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CIGRE US National Committee
2018 Grid of the Future Symposium

Design and Synchronization of the Dominion Energy Microgrid

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SUMMARY

The capacity of distributed energy resources (DER) on the grid is growing immensely. DERs have the potential to be a practical substitute for traditional energy production. DERs can be leveraged to create a smaller version of the grid, which is called a microgrid (MG). A MG can incorporate communication, and controls to create a smarter, more efficient, and more robust grid. The purpose of this paper is to design and integrate a MG into an existing campus expansion plan. Integrating a MG will improve reliability and resilience, as well as increase environmental and economic benefits. To validate the designed MG, a model of the MG is constructed in a Real Time Simulator Computer Aided Design (RSCAD) and is simulated using a Real Time Digital Simulator (RTDS). Two case studies are performed, including the synchronization and the battery frequency regulation assistance. The simulation results show the feasibility of the designed MG.

KEYWORDS

Real Time Digital Simulator (RTDS), Microgrid, Synchronization, Battery Storage

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I. Introduction

Historically, natural disasters have been the root cause of severe power outages around the world. As the distribution grid remains vulnerable to natural disasters it is important to focus on grid resilience, which is defined as the grid's capability to continuously function and recover from a disturbance on the grid. It is significant to restore and provide power to critical loads. Critical loads include of hospitals, street lights, military bases and water stations and many more life essential loads. Distributed Generation (DG) have increased in demand because of the potential it has to alleviate the burden to the electric grid by supplying power to critical loads. However, the integration between the two can cause issues if it's not properly managed. Thus, having a Micogrid (MG) that is self-sustained will control the increasing penetration of DG and enhance the reliability of the distributed system.

The microgrid (MG) concept was introduced in 2002 by the Consortium for Electric Reliability Technology Solutions (CERTS) [1]. Since then the popularity of MGs has increased immensely; Navigant Reach identified 1,869 MG projects in the world, representing 20.7 GW, in 2017 [2].The U.S. Department of Energy defines the a MG as "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode" [3]. The distributed generation (DG) in a MG can be microturbines, biomass, wind power, geothermal power, fuel cells, solar power, or traditional internal combustion engines. Overall the MG is a controllable system that can be operated in either an islanded or grid-connected mode. It is important for utilities to do research in this area because MGs will be a contributing factor of improving the grids' resiliency [4].

MGs have various benefits, such as being environmentally friendly, economical, and robust. MGs also give insight to the viability of energy resources and the integration of new technology. Dominion Energy is an electric utility company that produces and transports energy of approximately 26,000 megawatts in the United States. Dominion is expanding a storage yard into a campus, which is the opportune time to develop a MG. The main goal for this MG is to be able to island and provide power to critical loads during an outage or severe weather condition. This MG project is part of the Grid Transformation & Security Act, which describes the first three years ("Phase I") of a proposed 10- year program that will enhance the reliability, resiliency and security of the electric distribution grid, improve service for customers, and provide them with more options for communications and control as well as tools for managing their energy use [5]. As the company becomes familiarized with the MGs functionality, it will be possible to provide MGs as a service for hospitals, university campuses and military bases.

The objective of this work is to design and model the MG, including the diesel generator, PV arrays, load and batteries, in order to analyze the feasibility of the MG by conducting two cases studies. The first case study is related to synchronization of the MG with the main grid while the second case study is related to using battery storage to assist frequency regulation of the islanded MG.

The rest of the paper is organized as follows: Section II describes the load estimation method. Section III discusses methods to calculate the photovoltaic generation. Section IV describes different types of battery storage applications. Section V demonstrates the Real Time Digital Simulator (RTDS) model. Section VI explains the case studies and finally, section VII summaries the overall results and future work.

II. Load Estimation

The MG under investigation will expand a storage yard into a campus to incorporate new buildings such as a district office, fleet maintenance garage, mobile unit storage, transmission overhead line maintenance facility, and a high voltage lab. In order to properly model the MG the loads of these buildings need to be accurately estimated. There are three methods to conduct load estimation such as: watt/ft^2, having a load letter or comparing similar existing accounts. Included in the campus expansion plan is Dominion Energy's first high voltage lab. Given the uniqueness of a high voltage lab, there is no current internal account that it can be compared to. To determine an estimated load typically before the construction is done a load letter is provided. A load letter lists and describes the electric load, electric motor load, square footage of the building and more. The load letter for this entire campus hasn't been provided since many of the buildings do not have architecture plans at this time. Overall, using the density factor that describes the watts/square footage is applied. The density factor depends on the type of building. Table 1, demonstrates the variety density factors for the different types of building. After taking into consideration the square footage of each building the total load was estimated to be 1.02MW.

Table 1. Load Estimation Characteristics

Average Watts/Square Foot of Various Building Types (λ)	
Warehouse	0.82 watts / ft^2
Storage Unit	0.76 watts / ft^2
Maintenance Facility	6.7 watts / ft^2
Office Building	10 watts / ft^2

$$Load(kw) = \lambda \times A \quad (1)$$

III. Photovoltaic Generation

Photovoltaic generation was chosen to be within this MG because it's environmentally friendly and the company wants to investigate solar operations. A fixed tilt angle approach is applied in this case study. Equation 2 was used to calculate the maximum solar power possible, where S_d is the daily solar constant, A_T is the atmospheric transmittance, L is the latitude of the location and θ_{Tilt}, δ are the tilt and declination angle [6].The maximum power availability is determined when $(L - \theta_{Tilt}) = \delta$ .The declination angle varies seasonally $\pm 23.45°$ due to the tilt of the Earth on its axis of rotation and the rotation of the Earth around the sun. The maximum tilt angle is given in equation 3 for the northern hemisphere. In [7] a formula is generated based on collected data for each combination of latitude and season. The date, latitude and the angle of the sun with respect to the panel determined the insolation. By observing the maximum insolation the optimum tilt angles were calculated. A linear formula was determined based on the optimum dates and angles, as shown in equation 4.

$$P = S_d A_T \left[\cos(L - \theta_{Tilt} - \delta)\right] \quad (2)$$

$$\theta_{Tilt} = L - \delta \quad (3)$$

$$\theta_{Tilt} = 3.1 + (L \times 0.76) \quad (4)$$

Solar generation can be implemented in different ways such as rooftop, car port, and ground mounted, each with its own design specifications. When designing the structure of roof top solar not only does the tilt angle have is a significant factor but also the distance between each module in a row and the placement of the modules on the roof. In regards to roof top solar, there must be a clear 4-feet unobstructed pathway and a 4-feet clear parameter for emergency ventilation procedure on the building as stated by the National Electric Safety Code (NESC) [8]. In order to determine the correct spacing between each module in a row a sunchart is utilized. The sunchart in Figure 1 shows the azimuth and solar elevation angles at a specific time of date and season. The sun casts the longest shadow at 9am and 3pm and so these angles are evaluated.

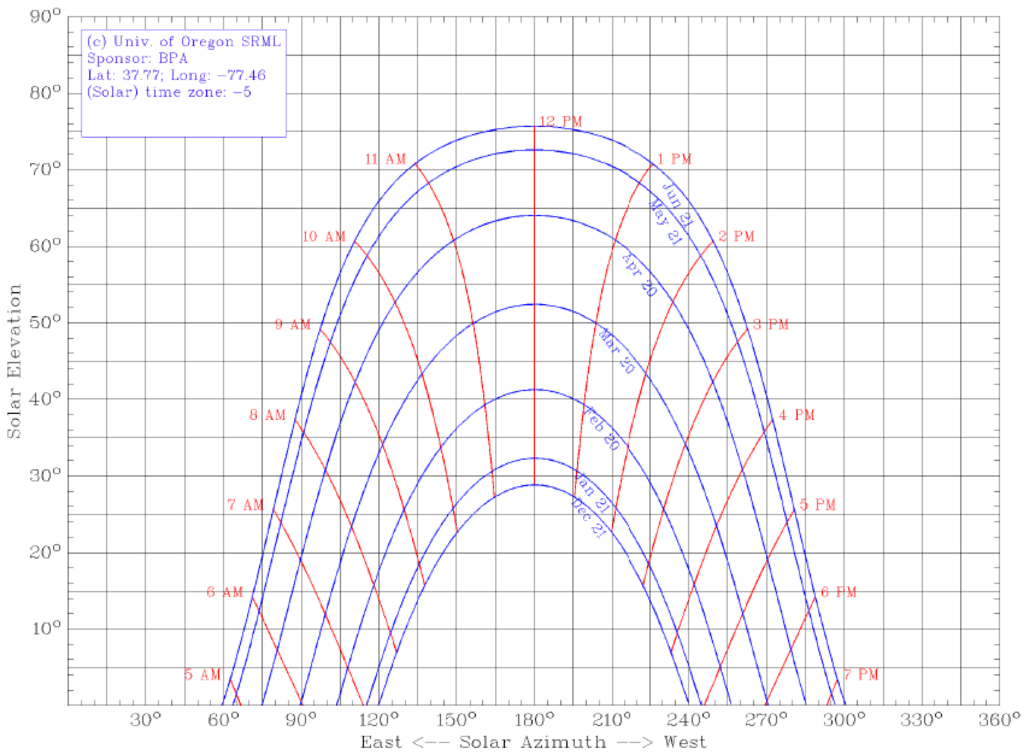

Figure 1. Sunchart for Campus [9]

Having the correct distance between the modules in a row can avoid potential shading issues and generates the optimum output power. Equations 5-7 were used to compute the space in between the row modules. The equations that determine the minimum row spacing X_{min} are represented by trigonometric equations.

$$H = sin(\theta_{Tilt}) \times W_{module} \quad (5)$$

$$X = \frac{\Delta H}{tan(\theta_{se})} \quad (6)$$

$$X_{min} = Module\ Row\ Spacing \times cos(\theta_A) \quad (7)$$

The following variables are defined: the width of the module W_{module}, solar elevation and azimuth angle θ_{se} and θ_A, module row spacing X, height H and the change of height ΔH.

$$H = sin(\theta_{Tilt}) \times W_{module} \quad (5)$$

$$X = \frac{\Delta H}{tan(\theta_{se})} \quad (6)$$

$$X_{min} = Module\ Row\ Spacing \times cos(\theta_A) \quad (7)$$

Base on the sunchart, the solar elevation angle and the azimuth angle are θ_{se} = 16 ° and $\theta_A = 135°$; the width module, W_{module}, utilized was 3.26ft. The computation of the minimum row spacing for the rooftop solar was found to be 4.45ft. The software program Helioscope was used to simplify the process of predicting the total output power based on the specifications. The total output power for rooftop solar was estimated to be 601.3kW [10].

In this design the ground mounted solar has a larger frame size in comparison to the rooftop solar. Therefore, the module's width is longer and there is more space between the rows, which lowers the overall PV output power. In order to optimize the amount of solar arrays in the total capable area, the tilt angle needs to be decreased. The tilt angle chosen in the ground mounted solar design is 25° which produced a row spacing of 19.48ft. In a ground mounted solar farm there must be a 10 feet surrounding perimeter of empty space [11]. The total generation capacity from ground mounted solar was calculated to be 394.2kW.

Another location where PV modules can be utilized is on existing parking areas. Solar carports can simultaneously generate power and provide shade for parked cars. After evaluating the parking lot area in campus, nine carports can be constructed. Taking into consideration the average van size of 8.6ft., the initial height of the carport was selected to be 9ft tall. The solar carport styles in this campus consist of single column double and louvered single with a tilt angle of 10°. The output power generated with the carports is projected to be 595kW. Overall, the total amount of PV generation predicted when including the solar carports, rooftop solar and grounded solar is 1.6MW.

IV. Battery Energy Storage System

There are various reasons why utility companies would want to integrate a Battery Energy Storage System (BESS) in their electric grid. BESS are utilized for peak shaving, load levelling, frequency regulation, voltage regulation and peak shifting and load smoothing.

Peak Shaving: During peak hours the BESS operates in the discharging mode to reduce the power imported from the grid and lower peak demand. During the off-peak load period the BESS functions in the charging mode.

Load Levelling: Transient cloud movement can cause power fluctuations. BESS is designed to smooth out the PV array output and load by absorbing and delivering power such that the net power, which is the summation of PV array, load power and battery, is relatively constant [12]. The BESS incorporated in this work is designed to assist frequency regulation when the MG is islanded.

Frequency Regulation: A variation of frequency in the power system is caused by the power mismatch between generation and the load demand. Since the inertia of the MG is small when the MG is islanded, it is very challenging to regulate the frequency of the MG. Due to the relatively fast response rate; BESS can help regulate frequency by absorbing real power when the MG frequency exceeds its threshold and inject real power when the MG frequency decreases below its threshold. In this model two lithium-ion phosphate batteries are used because of its safety record and robust life cycle [13]. Both batteries have an initial state of charge (SOC) of 20% and have a power rating of 0.58MWh [14].

In order to regulate the frequency to 60 Hz an integral controller is implemented and designed in order to compensate for the frequency error. In Figure 2, the difference between ω_{ref} and ω_{gen} represents the angular frequency error. After converting the error to per unit it is multiplied by the integral controller gain based on equation 7 to calculate the additional active power needed to be provided by the battery in order to regulate the frequency back to 60 Hz. This controller is implemented in the RTDS model.

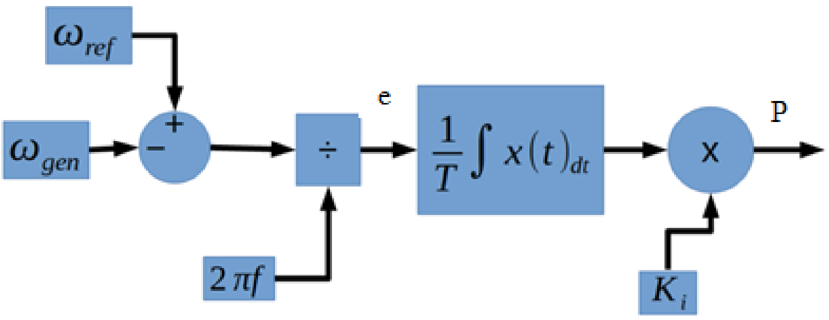

Figure 2. Frequency Control

$$P(t) = k_i \times \int_0^t e(t) \tag{7}$$

V. Real Time Digital Simulator Model

When selecting which bulk feeder will power the MG it is important to consider the topology of the substation. It is ideal to select two feeders, in order to add resiliency to the system. One of the cables used was the UG 1000 kcmil AL XLPE 35kV which has an impedance of $0.9821 + j0.4794\ \Omega/m$. The other cable used is UG 1/0 3Ø AL XLPE 35kV and it has an impedance of $0.2101 + j0.3047\ \Omega/m$. The line impedance can be calculated by knowing the length of the line and the impedance per mile of each cable type. The Real Time Simulator Computer Aided Design (RSCAD) model of the MG is shown in Figure 3. The circuit model was created in RSCAD based on the estimated load, predicted generation, the designed BESS and generator, and the line impedance calculations. The main grid has an impedance of $0.00347 + 0.04373j$ and the X/R ratio is 12.6.

The RTDS operates in real time, allowing the user to interface physical equipment with the simulated model in order to test and validate the operation of MG protection and control devices under realistic conditions [15]. A 3-phase fault was simulated before the point of common coupling, the fault level was 250kA.

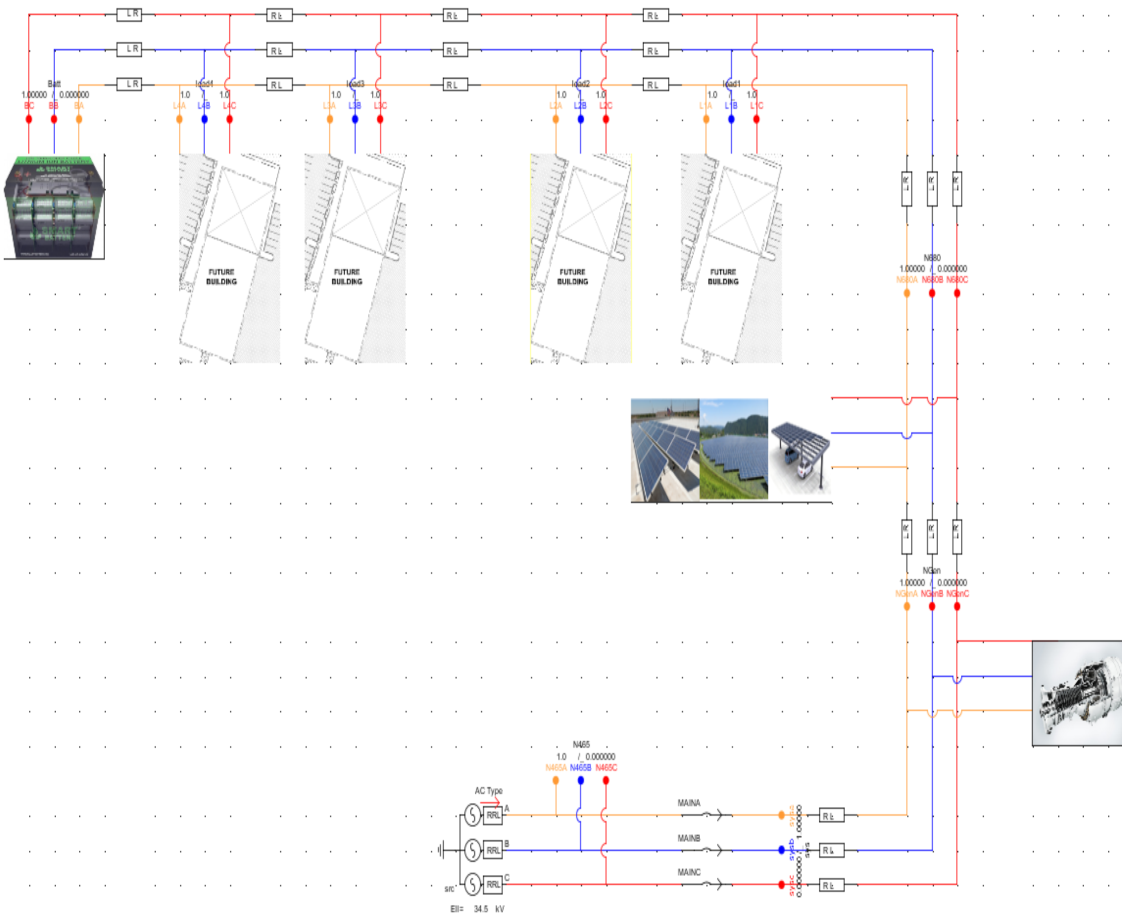

Figure 3. Real Time Digital Simulator Model Circuit

I. Case Studies Results

A. Grid Synchronization

Synchronization of the MG to the electric grid is a crucial task. An abnormal synchronization can cause a disturbance in the system, damage equipment, and cause relays to misoperate. Since the systems rating of DER is between 500 and 1500 kVA it has a particular tolerance limit base on IEEE 1547 standard [17]. The tolerance limits for a proper synchronization of a DER to an Electric Power System (EPS) are:

- Frequency difference: 0.2 Hz
- Voltage difference: 5%
- Phase angle difference: 15˚

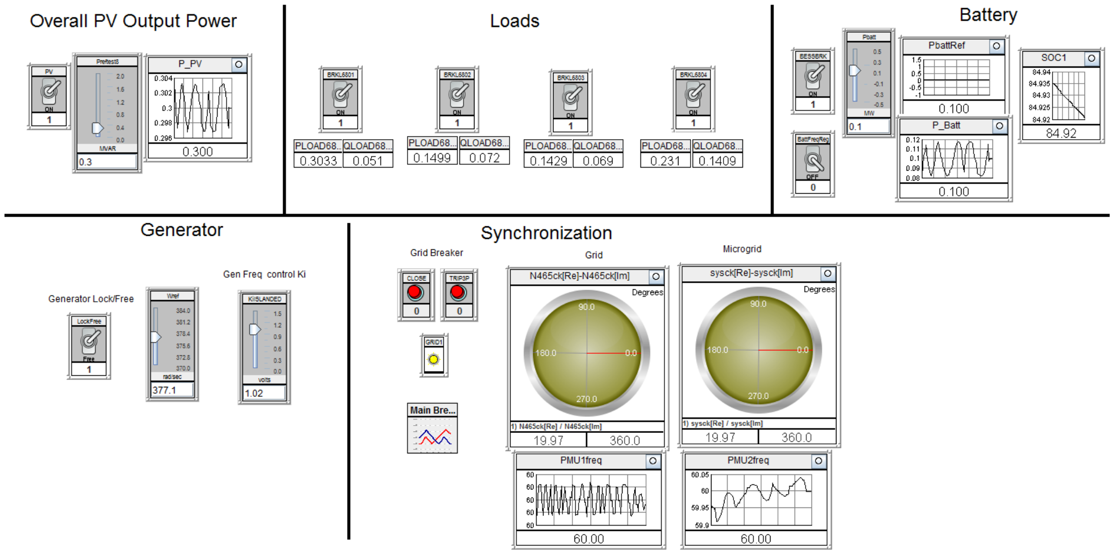

Figure 4. Runtime Controls

During the simulation the runtime file allows the user to control switches, sliders and buttons. The controls in Figure 4 are used to test the synchronization between the MG and electric grid. In this case study, a breaker command is given to synchronize the MG to the electric grid.

The synchro check relay (ANSI/IEEE device 25) is utilized in this case study. This relay can automate closing [16]. The relay will close the breaker when the imputed tolerance limits are satisfied and thus conducting synchronization. The parameters of the synchro-check element are shown in Figure 5.

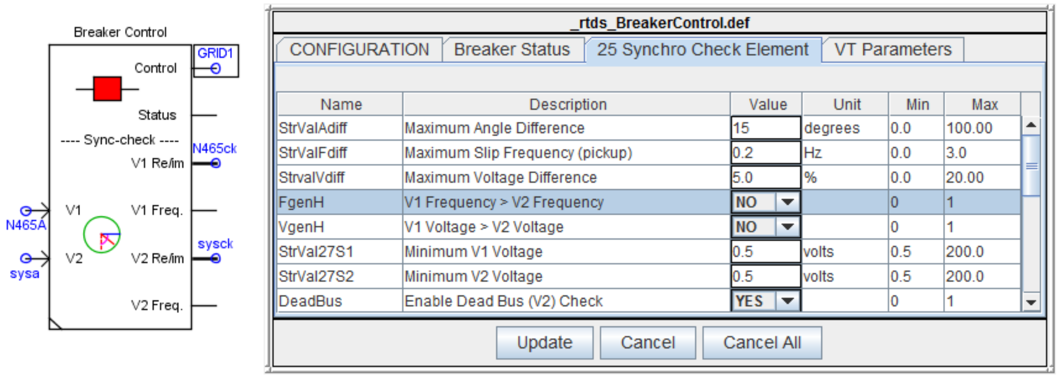

Figure 5. Relay Synchro check element

As you can see in Figure 6, the breaker command is given at 1.97 seconds and the breaker closes at 2.49 seconds, when the tolerance criteria are fulfilled. Since there was a phase angle difference greater than 15° degrees the breaker did not close until the phase difference between the MG and the grid was 15° degrees or less.

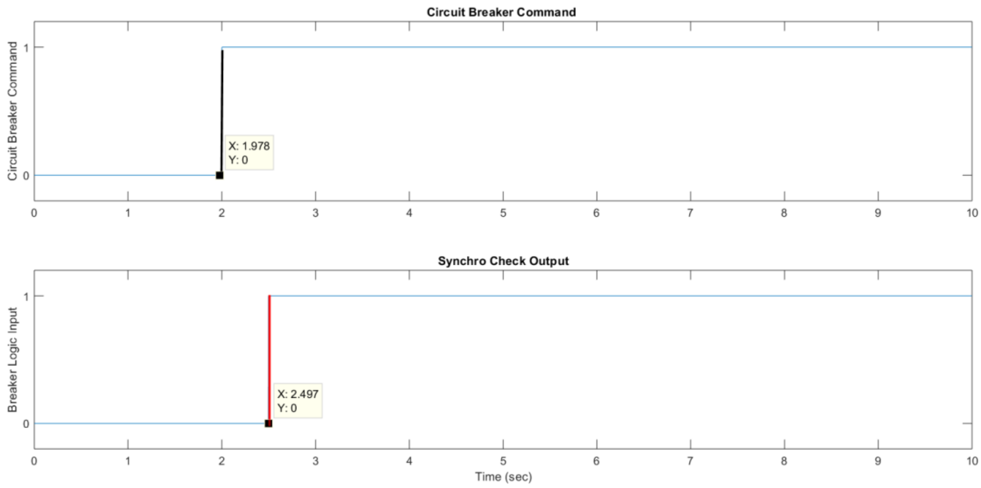

Figure 6. Circuit Breaker Results

In order to correct the phase angle difference previously mentioned, the generators speed was increased, the blue line in Figure 7 shows this action. After this correction the phase, frequency and voltage difference are all within the required limits at 2.5 seconds and the MG and grid synchronized.

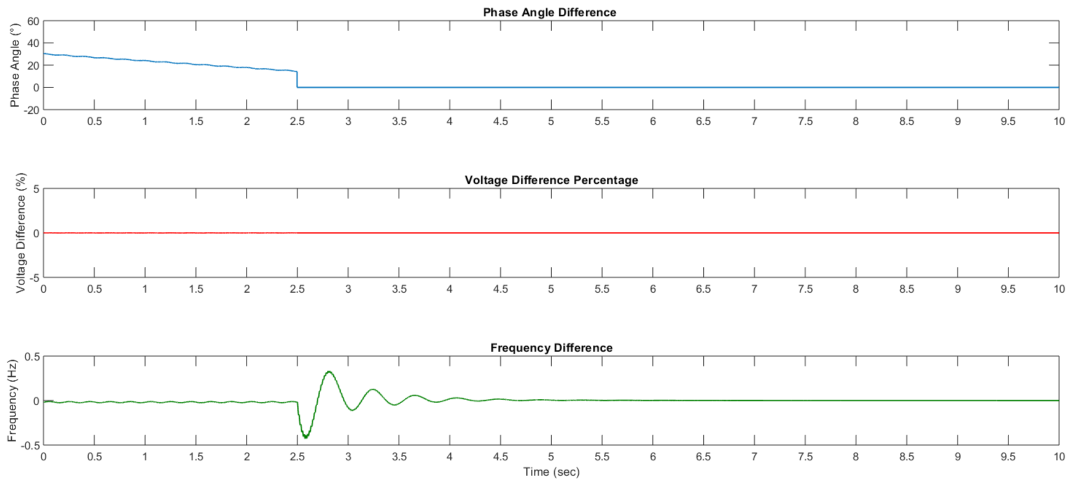

Figure 7. Synchronization Results

B. Battery Storage used to support frequency regulation

As mentioned in section IV, the battery storage can help regulate the frequency due to its fast response time; the controls shown in Figure 2 were implemented in RSCAD, shown in Figure 8.

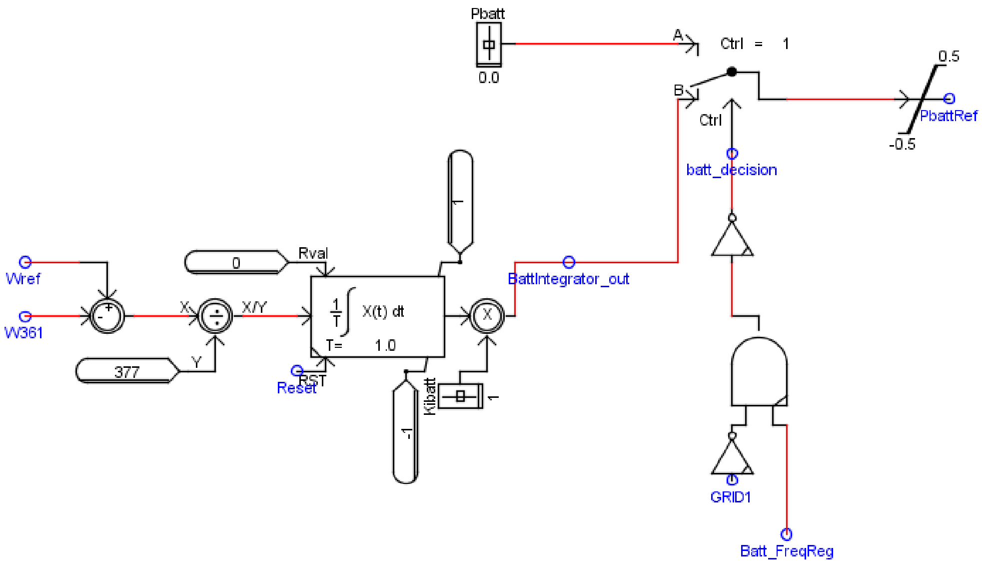

Figure 8. RTDS Frequency Control Circuit Model

In this case study the MG is in islanded mode and the initial load is 0.68MW. During the simulation the load increases by 0.15MW. In the first scenario the battery storage is not used for the assistance of frequency regulation. Only the generator is used for frequency regulation. It takes the system 32 seconds to bring the frequency back to 60 Hz as shown in Figure 9.

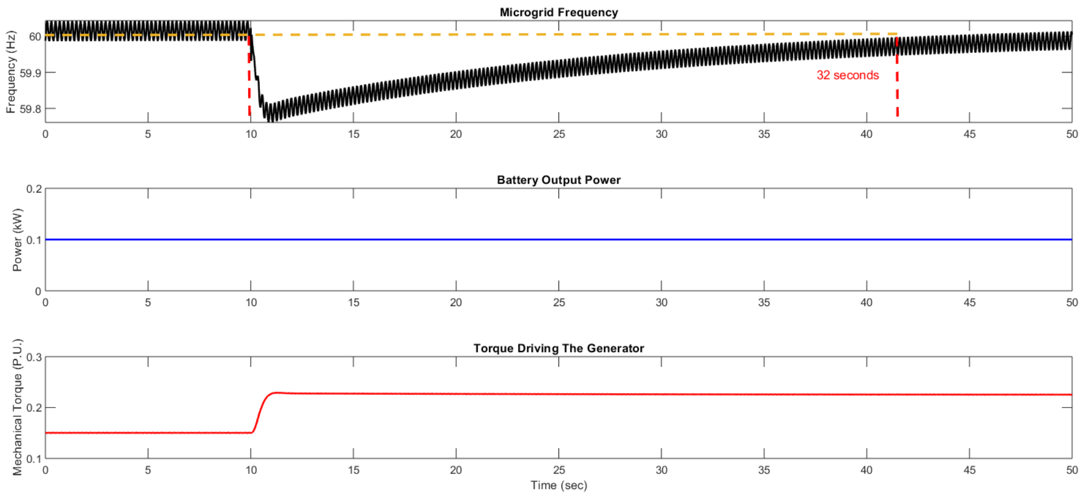

Figure 9. Generator used to regulate frequency

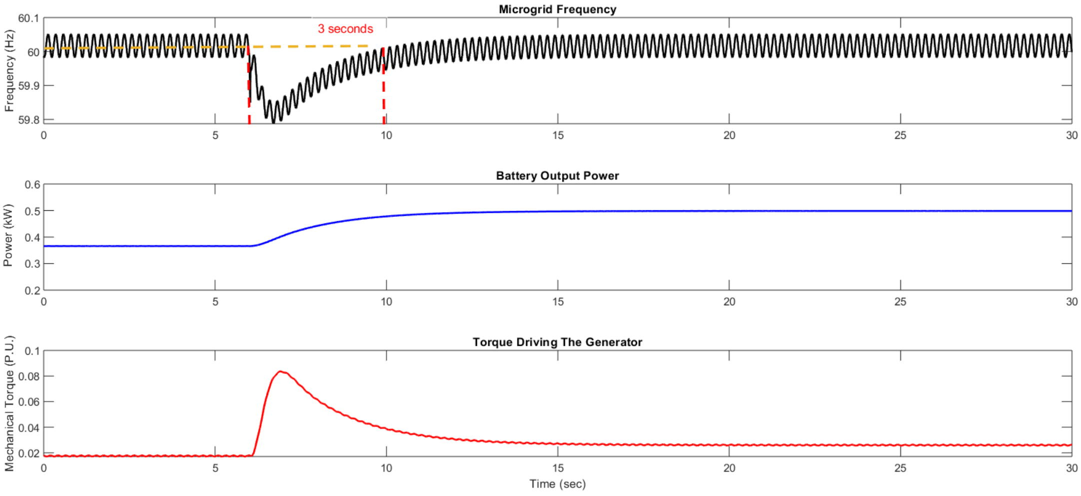

Figure 10. Generator and battery storage are used to regulate the frequency

In the second scenario the battery storage is used to assist the generator to regulate the frequency. It can be observed that with the help of battery storage, desired frequency regulation was achieved within 3 seconds, Figure 10.

II. Conclusion

The need for a robust environmental and economically friendly system created the need for MGs. Part of the Grid Transformation & Security Act calls for Dominion to build a Microgrid Demonstration Project in order to gain real-world knowledge and experience associated with MGs [5].The main goal of having MGs is to provide constant power for critical loads during outage events .The first step in this process is to build a simulation model of the MG in order to analyze the challenges that lay ahead. This paper focused on investigating the feasibility of implementing a MG at Dominion owned facility/campus by conducting load estimation, designing PV generation and battery storage, and constructing a RTDS model in order to run simulations on different case studies. Two case studies that were examined: synchronization of the MG to the grid and using battery storage to support frequency regulation. Based on the simulations above, it has been proven that including a BESS will help the generator maintain the frequency within the permitted range and restore the frequency of the MG to nominal value. Once the BSSE has a SOC of 20% then the battery will turn off, if the frequency still has a deviation from nominal frequency then the generator will continue to regulate the frequency.

Future work includes conducting hardware-in-the-loop testing using relays required at the DG site as well as designing a comprehensive MG Controller that will coordinate and encompass the battery, PV and generator controller.

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