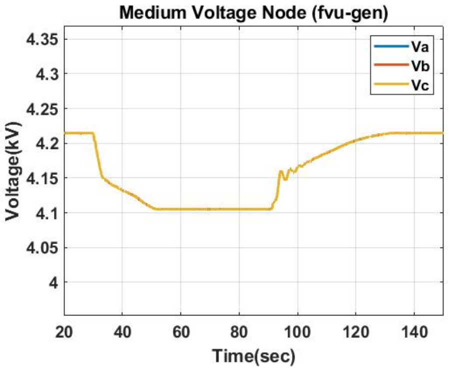


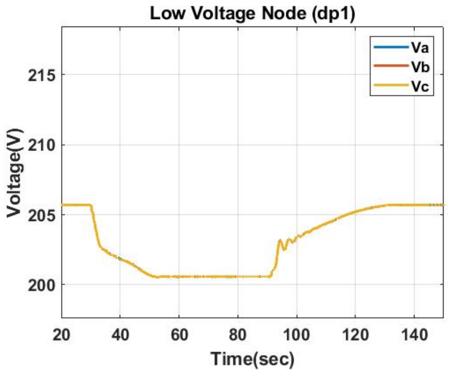




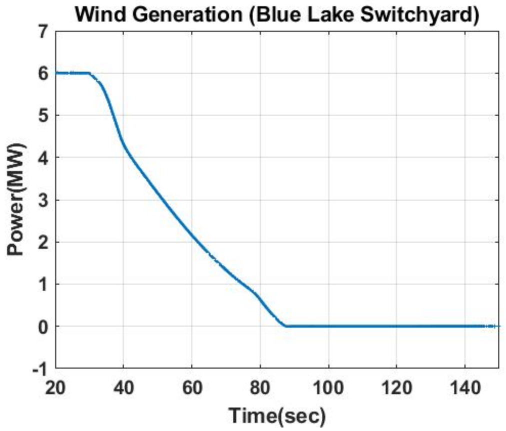


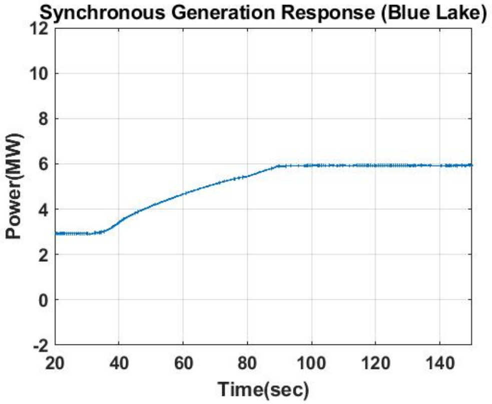


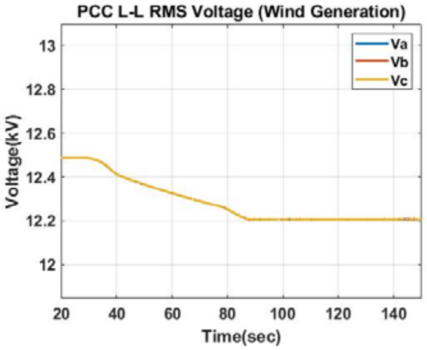


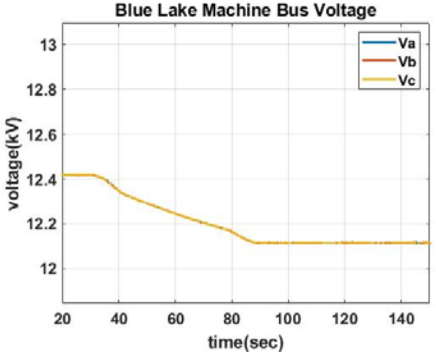


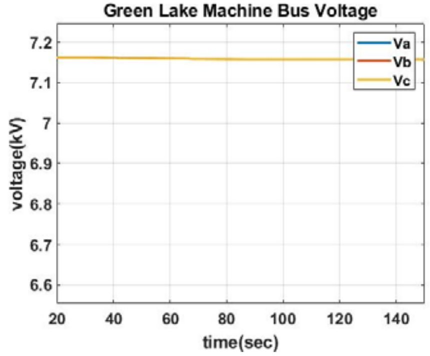
Ramp Down in 6 MW Wind Generation (Blue Lake)

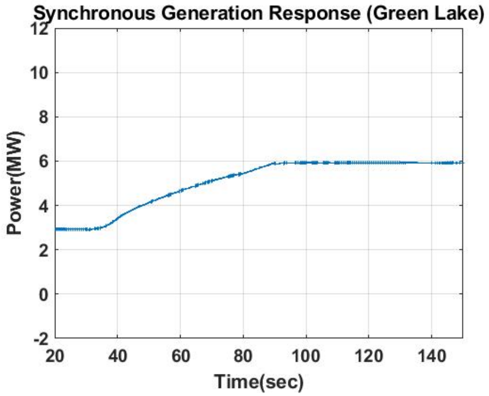


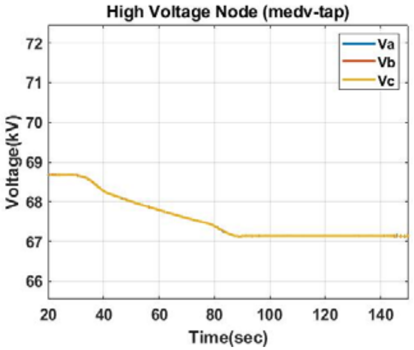


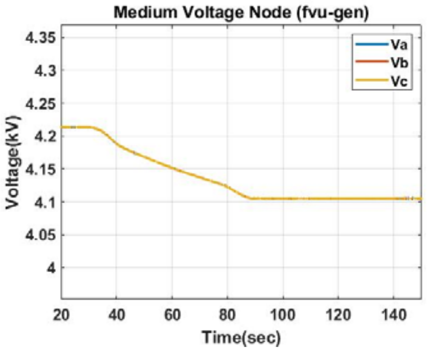


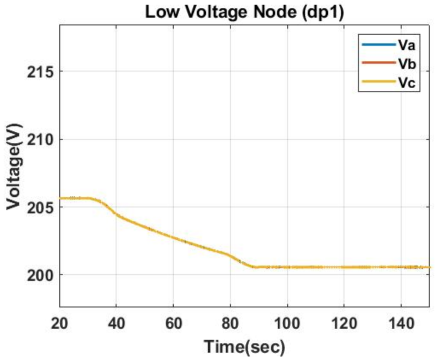




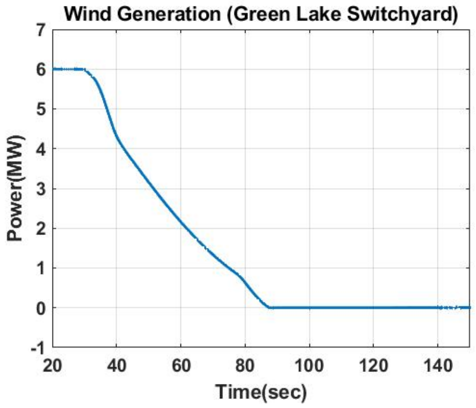


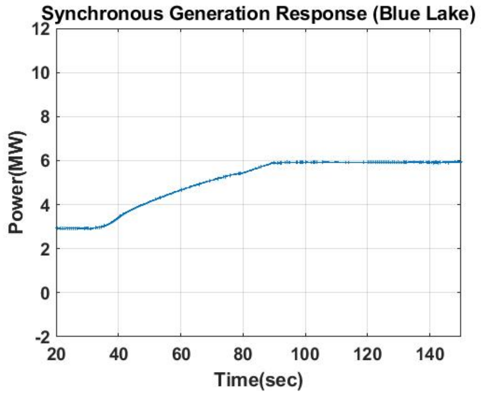


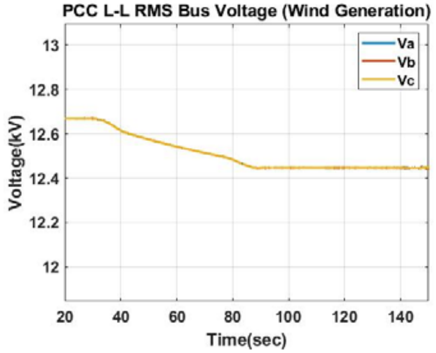


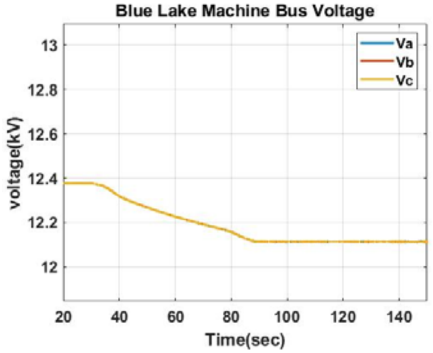


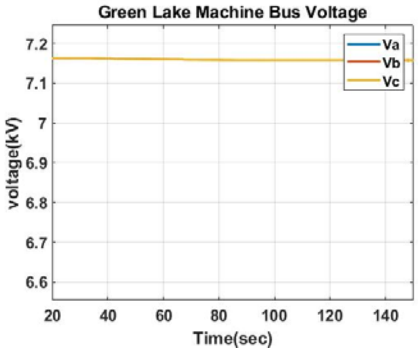
Ramp Down in 6 MW Wind Generation (Green Lake)

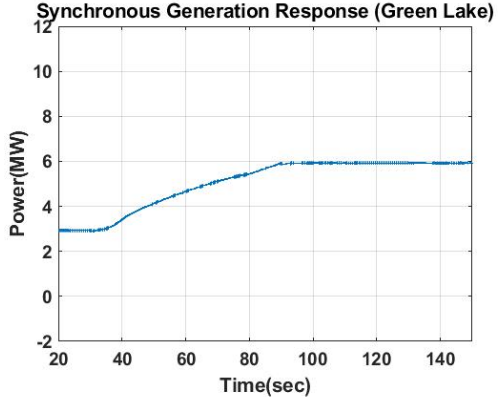


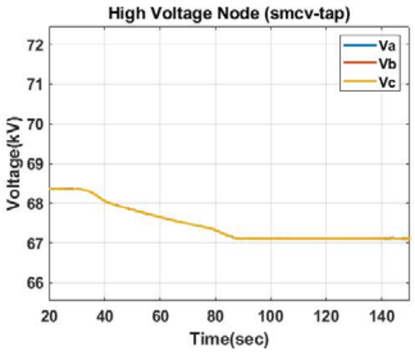


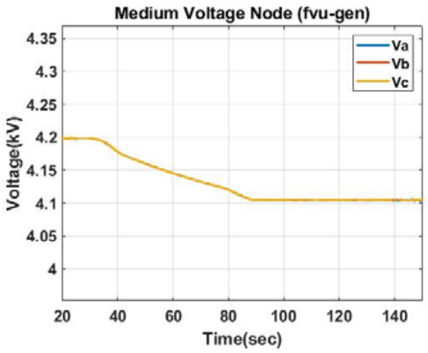


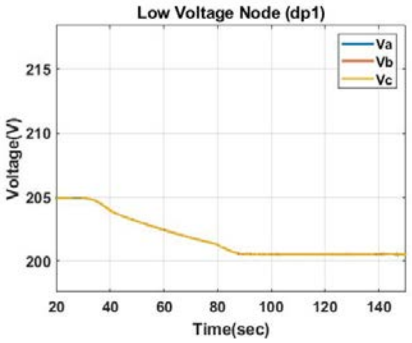




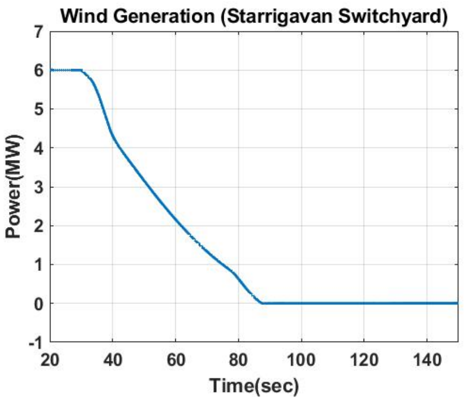


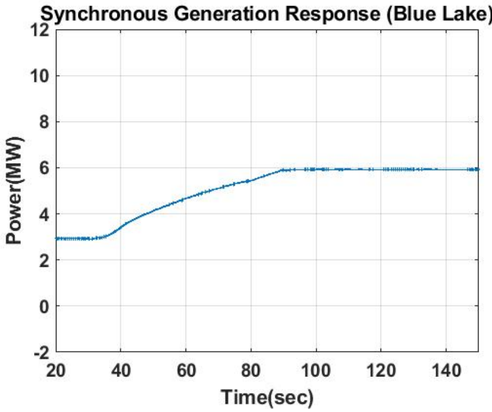


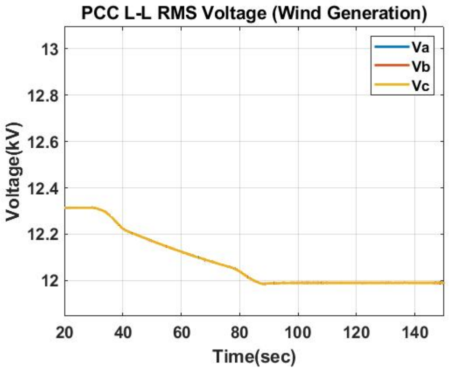


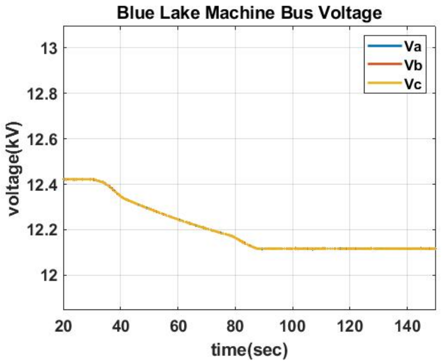


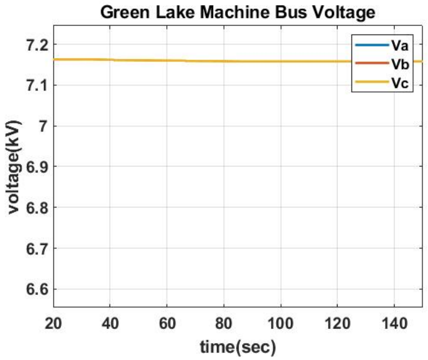
Ramp Down in 6 MW Wind Generation (Starrigavan)

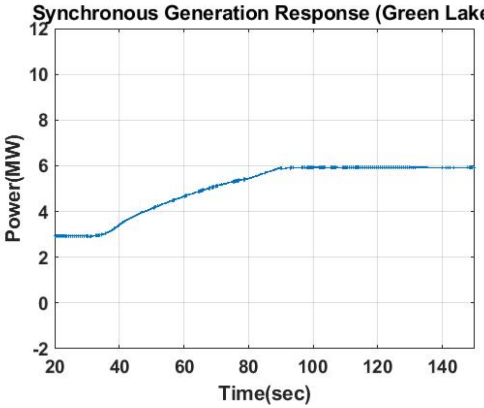


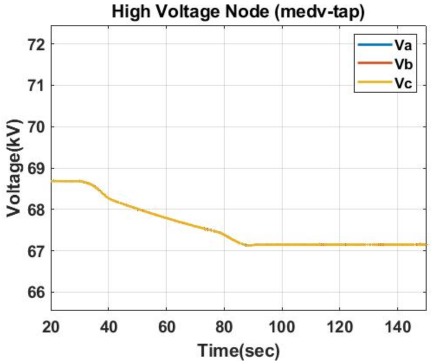


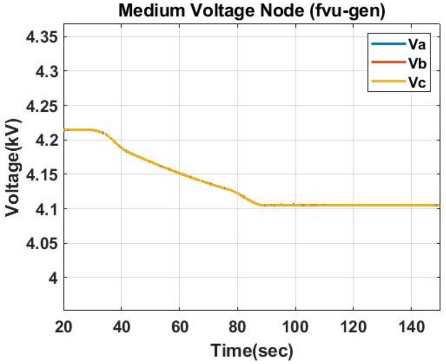


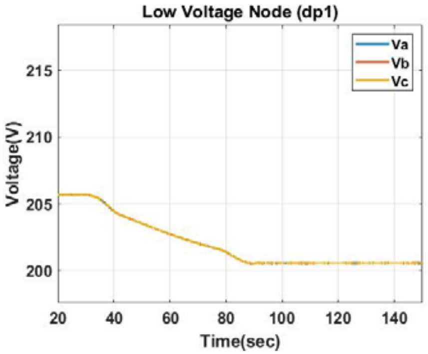




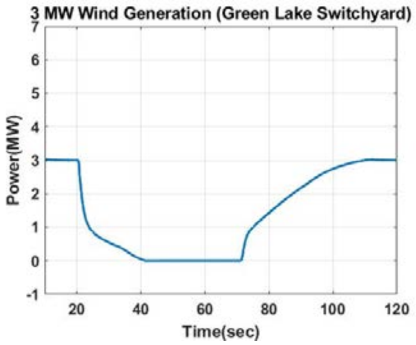


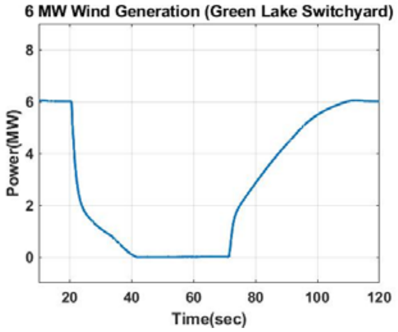


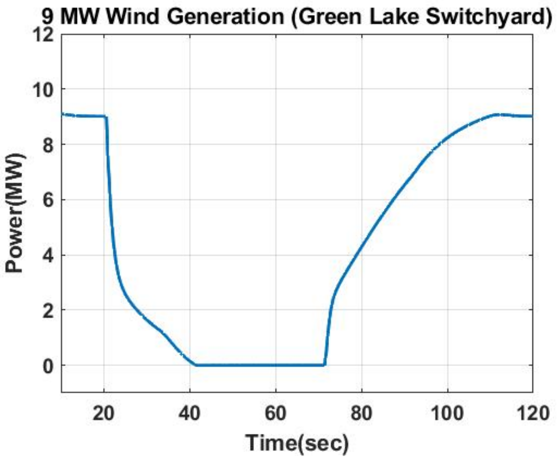


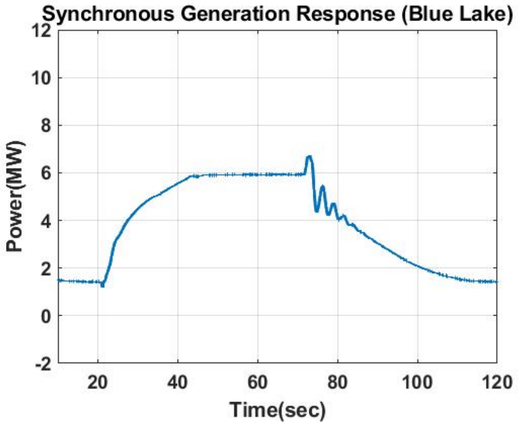


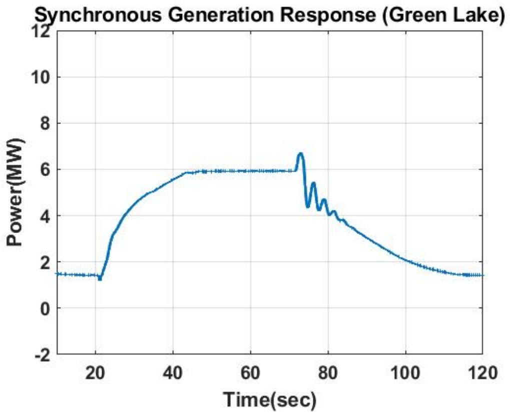
Step Change in 9 MW Wind Generation (Green Lake)

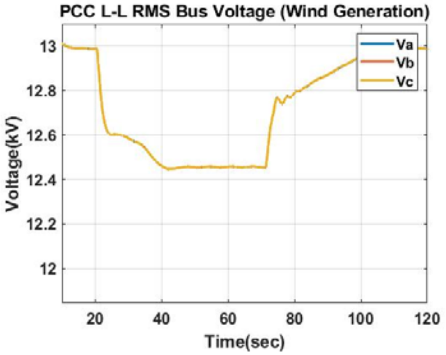


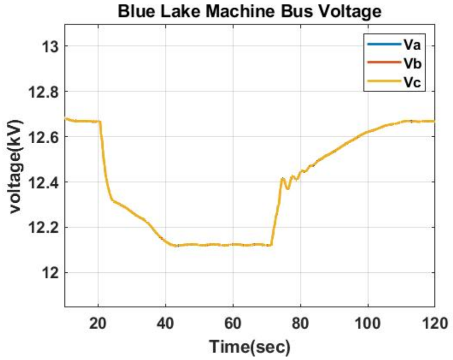


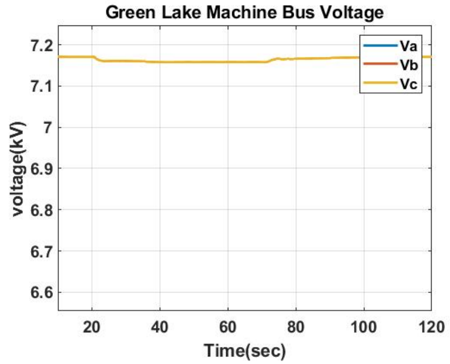


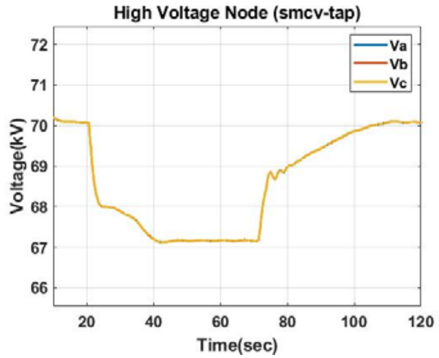


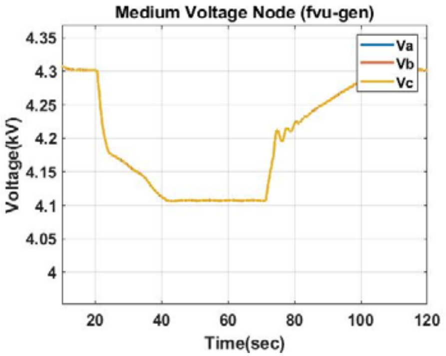


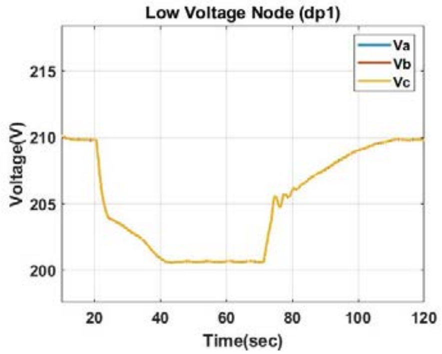






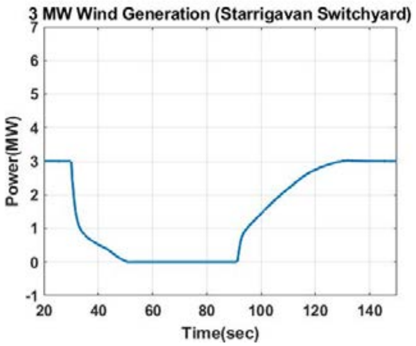


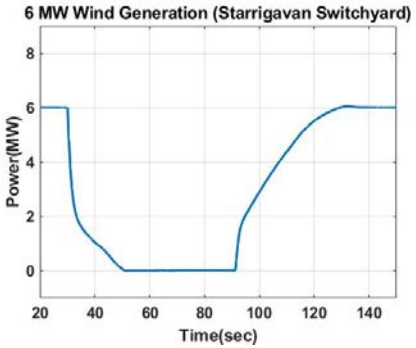


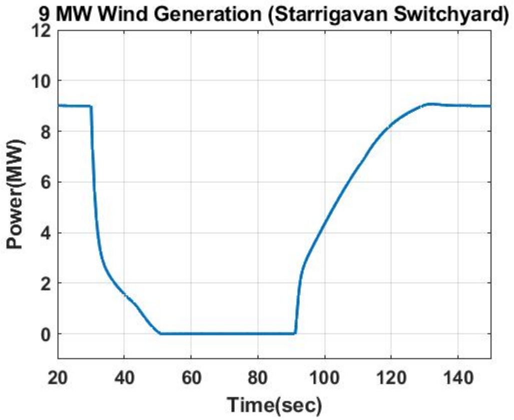


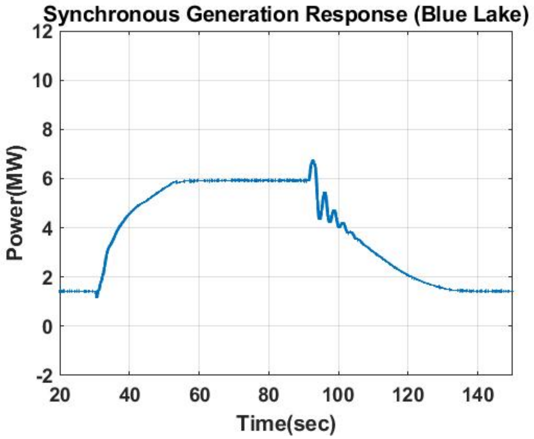
Step Change in 9 MW Wind Generation (Starrigavan)

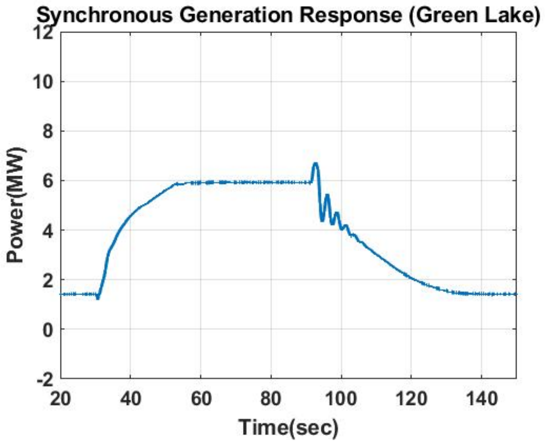
Total Load is 11.85 MW

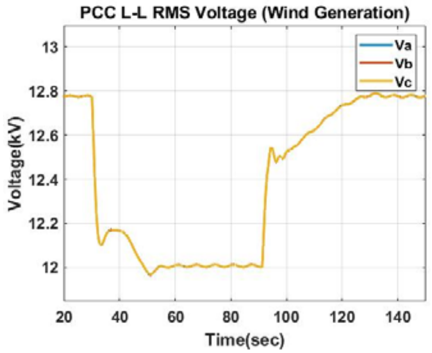


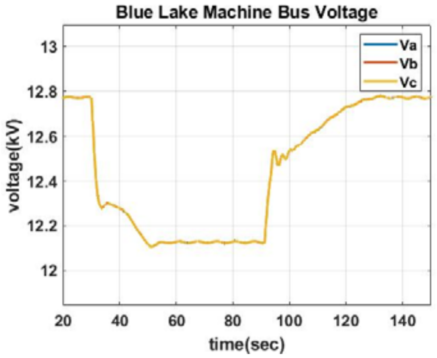


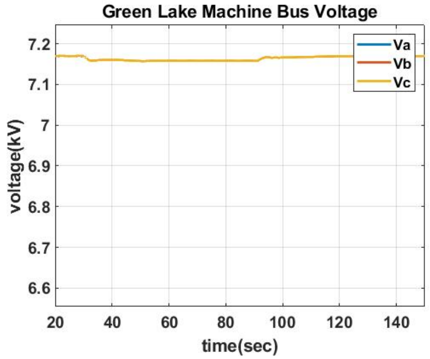


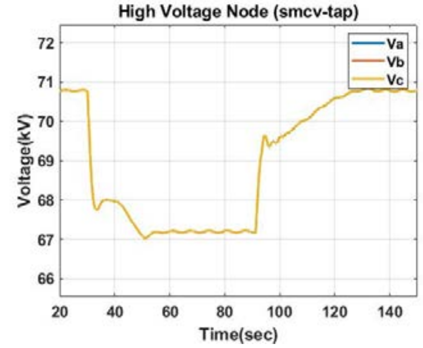


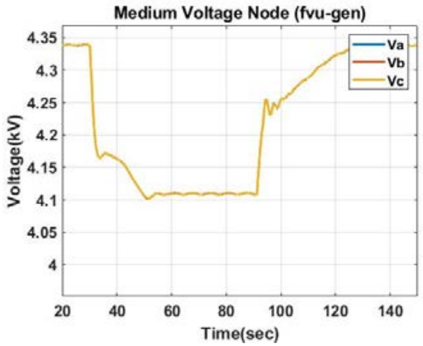


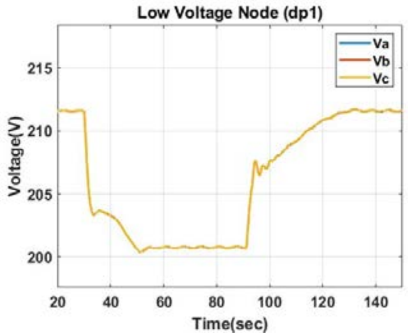






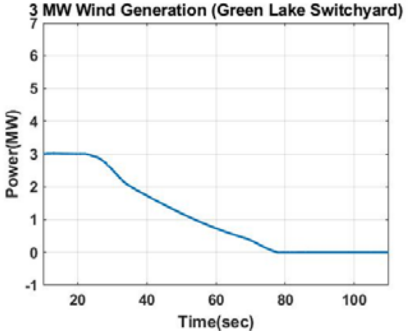


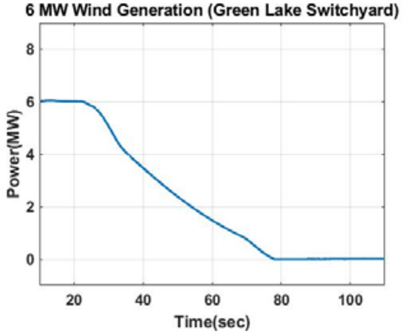


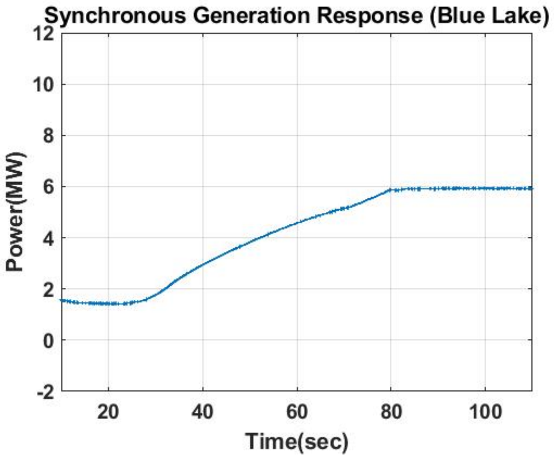


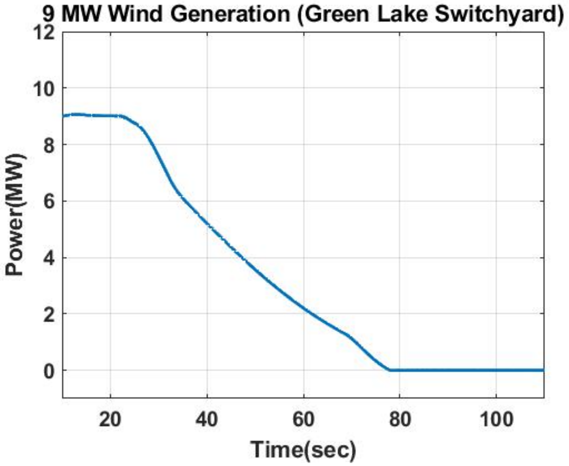
Ramp Down in 9 MW Wind Generation (Green Lake)

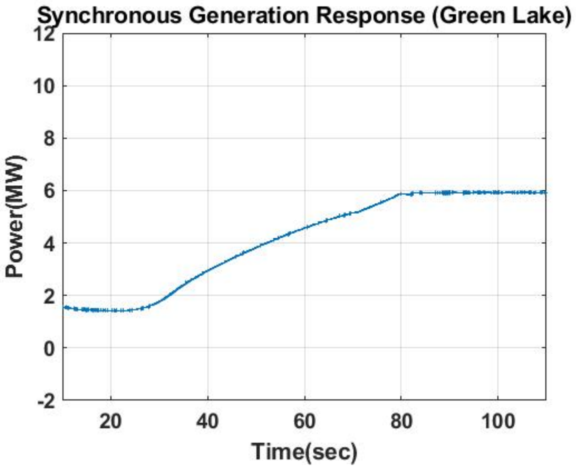
Total Load is 11.85 MW

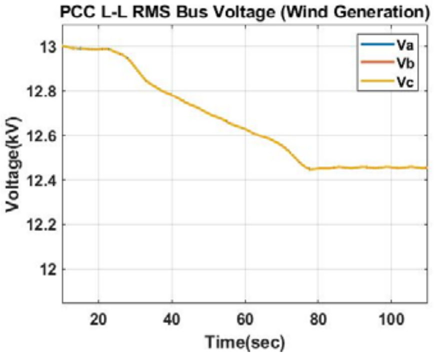


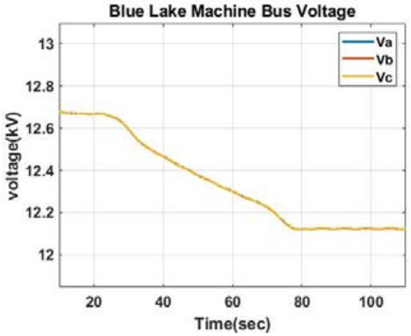


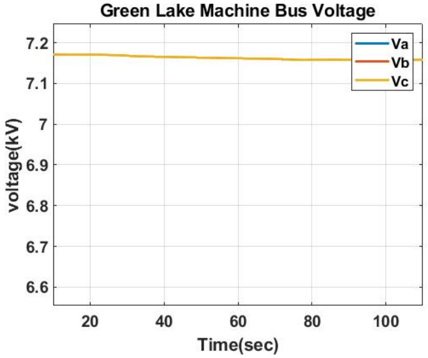


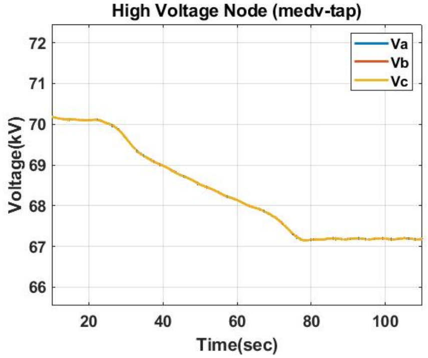


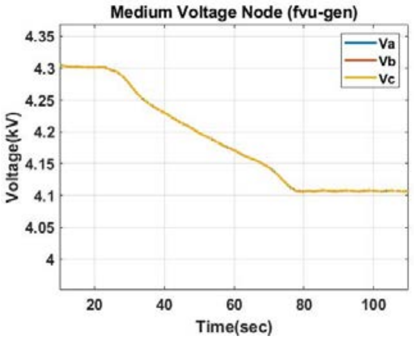


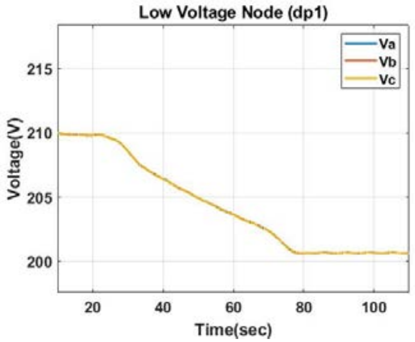






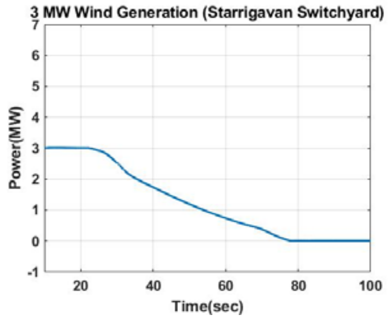


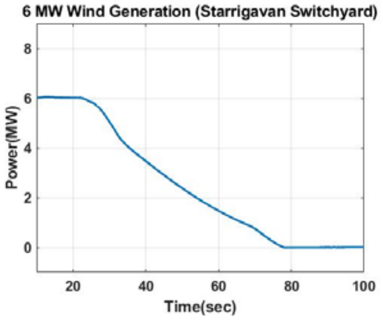


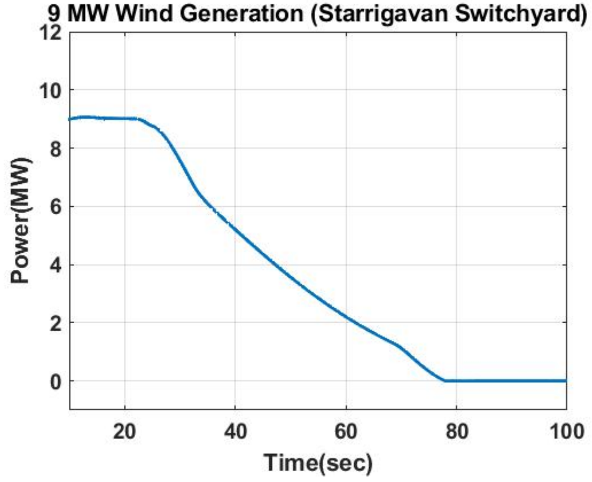


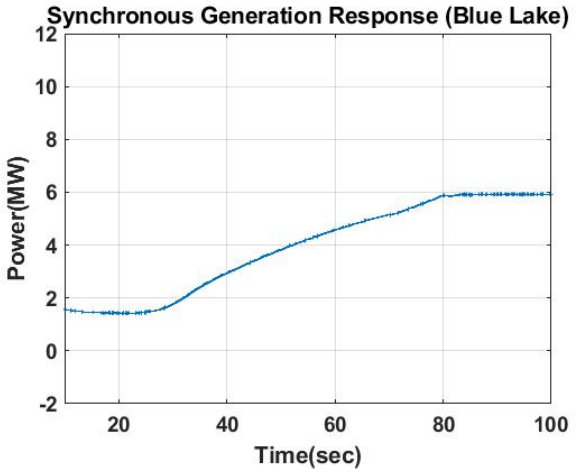
Ramp Down in 9 MW Wind Generation (Starrigavan)

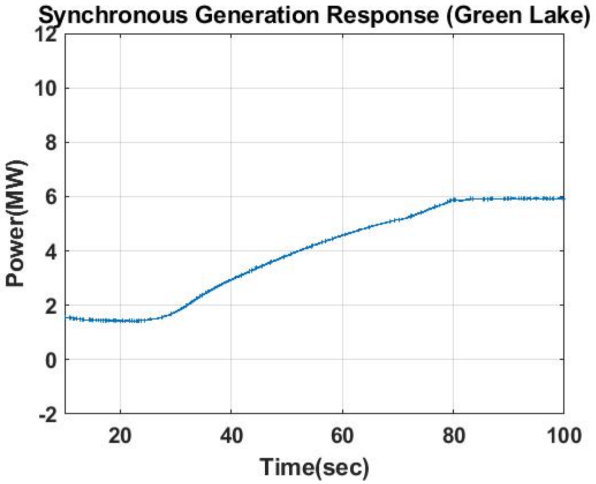
Total Load is 11.85 MW

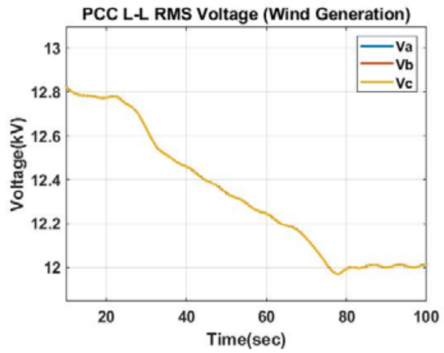


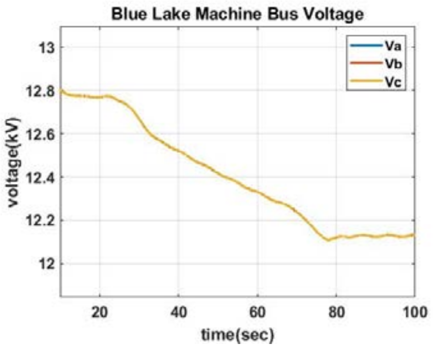


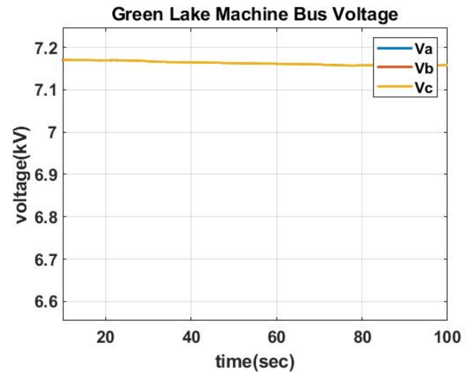


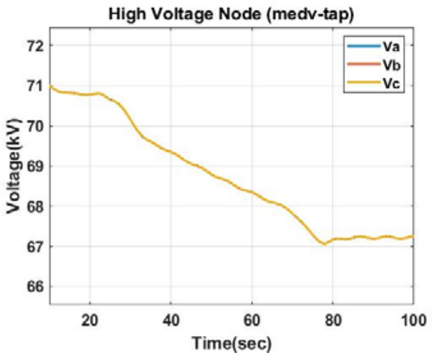


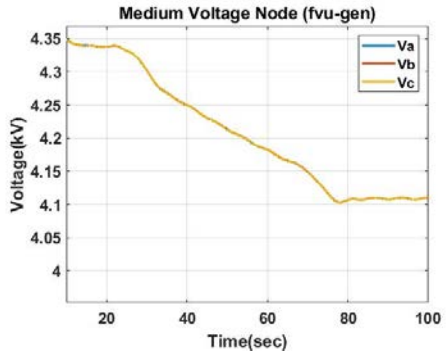


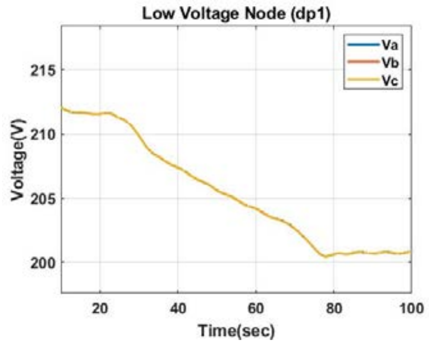






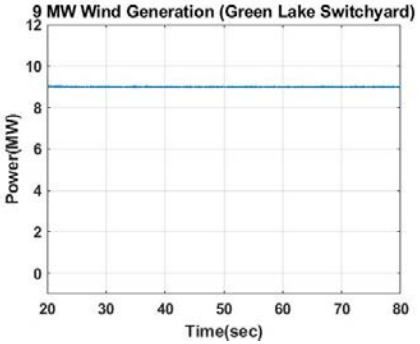


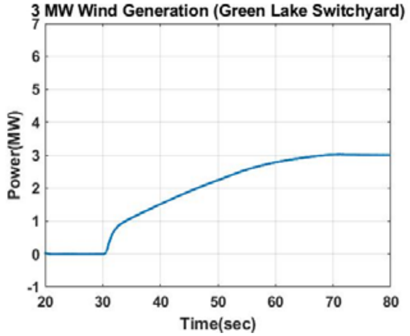


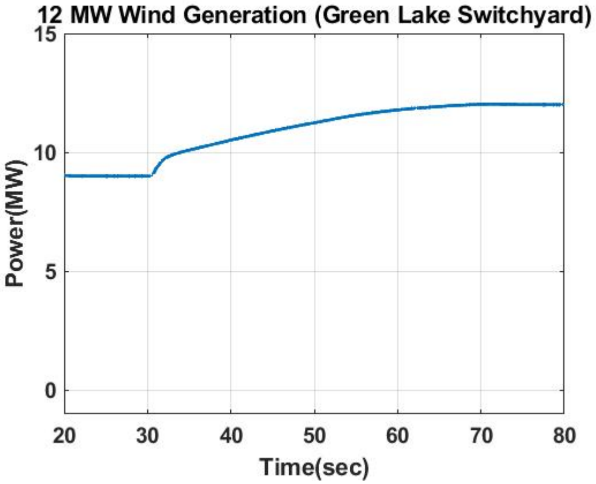


Bus Over-Voltage Tests for 12 MW Wind Turbine Installation (Green Lake)

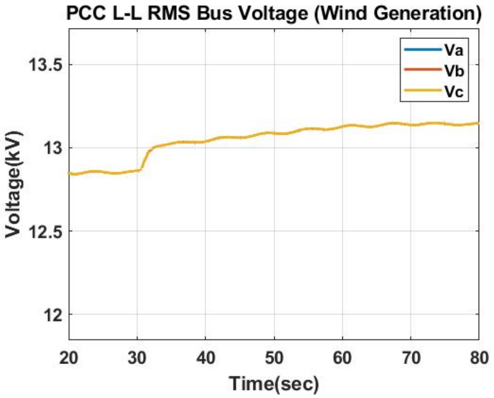
Bus voltage stability limit should be ± 5%



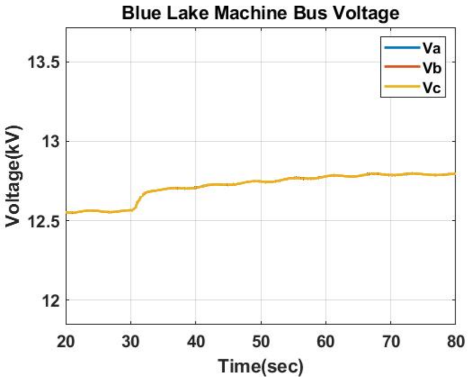


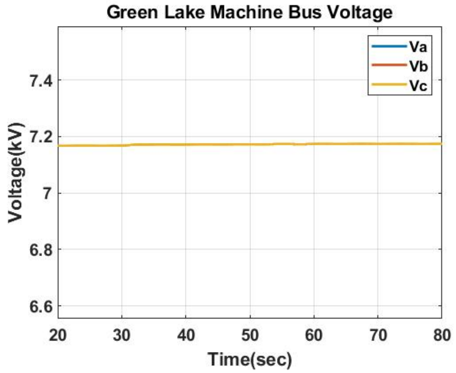


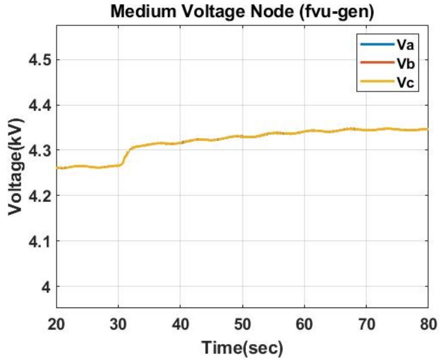
Total Wind Power: Step from 9 MW to 12 MW

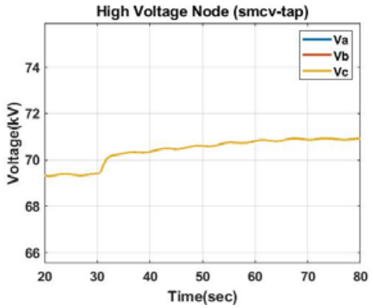


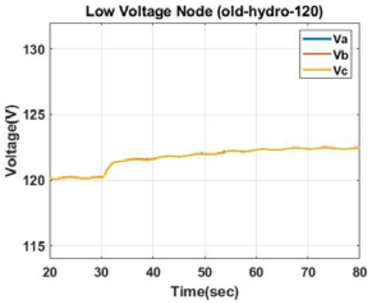
≈1.055 pu

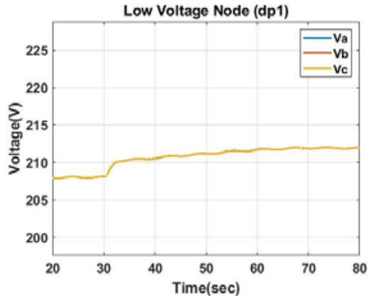






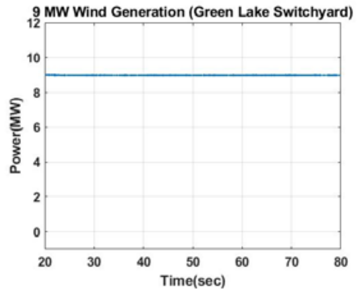


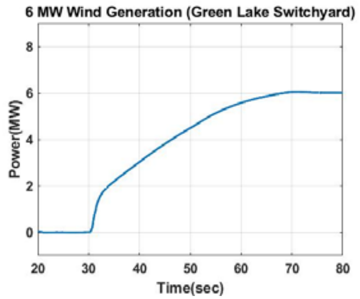


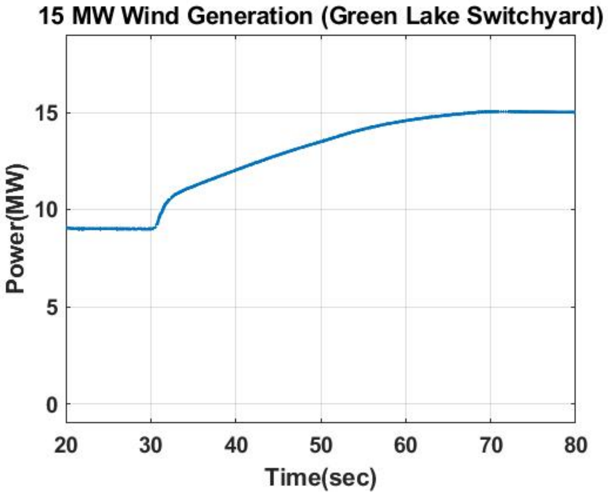


Bus Over-Voltage Tests for 15 MW Wind Turbine Installation (Green Lake)

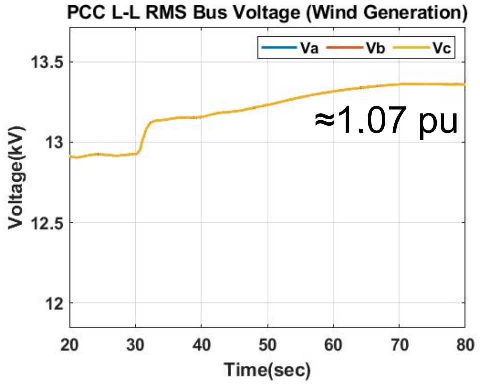
Bus voltage stability limit should be ± 5%

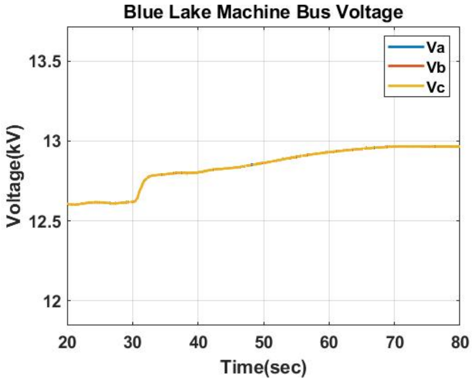


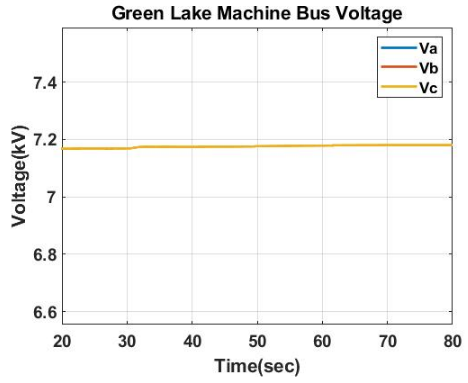


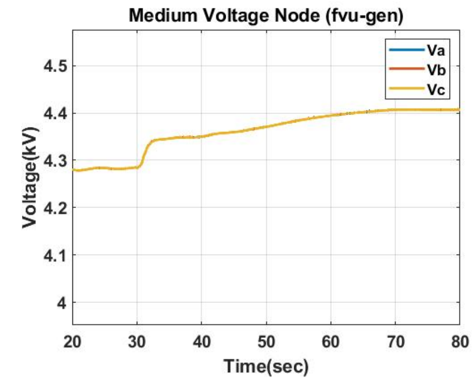


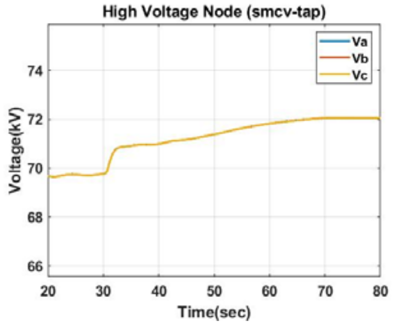
Total Wind Power: Step from 9 MW to 15 MW

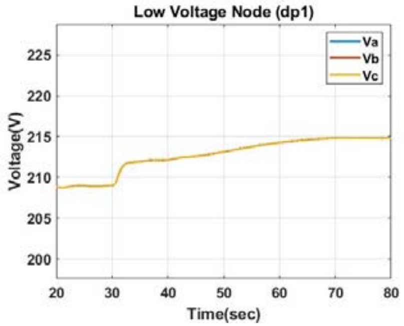


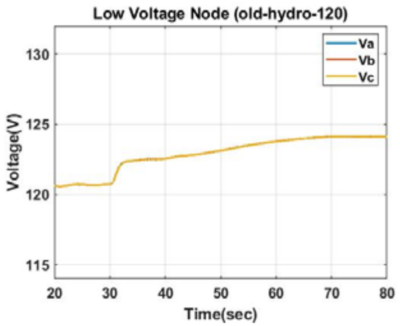






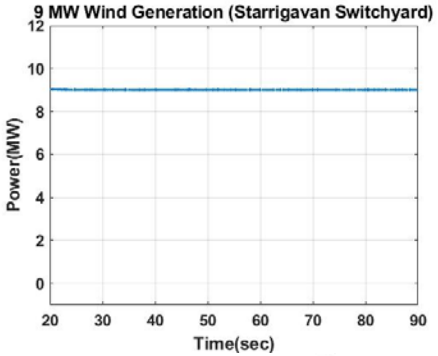


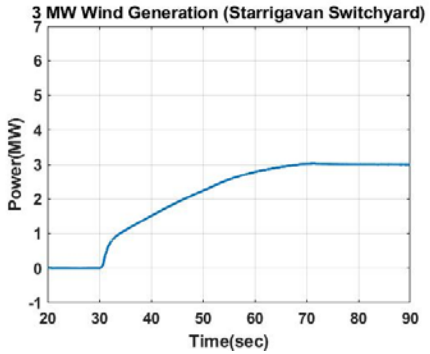


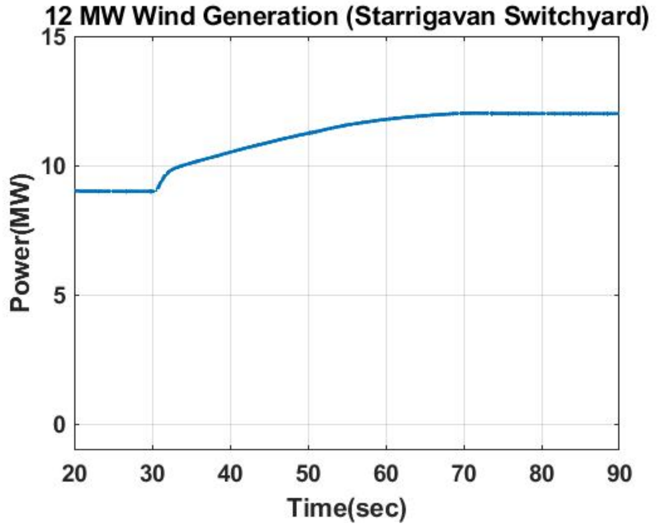


Bus Over-Voltage Tests for 12 MW Wind Turbine Installation (Starrigavan)

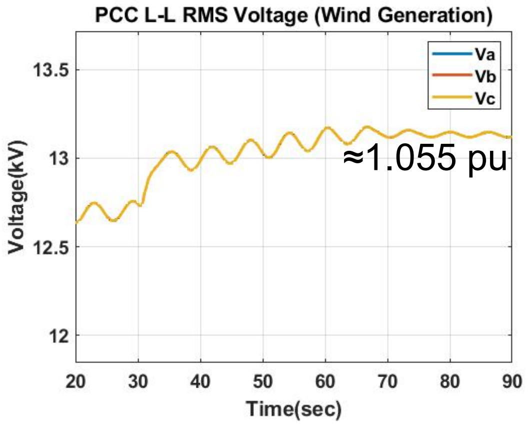
Bus voltage stability limit should be ± 5%

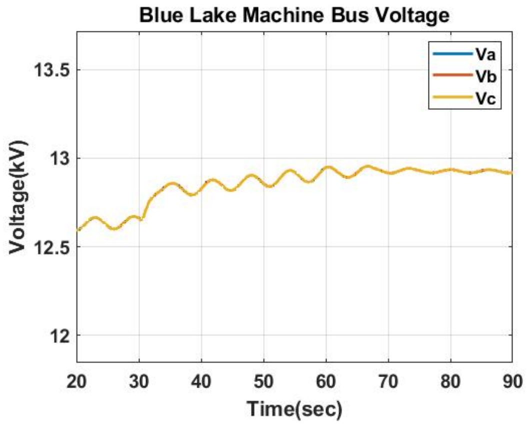


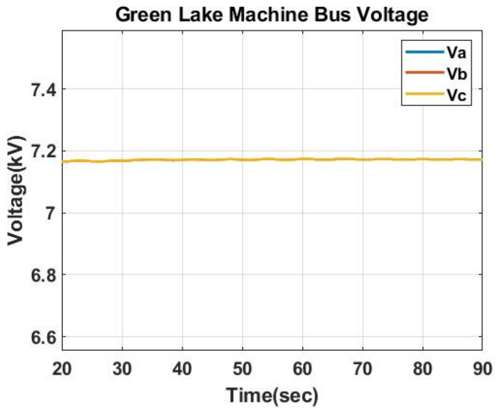


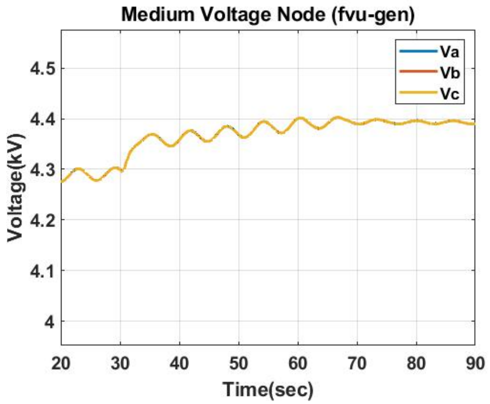


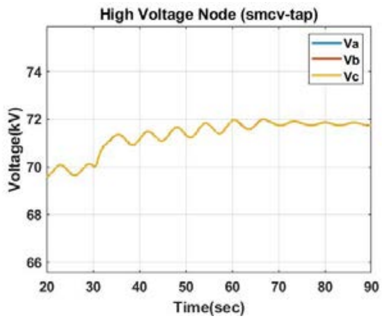
Total Wind Power: Step from 9 MW to 12 MW

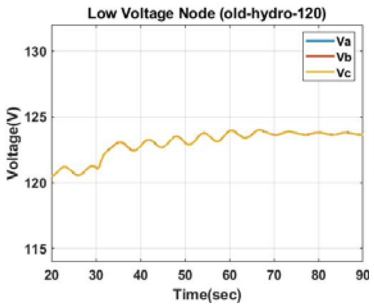


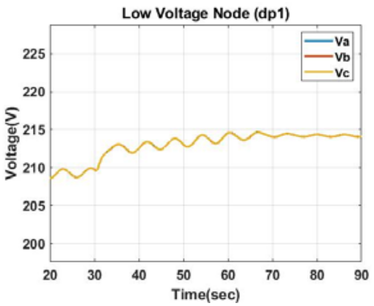






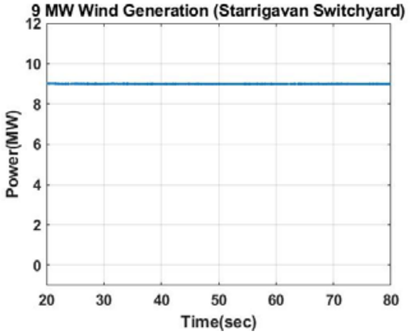


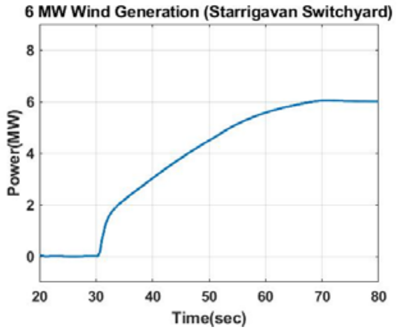


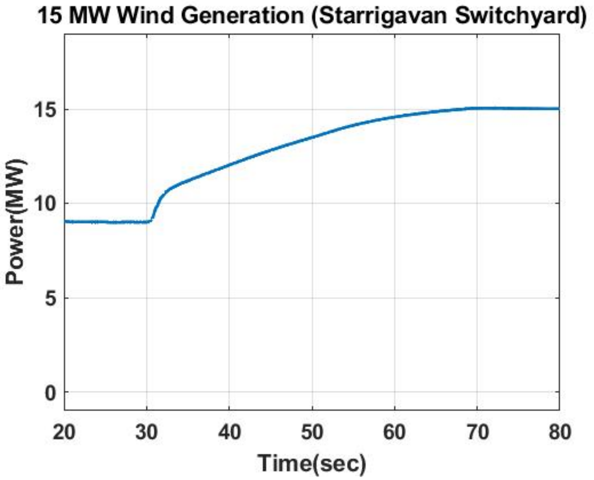


Bus Over-Voltage Tests for 15 MW Wind Turbine Installation (Starrigavan)

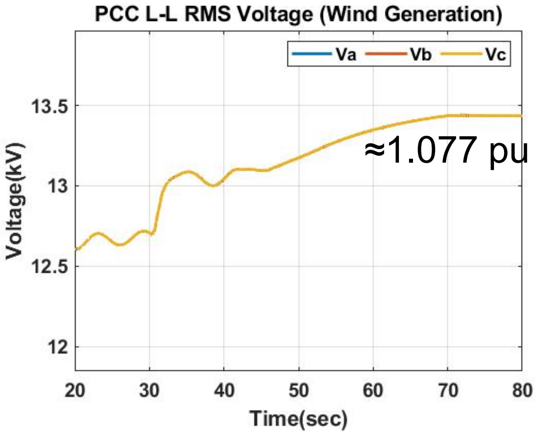
Bus voltage stability limit should be ± 5%

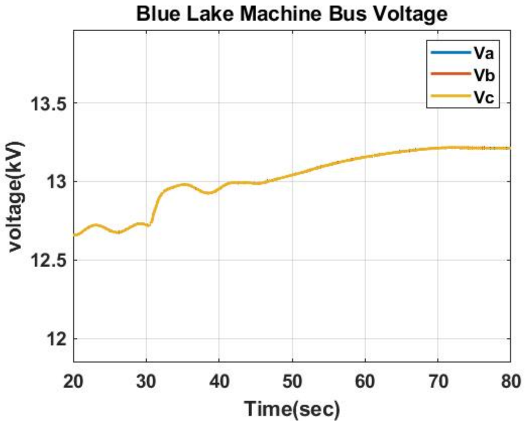


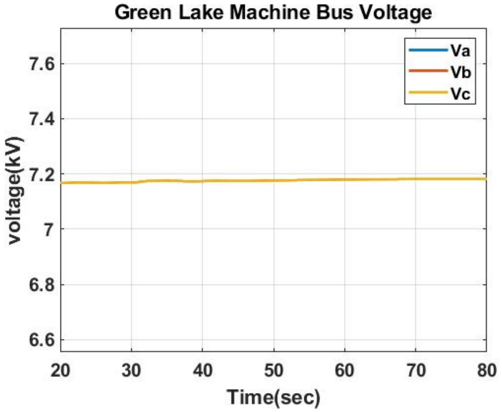


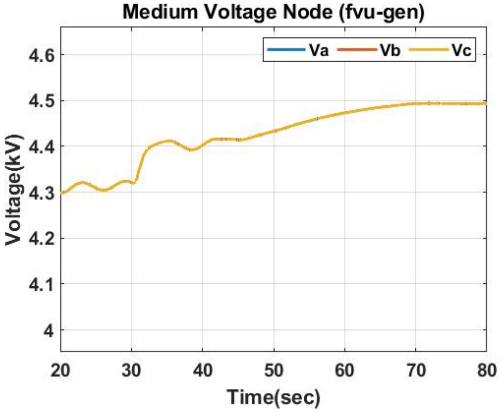


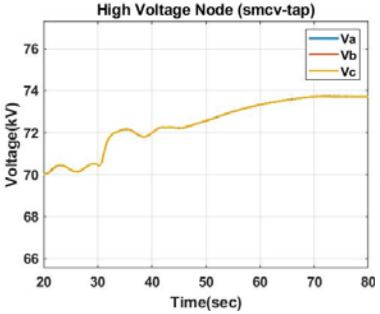
Total Wind Power: Step from 9 MW to 15 MW

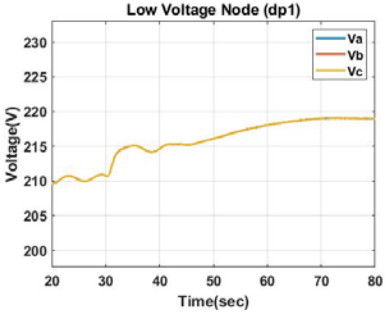


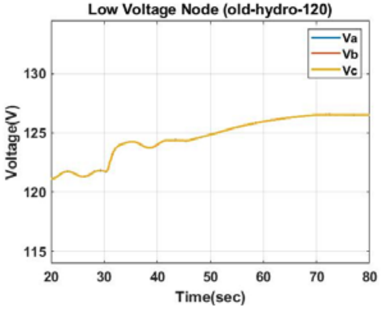






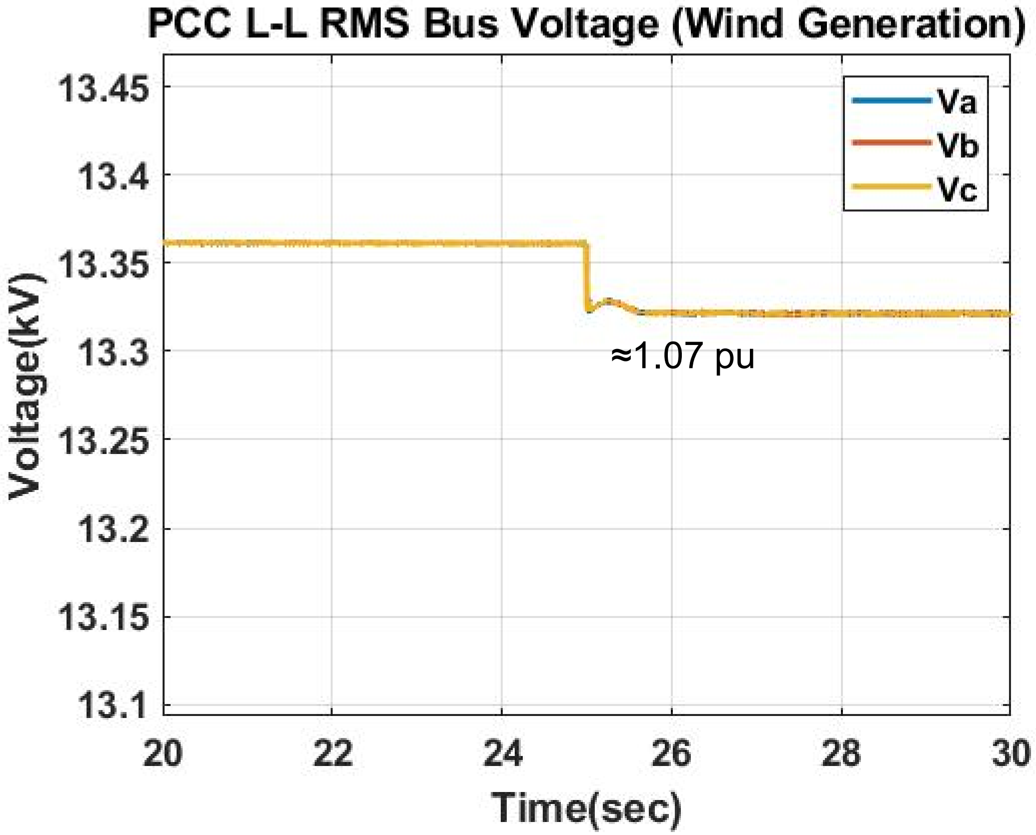




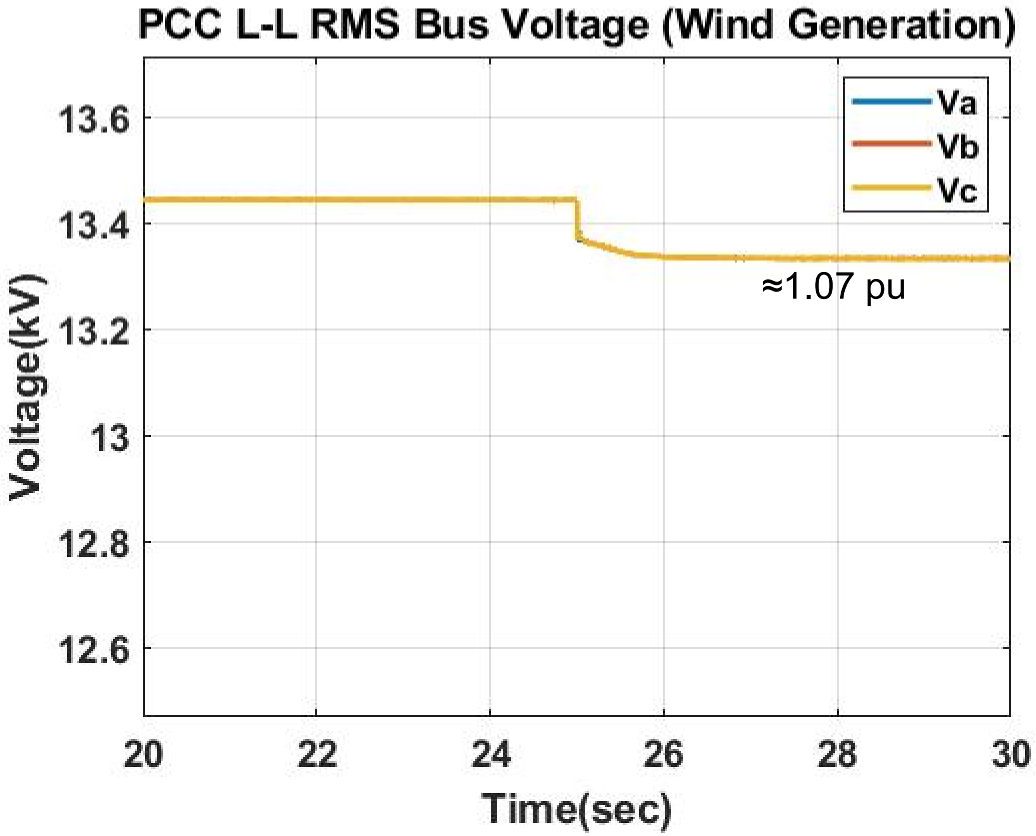


Load Increase to Limit Bus Over-Voltages

- 3 MW load control is activated to mitigate over-voltage due to 15 MW wind turbines installation
- PCC bus voltages are still outside the limit



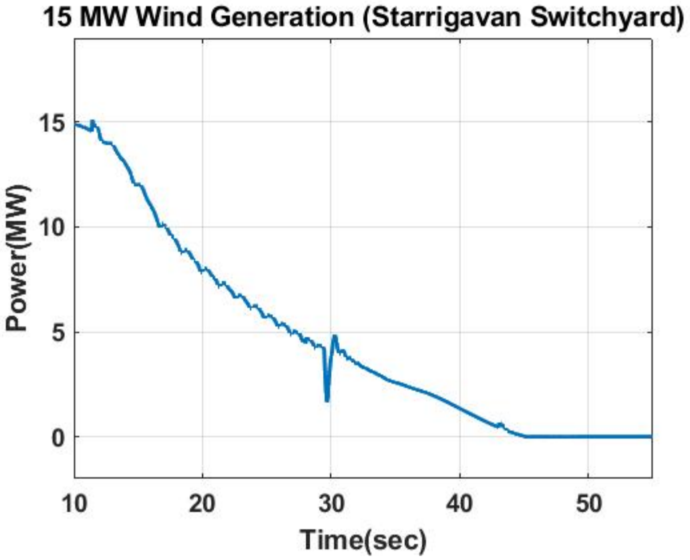
Green Lake



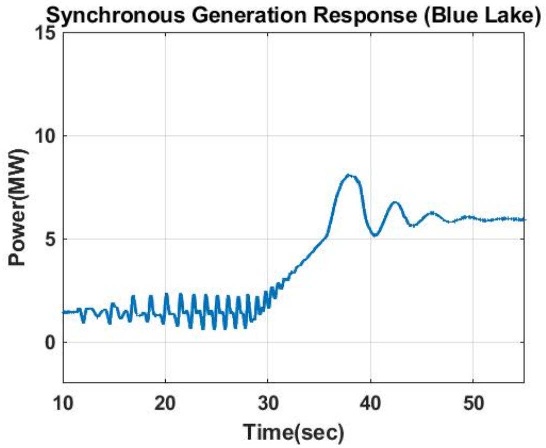
Starrigavan

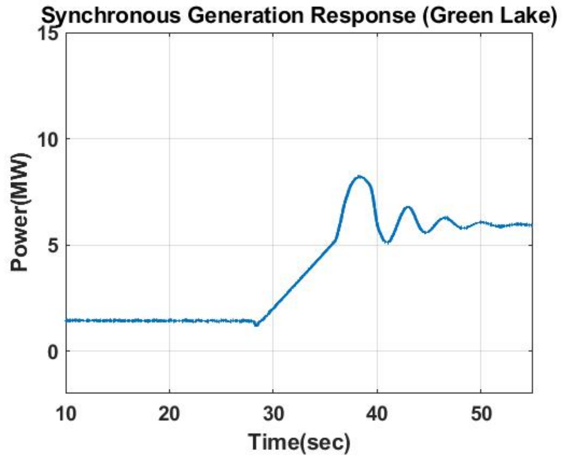
Frequency Instability and Generation Control

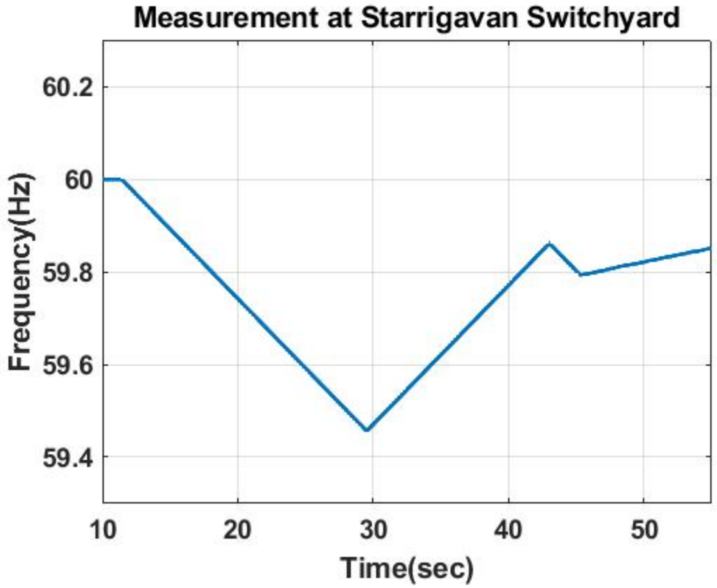
- 15 MW wind power is ramping down to zero
- Frequency ramps down. Restoration by hydro generation control after it's below 59.5 Hz
- At t = 28.5 s, synchronous machine controls are activated, load is reduced by about 3 MW and each machine supports around 6 MW to stabilize frequency.



Ramp Down in Wind Generation







Frequency restoration starts below 59.5 Hz via the generation controls

For Stability:

- Load-Generation balance is crucial
- Only load control cannot ensure stability
- Blue and Green synchronous generation controls are essential

Conclusions

- Built dynamic model which evaluates grid stability and control impacts with addition of renewable generation
- As wind generation size grows **voltage stability** can be a potential challenge.
- As wind gusts ramp up/down, **frequency stability** can be a potential challenge (*especially at higher wind generations).*
- **Wind-Hydro control coordination** is essential to achieve robust Sitka grid control.
- Hydro generation **load acceptance, and ramp up/down capability** should be assessed *(especially at higher wind generation)*

Conclusions

- Existing hydro and load control **can support up to 9 MW** of wind penetration.
  - Advanced **load control** in microgrid is not sufficient to achieve robust voltage stability in Sitka grid.
  - **Upgrades to controls/storage** needed for stability and control with additional wind/solar generation.

Thank You

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 Energy Transitions Initiative, Geothermal Technologies Office, Solar Energy Technologies Office, Water Power Technologies Office, and Wind Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government.

NREL/PR-5C00-86347

Energy Transitions Initiative Partnership Project