Modeling & Analysis of a Small Hydropower Plant and Battery Energy Storage System Connected as a Microgrid

Kelly Kozdras

University of Washington, Seattle, June 2015

Acknowledgement:

The information, data, or work presented herein was funded in part by the Office of Energy Efficiency and Renewable Energy (EERE), U.S. Department of Energy, under Award Number DE-EE0002668 and the Hydro Research Foundation.

Disclaimer:

The information, data or work presented herein was funded in part by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes and warranty, express or implied, or assumes and legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Contents

Problem Description

Puget Sound Energy Project Description

Puget Sound Energy (PSE) is a utility with headquarters in Bellevue, WA that provides electric and gas service to customers in many regions of western Washington State. PSE is undertaking the implementation of a battery energy storage system pilot project in Glacier, WA, a small town located in the North Cascade Mountains near Mt. Baker Ski Area. Glacier experiences power outages that are both somewhat frequent and lengthy (roughly 2.8 outages per year with a duration of 7.5 hours average). The primary cause of the outages is faults on a long 55 kV transmission line that serves the town of Glacier from the Kendall substation. This approximately 10-mile long line is shown in the upper left of Figure 1 below. The Kendall-Glacier transmission line extends through an area of heavy forest with few reasonable options for increasing the line's reliability. The substation in Glacier (also shown on figure below) serves over 1000 customers that are mostly residential but includes over 50 small businesses [1]. The town has approximately 250 year-round residents, and a peak in visitors during the winter ski season when storms are also more likely to cause power outages [2].

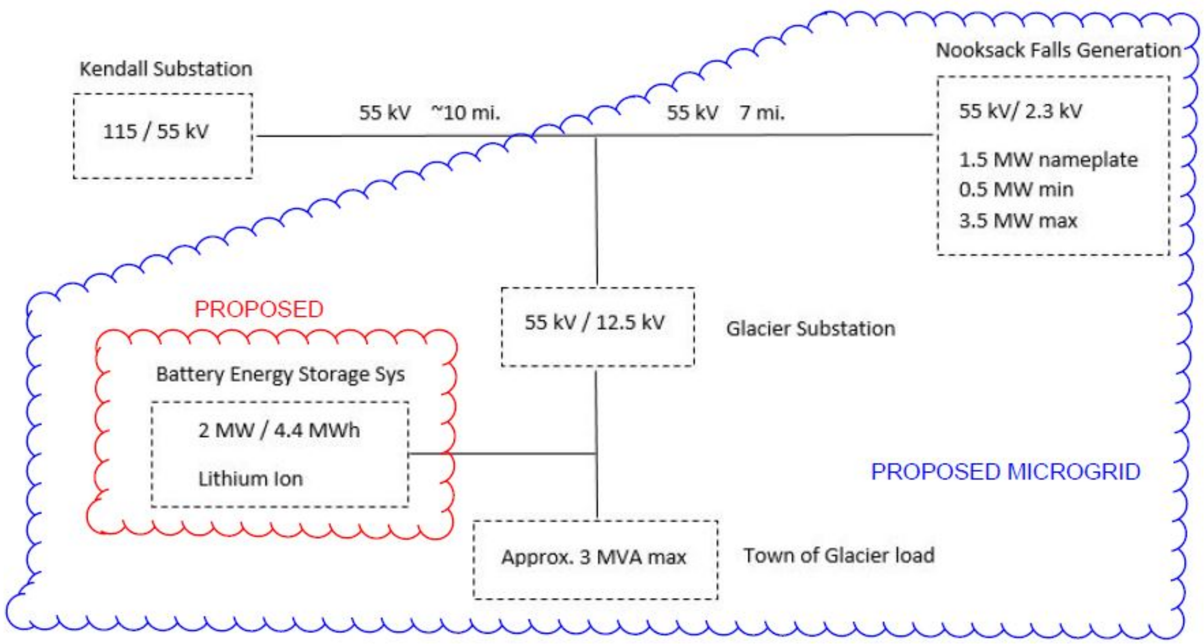


Figure 1: Proposed Microgrid in Glacier, WA

Given the reliability challenges in Glacier, PSE is assessing the feasibility of a 2MW/4.4MWh battery energy storage system (BESS) that would allow for improved reliability (shown in figure above). The BESS would also allow for the ability to investigate other applications for utility-scale energy storage. This energy storage system is being considered for operation in "planned islanding" and "microgrid" mode. "Planned islanding" indicates use of the BESS to provide power to part or potentially all of the load in the town of Glacier during an outage. "Microgrid" indicates utilization (during an outage) of the BESS in parallel with Nooksack Falls Hydroelectric Power Plant, a small (nameplate 1.5 MW/2000 HP) hydro power plant less than 10 miles from the town of Glacier (also shown in Figure 1). Nooksack is a run-of river small hydro generation plant with a gross head of 226 ft. The site has a 5-foot diameter penstock which enters the powerhouse and goes into a pelton turbine with six runners on one shaft [1]. It was originally constructed by Stone & Webster in 1906, which makes it the second oldest operating power generation facility in Western Washington. It was placed on the National Register of Historic places in December of 1988. The plant operated until 1997 when a fire destroyed the generator. The project continued operations in 2003 after the replacement of the generator and other updates [14].

Description of this Project

The project described in this paper models and analyzes the "microgrid" aspect of the project described above. Data on the system was gathered about the existing and proposed systems to prepare a model of the microgrid in PowerWorld. This includes:

- Data about the existing <u>transmission</u> and <u>distribution</u> system in area of Glacier, WA based on PSE's own models.
- Drawings and data about the <u>generator</u> at Nooksack Falls and its control from PSE engineers and the facility owner. This generator had not been modeled by PSE as its size does not require a model to be prepared (under WECC guidelines) [3].
- The proposed <u>energy storage system</u> design and procurement is being done by a contractor to PSE, and coordination with them is occurring to determine appropriate input parameters for the battery model.

This report includes a few key elements. First, it describes the basic model of the system in PowerWorld from the data collected about the system. Next it provides results of an initial transient stability analysis of the existing installed equipment if it is connected as a microgrid. There is likelihood that the existing system would not maintain stability when operating as a microgrid. Finally, this report provides initial recommendations for modifications to consider to improve stability.

Methodology

Modeling & Analysis in PowerWorld

A software program called PowerWorld was the tool used to generate a model of the microgrid system and perform a transient stability analysis of that system. PowerWorld is a power system simulation software to model all network components in steady-state or in various other conditions such as transient stability that are of interest for study. This report describes the basic PowerWorld model generated to simulate the microgrid at Glacier. Some elements that make up the proposed microgrid were already modeled by PSE, while the development of other aspects of the model is described here.

In order to perform a transient stability analysis in PowerWorld, a dynamic model of the system components was required. This model was generated by selecting block diagrams with transfer functions that most reflected the configuration of each individual system element. The system elements of the microgrid that were modeled with these block diagrams included the hydro generator at Nooksack, the generator's exciter, and the BESS. PowerWorld contains dozens of potential block diagrams to select from for most categories of components [5]. Once a block diagram is selected that best models the particular component, various parameter values are calculated or chosen to further describe that dynamic model. Once these block diagrams and their parameters are completed, there are various types of transient contingencies available to model in PowerWorld. These include contingencies such as application of a fault or an increase or decrease in load at a selected point within the system.

Generator Model

A variety of data was available from PSE and the generation site owner about the existing hydro power generation site at Nooksack Falls. A few pieces of information about this generator were most relevant to the selection of the appropriate block diagram and its parameters:

- The generator is salient pole [6]
- The generator nameplate rating is 1.5 MW, with a minimum generating turndown of 0.5 MW and a maximum generating output of 3.5 MW [2]
- Direct-axis reactances and time constants for the generator were provided by the generator manufacturer

Once this key information about the generator characteristics was gathered, an appropriate generator block diagram model could be selected from PowerWorld. In the case of selection of appropriate block diagrams, determination of the diagram for generators is among one of the more simple selections. The most commonly used generator models are GENSAL (a simple model for salient machines) and GENROU (a simple model for round rotor machines). Knowing that the generator at Nooksack Falls is salient pole indicated that the GENSAL model would be appropriate for this study. That block diagram for the GENSAL model is shown below in Figure 2.

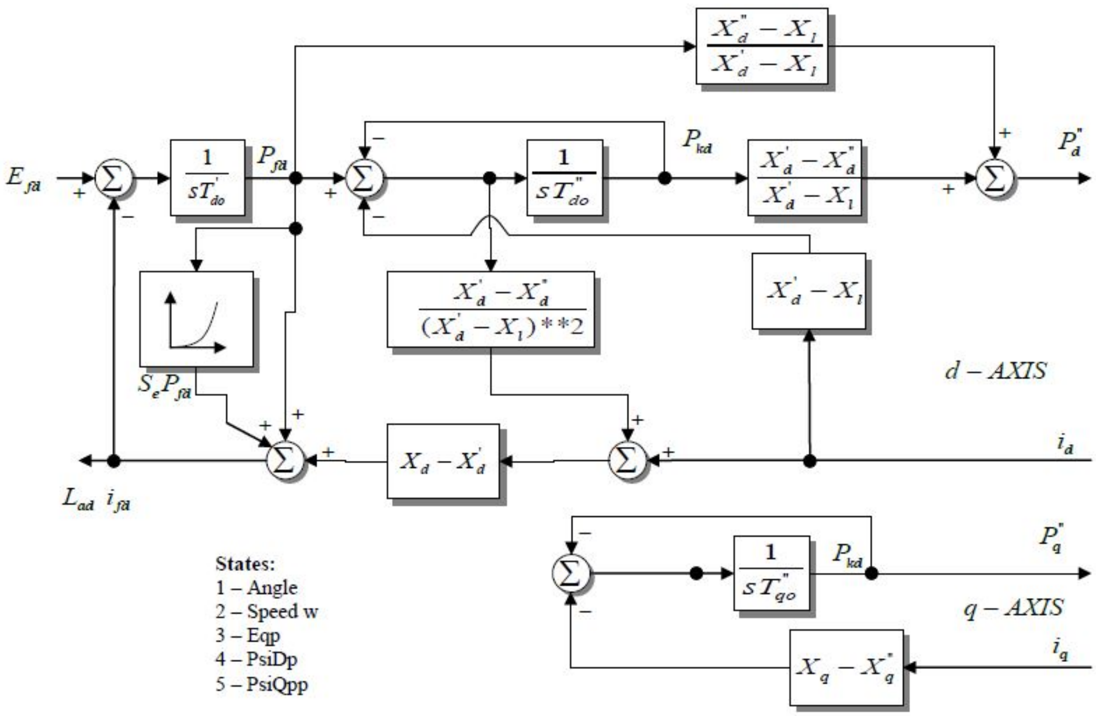


Figure 2: GENSAL Block Diagram [5]

The block diagram parameters that are required to be entered into the PowerWorld model are mostly noted within the blocks in the diagram in Figure 2. They include d-axis reactances (X_d, X_d', X_d''), q-axis reactance (X_q, X_q', X_q''), d-axis and q-axis time constants (T_{d0}', T_{q0}'), stator resistance (R_a), stator leakage inductance (X_l), inertia constant (H), and damping factor (D). These machine parameters were selected or calculated by a variety of methods. In the case of the d-axis reactances and time constant, the values were provided in documentation from the generator's manufacturer. Receiving these machine parameters directly from the manufacturer is the most accurate way to determine these values. Values for the q-axis reactances and time constant were requested from the manufacturer, but not available. However, given the availability of the d-axis values allowed for an approximate calculation of the q-axis values by use of formulae obtained from textbooks on power system dynamics and stability [4]. Finally, the stator reactance and leakage inductance, inertia constant, and damping factor were estimated. These estimations were based on typical values provided for hydraulic generating units noted in another popular textbook on power system stability [7]. With the generator block diagram and its parameters selected, attention could be turned to other aspects of the dynamic model.

Exciter Model

A generator exciter provides a DC excitation current that will produce the magnetic field within the generator. The existing excitation system at Nooksack Falls consists of a static exciter under manual control. More specifically, this is via an AC/DC converter. The AC/DC converter takes AC line current and transforms it to a DC current which supplies the generator with the DC field current. The AC/DC converter uses silicon-controlled rectifiers (SCR) arranged in a bridge circuit. This converter is under manual control via a potentiometer that the site operator utilizes.

As was the case with the model of the generator, there are dozens of block diagrams available to describe the dynamics of the exciter system. However, unlike the case of the generator, there are not just a few exciter block diagrams that are typically used for their modeling. Given the breadth of options, the manufacturer of the AC/DC converter was contacted for recommendations of the device's modeling. The manufacturer noted that their simple converter has been used for a few decades and before this type of transient modeling in computer software was typical. Based on this, an appropriate exciter model was selected based on the following standards:

- The simplicity of the block diagram to mimic the simplicity of the device being modeled
- Preference for any of the IEEE exciter block diagrams. These are standardized models to represent a variety of exciter systems presently in use. A benefit of these models is that a reasonable amount of documentation exists to describe both the models and their parameters [8].
- Recommendation of technical support engineers at PowerWorld with experience in which exciter models work well with the GENSAL generator model being used [11].

Based on these qualities that were preferred in a block diagram to model the exciter system, the IEEE T1A or Modified IEEE Type 1 Excitation System was chosen and is shown below in Figure 3. The values for these parameters were a mixture of the model default parameters and recommendations from engineering staff at PowerWorld. With the completion of the block diagrams for the generator and the exciter, the attention could be turned to aspects of the microgrid other than the existing generation. Nooksack Falls does not presently have a governor installed, and so a governor model was required for the initial analysis of the existing system.

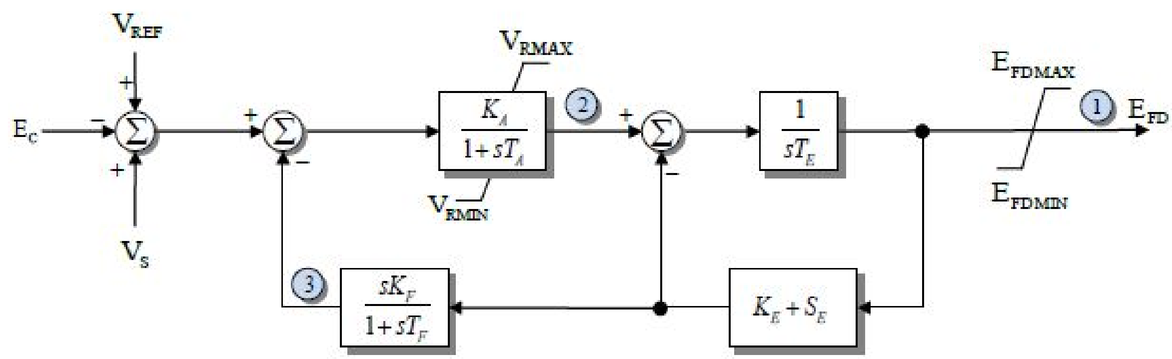


Figure 3: IEEET1A Block Diagram [5]

Transmission & Distribution Model

The transmission and distribution system in the area of Glacier were the other piece of the existing system that needed modeling for the microgrid. The power flow data for the transmission lines of all the Western interconnect was imported into the PowerWorld model. The data available was a 2024 prediction of expected transmission lines, loads, and generation. This data was amended with PSE's 2015-16 winter base planning case for the 55 kV transmission lines and loads around Glacier. For the distribution system in the area of Glacier, some minimal detail of the existing transformers was available and incorporated into the PowerWorld model. Data about the average, maximum, and minimum load for Glacier was also available. This data becomes especially useful when various transient contingencies are analyzed.

In order to model the 55 kV transmission and 12.5 kV distribution lines in PowerWorld, the line resistance and reactance are incorporated in the model. Additionally, the transformer rating is entered as appropriate. The load at Glacier is presently entered as a constant power load, but could be entered as a combination of constant power, constant current, and constant impedance. If further details become available about the distribution lines and transformers and the location of loads within that topology, that information will be incorporated into the PowerWorld model.

Battery Energy Storage System Model

The proposed BESS to be installed in Glacier is presently being designed by a contractor to PSE. The system consists of 2 MW / 4.4 MWh lithium-ion batteries. The system will be tested for use in a few functions:

- Operate as a short-term backup power source when Glacier experiences an outage. With implementation of the proposed microgrid, the back-up power capability will extend a longer time as the small hydro generation at Nooksack Falls will be able to charge the BESS (the functionality this project considers).
- Reduce system-wide load during times of high demand. The BESS can be charged during periods of lower demand and discharged when load increases.
- React readily if there is a sudden drop or spike in generation from less predictable generation sources such as wind or solar, or a change in power demand that was not predicted [10].

We have previously discussed aspects of the microgrid that had many possible block diagrams to consider for representation of the system element (generator, exciter). As utility-scale energy storage is much newer in its application, there was only one block diagram available for use in PowerWorld that was applicable for an energy storage system. This is the CBEST model that is shown in Figure 4 below. Since this BESS is presently being designed, coordination was possible with the design engineers to appropriately select the parameter's values. The parameters that were selected based on input from the BESS engineering staff included P_{max}, I_{acmax}, K_{AVR}, V_{max}, V_{min}, OutEff, and InEff [11]. The remaining parameters (T1 – T4, Droop) represent how the control of the device is programmed. Parameters T1 – T4 relate to how quickly the device will respond, while droop represents how the voltage setpoint would change as the reactive power output changes [12]. These control parameters will be experimented with further this summer as the use of the BESS for possible control within the microgrid is investigated.

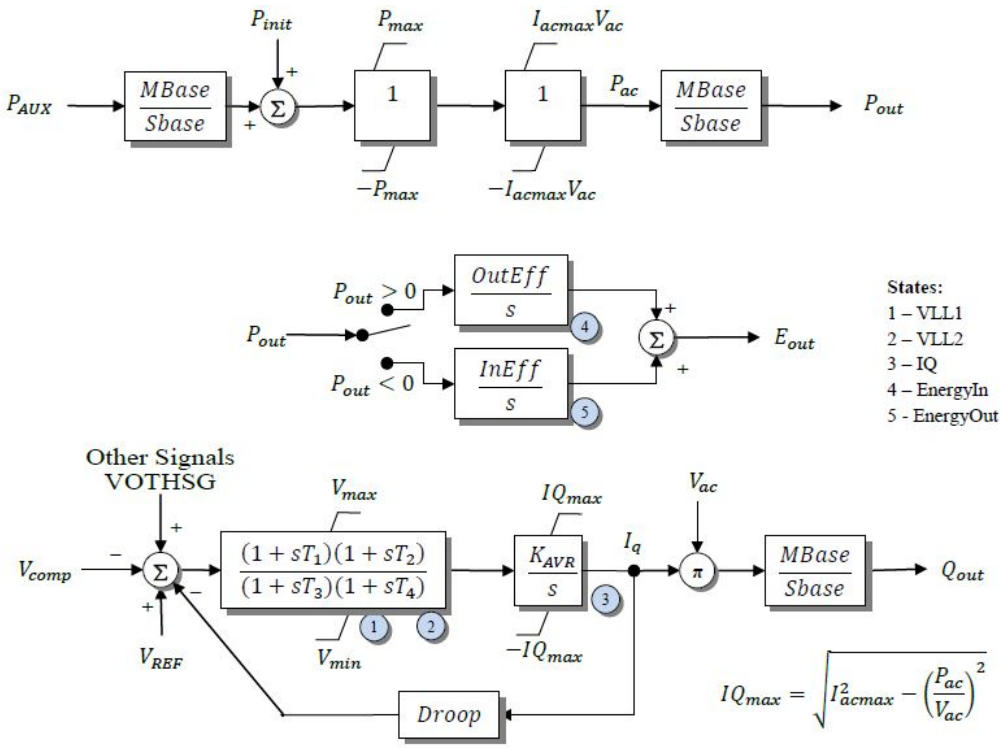


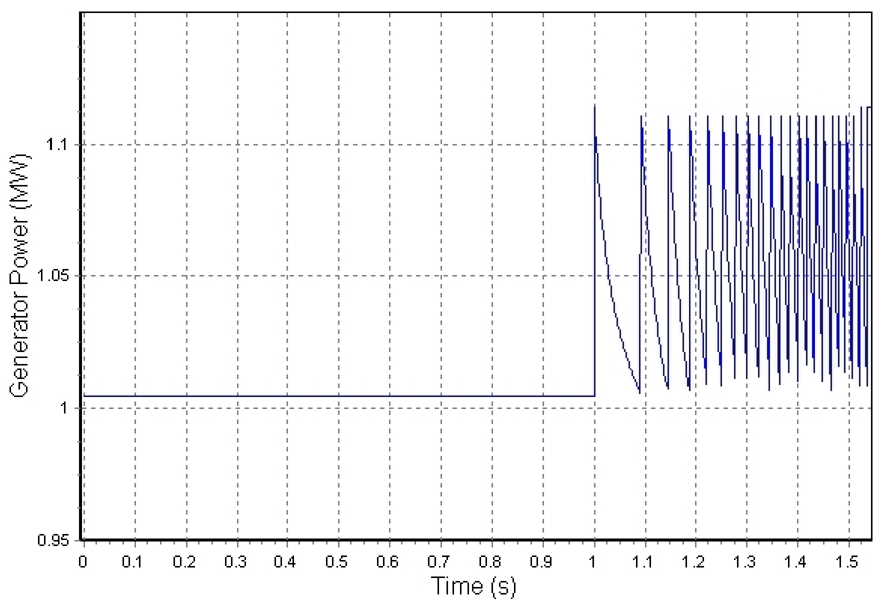
Figure 4: CBEST Block Diagram [5]

Results

Transient Stability Analysis

Transient stability as related to a power system refers to the system's ability to return to a stable condition after a large disturbance. In this application a large disturbance refers to a fault or switching in or out of circuit elements. The dynamics that will be considered in this report are on the order of a few milliseconds to a few seconds [4]. Once the model was generated and all block diagrams were inserted, the transient stability study began in PowerWorld. For this report the stability analysis consisted of modeling the generation (and excitation) at Nooksack Falls, and 55 kV transmission and 12.5 kV distribution in the area of Glacier. The breaker at Kendall substation is left open for this simulation (reference Figure 1) so that the hydro generation, transmission, and distribution around Glacier are isolated. The BESS is not included in this stability analysis. It is likely that the control capabilities in the BESS could be useful to help the Nooksack Falls generator maintain stability. For this initial transient stability analysis, the goal was to see how the system that already exists at Glacier and Nooksack performs when isolated from the rest of the grid.

There are several options for insertion of a transient contingency element into a PowerWorld model. The options available allow for insertion of an action such as applying a fault, opening or closing an element's status to add or remove the element from the model, or changing of an element's associated values. These actions are available to apply (as relevant) to system elements such as buses, lines, breakers, loads, generators, and transformers. For this analysis, load was added to the Nooksack generator in small increments to analyze the isolated system's ability to maintain stability after the load increases. A certain amount of load was assumed to be already connected and being fed from the hydro generator (anywhere from 0.5 MW to 3 MW). An increase in load of anywhere from less than 5% to 100% was added after 1 second of running. In all cases (with the system consisting of the Nooksack Falls generator, exciter, transmission, and distribution) the generator output MW would swing back and forth before the simulation failed. Similarly, the rotor angle and generator speed fell, and were not able to recover before simulation failure. A sample of these outputs are shown in Figure 5 below. This case is with a base load of 1 MW and an 11% load increase after 1 second. It can be seen that the generator starts to oscillate, and without the help of a governor to control the speed as the power is increased the generator goes unstable (and the simulation fails). The failure occurs just after 1.5 seconds as opposed to running for the desired full simulation time of 5 seconds.



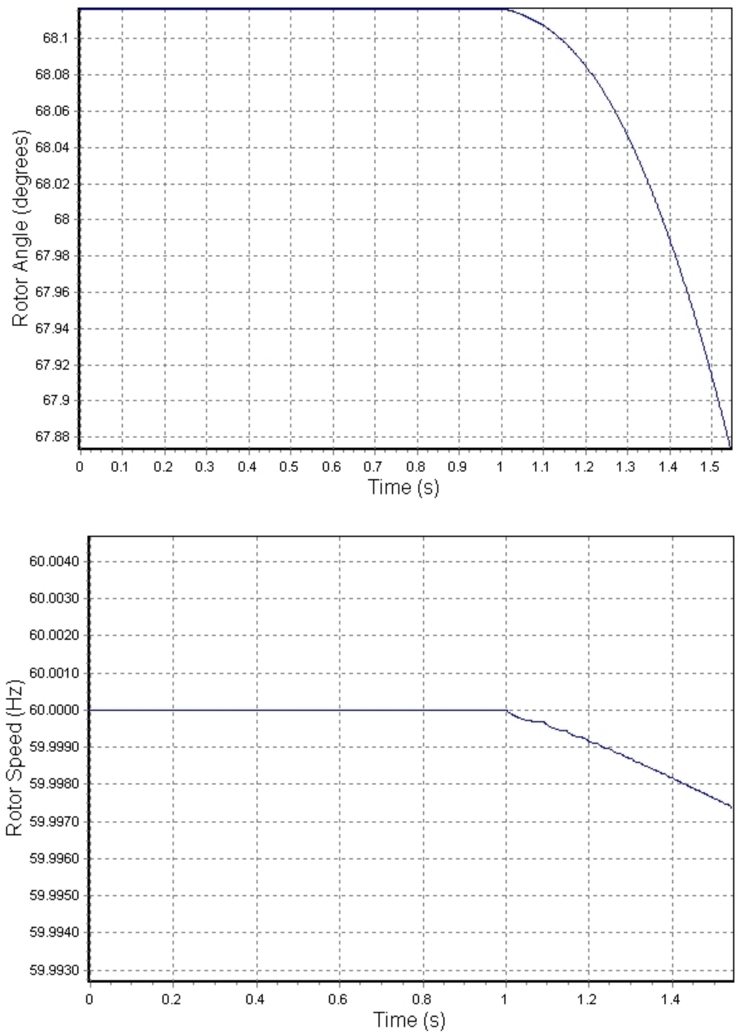


Figure 5: Transient Stability, No Governor

The final analysis performed was to investigate whether the outputs of the simulations shown above were actually failed simulations due to instability and not errors in the set-up of the simulation within PowerWorld. In order to make this verification, a simple governor model was added to the simulation. The governor block diagram was selected based on similar standards as the exciter model, and as such an IEEEG1 governor model was selected and inserted. With the insertion of this element into the PowerWorld model described above, the outputs of the same simulation (11% load being added to a 1 MW base load) are much different. As can be seen in Figure 6 below, the generator output MW, speed, and rotor angle all oscillate before returning to their new steady state value. These outputs reflect the type of generator response that is desired for a generator that can maintain stability in the midst of changing load conditions.

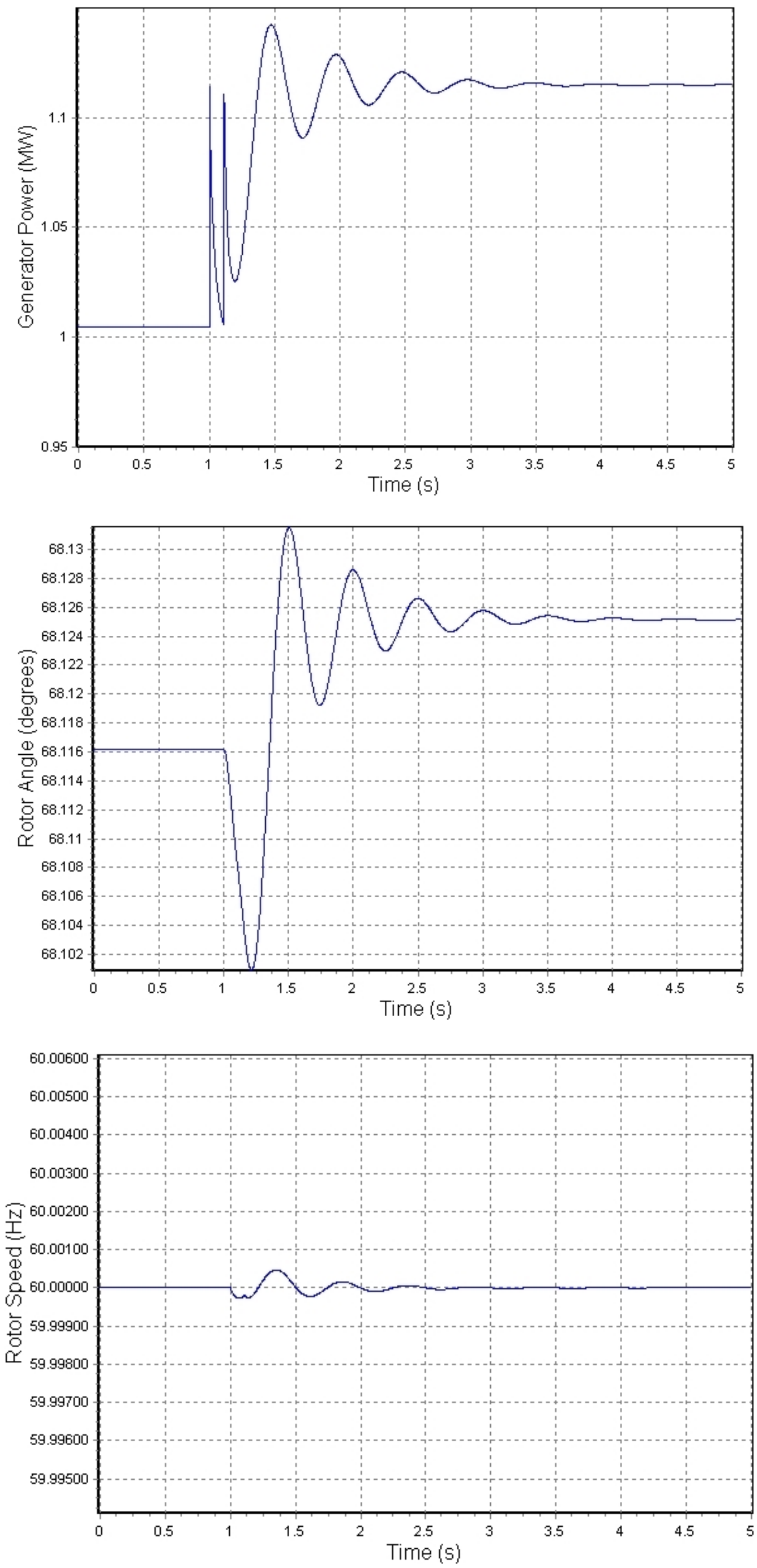


Figure 6: Transient Stability, Governor Included

Potential Stability Modifications

The transient stability analysis described in the previous section reviewed the existing system in Glacier and Nooksack if isolated from the grid. From that analysis it can be seen that updates to the existing system would be needed in order for the isolated system to operate without stability issues. There are a few possibilities for updates to the system which include use of the control capabilities of the BESS, a governor, and control via load.

Given that a BESS is already being designed for deployment in Glacier, it is natural to consider use of its control capabilities. Study of BESS has concluded that the control of BESS can be designed for many functions including potentially to improve the stability of a power system via frequency regulation [13]. The previous section that discussed the BESS block diagram development noted that the time constants (T1 – T4) and droop could be varied to achieve desired control strategies. Further research into BESS control and the CBEST block diagram parameters will provide insight into appropriate values to consider for improving the microgrid system stability. Another option to consider for improving the stability by a more traditional method would be installation of a governor. A governor would control the speed or output power of the hydro turbine according to pre-programmed power-frequency characteristic. As was seen in the transient stability analysis, addition of a governor will allow the system to remain stable even when a load increase occurs. One final control strategy to consider is control actions being performed through use of system loads. Thermostatically controlled loads are a useful type of load to consider for their potential to contribute to a control strategy where frequency regulation is achieved. These loads can have their operation delayed for short time periods that then allow for storage of thermal energy. Similar to how BESS can provide ancillary control services, control of thermostatically controlled loads (that have stored energy during periods of generation "surplus") can also allow for investigation into their control capabilities [15, 16]. These three control strategies offer various advantages and disadvantages in factors such as cost, ease of implementation, and functionality, and are an interesting array of options to consider for improving the microgrid stability.

Future Work

Further work on the PowerWorld model and transient stability analysis will allow for interesting continued investigation. This future work will be undertaken this summer and includes three areas. First will be updates to the basic PowerWorld model. Updates to the basic model have been discussed throughout this paper and can include further improvement to the exciter model block diagram selection and parameters to best model the existing exciter. Another update to the basic model is integration of further detail about the distribution system in Glacier as that data is available from PSE. Second, the possible control systems updates to improve stability will be modeled. This includes updating the BESS model parameters, looking into appropriate governors and creating an associated governor model, and modeling control via load. Finally, once the basic PowerWorld model is updated and the block diagrams for the potential control system updates have been incorporated, further transient stability studies can be performed. These studies can include both changes in load on the Nooksack Falls generator and faults within the microgrid system.

Summary & Conclusions

This project developed a model in PowerWorld for a small microgrid being considered to improve reliability in a Washington mountain town. The microgrid utilizes both an existing small hydro generation site and a proposed Battery Energy Storage System (BESS). The transient stability of this microgrid was analyzed based on the system model, and potential system modifications considered. The software used in the analysis allows for many types of transient contingencies to be analyzed, which will aid in the future modeling and analysis of potential control strategies.

A lesson learned from this project is that while modeling of existing systems is involved, it is not unmanageable. The support of the agency/utility whose system is being modeled is certainly important, and I have had excellent support (and supply of system data) from management and engineers at PSE. Additionally, input from skilled engineering staff at PowerWorld has been quite helpful in understanding and utilizing the functionality of their software. PowerWorld also provided free access to the software add-ons that PSE utilizes. This allowed for use of the transient stability analysis functions in PowerWorld, as well as being able to import all buses of the WECC system model rather than model just a subset of the system. This free access was greatly appreciated. Finally, technical advice from professional and academic contacts has been quite useful as some aspects of this project are either newer in their application or have had a more recent spike in their interest level (BESS, small hydro generation, microgrids). This advice primarily came through professors at University of Washington and contacts from the Hydro Research Foundation (the organization providing funding for this project). This project has thus far been very engaging, and the support of all those involved is noted and most appreciated.

REFERENCES

[1] “Glacier Planned Islanding & Microgrid Feasibility Assessment”, Puget Sound Energy, Unpublished.

[2] J. Roach. “Will Huge Batteries Save Us From Blackouts?” Internet: http://news.nationalgeographic.com/energy/2015/04/150429-batteries-grid-energy-storage/ [June 6, 2015].

[3] E. Ewry, private communication, January 2015.

[4] Jan Machowski, Janusz Bialek, and James Bumby, Power System Dynamics, 2nd ed. West Sussex, UK: Wiley, 2008.

[5] “PowerWorld Simulator 18 Block Diagrams”. Internet: http://www.powerworld.com/files/Block-Diagrams-18.pdf [June 6, 2015].

[6] J. Heil, private communication, May 2015.

[7] Prabha Kundur, Power System Stability and Control, New York, NY: McGraw-Hill, Inc., 1994.

[8] *IEEE Recommended Practice for Excitation System Models for Power System Stability Studies*, IEEE Standard 421.5, 1992.

[9] A. Aquino, private communication, June 2015.

[10] “Glacier Battery Storage Project”. Internet: http://pse.com/inyourcommunity/whatcom/ConstructionProjects/Documents/Glacier_Battery_Storage_factsheet.pdf [June 6, 2015].

[11] A. Arifujjaman, private communication, May 2015.

[12] M. Laufenberg, private communication, June 2015.

[13] K. C. Divya, J. Ostergaard, “Battery energy storage technology for power systems – An overview”, *Elec. Power Sys Res.*, Vol. 79, pp. 511-520, 2009.

[14] “Nooksack Falls Hydroelectric Power Plant”. Internet: http://en.wikipedia.org/wiki/Nooksack_Falls_Hydroelectric_Power_Plant [June 6, 2015].

[15] D. S. Callaway, I.A. Hiskens, “Achieving Controllability of Electric Loads”, *Proc. IEEE,* Vol. 99, no. 1, pp. 184-199, Jan. 2011.

[16] D.S. Callaway, “Tapping the energy storage potential in electric loads to deliver load following and regulation, with application to wind energy’, *Energy Conversion And Management*, Vol. 50, No. 5, pp. 1389-1400, May 2009.