21, rue d'Artois, F-75008 PARIS
http://www.cigre.org

CIGRE US National Committee
2019 Grid of the Future Symposium

A Continuation of Blackstart Studies for Future Scenarios

M. BENNETT
University of Tennessee-Knoxville
USA

R. LIU, Y. WANG, R. SUN, K. THOMAS
Dominion Energy, Inc.
USA

SUMMARY

Restoration plans are guidelines for system operators to use during blackout and blackstart events. However, many utilities face several challenges to their restoration plans including generation retirements affecting the availability of next-start generators and steep increasing levels of renewable generation. This paper addresses the two challenges highlighted by dynamically assessing one of Dominion Energy's blackstart cranking paths and studying the impact of photovoltaic (PV) generation during restoration events. Potentially useful PV inverter control schemes are identified and studied to aid the restoration process. One of the blackstart cranking paths that is currently in Dominion Energy's system restoration plan is studied using PSSE. A 20 MW capacity PV farm located on the path is used to study the impact of PV considering no control scheme, a voltage control scheme, and two active power control techniques: curtailment-based or battery storage. The voltage control scheme is found to successfully mitigate over-voltage from energizing long and extra-high voltage lines. Both active power control techniques improve the frequency nadir although, operational and implementation challenges have been identified for these schemes.

KEYWORDS

Restoration, Blackstart, Renewable Energy, Solar.

mgonza23@vols.utk.edu

I. Background and Introduction

Blackouts can occur for many reasons such as natural disasters, cyber or physical attacks, human error, equipment failures, and so on. The livelihood of many people depends on a properly working electric grid, thus when major events throw the grid into a blackout, it is extremely costly. Not only is it costly for grid customers, but utilities also face expenses as there is an instantaneous loss of income during a blackout and costly repairs that may be required. If the blackout is severe enough such that the entire grid has de-energized, utilities must perform a blackstart. The blackstart process is highly complex and non-trivial since many traditional generation units require external power sources to start-up and generate electricity. Even after generation units have been started, the restoration process is similar to a tightrope walk to balance the frequency and voltage while re-energizing the system. Furthermore, as the duration of a blackout increases, many cooling type loads such as residential air conditioning and refrigerators are more likely to turn on at the same time once power is restored. This effect is known as cold load pickup and if aggregated over an entire feeder, it can increase loading conditions up to 200% for as long as thirty minutes [1].

New environmental rules and regulations placed on utilities to generate cleaner electricity make it economically challenging to justify using traditional generator fuel such as coal. Because of this, generators are being retired across many utilities. Several of these generators being retired pose challenges to Dominion Energy’s system restoration plan because they may limit the options for next-start generation units during restoration and blackstart. Instead, cleaner, natural gas-fueled generators are replacing older generators. On Dominion’s grid, these natural gas generators are located on the 500 kV transmission lines. This fact itself also poses a challenge to restoration plans since it is difficult to maintain adequate reactive resources to reduce the charging capacitance from energizing high voltage transmission lines, especially for a fragile grid in a blackstart scenario.

Looking towards future grids, the variability and availability of solar power is difficult to anticipate, even with forecasts. Unintentional changes in generation supply can dramatically affect the outcome of restoration events, such as load pickup. This lack of controllability is reason enough for utilities to not consider renewable energy during restoration and blackstart. Additionally, even if renewable energy is available during a restoration event, there can be drastic fluctuations in frequency and voltage that may encroach on ride-through requirements causing unintentional tripping. Currently, PV generation and other renewables are disconnected during grid restoration to reduce the chances of failure. However, the push towards providing cleaner energy and the decreasing price of renewable generation will increase the availability of renewable energy. As many states are reaching towards their renewable portfolio standards, the impacts are critical to consider during restoration. By 2033, Dominion Energy will experience an increase in its solar generation fleet with an additional 4.7 GW, more than doubling its current solar penetration, as outlined in the integrated resource plan [2]. This trend is expected to continue in the future and it may eventually become fact that renewables will be a primary source of energy on the grid such that it may be difficult to simply be tripped offline during restoration. With advanced inverter capabilities and fewer restrictions on inverter-based resource operation as set forth in IEEE 1547-2018, PV has the capability to provide both voltage and frequency regulation at the transmission level.

Previously, Dominion Energy conducted a study using PV with reactive power control to mitigate changes in bus voltage during restoration events [3]. The reactive power control scheme was implemented using the PSSE dynamic model discussed in the following section.

However, several points of the study needed to be improved. First, an active power control scheme was not implemented due to the PV model limitations. Second, the location and size of the PV farm was hypothetical to help study a future blackstart path that considered energizing to the 500 kV, large gas-fired generators. To improve upon the previous work, this paper assumes a more realistic scenario and location of PV on one of Dominion’s current blackstart paths. An active power control scheme is developed and implemented in this study using Python API for PSSE. For completion, the reactive power control scheme is also illustrated in this paper. The PV farm studied was assessed and deemed feasible based on its location and point of interconnection. Other criteria are considered that could restrict or inhibit the use of PV such as a minimum ramping rate as outlined by IEEE 1547-2018.

II. PV Dynamic Model

To model a solar plant in PSSE, it must be specified as a wind generator, according to the Siemens documentation. A generic PV plant model is provided in PSSE and the interactions are shown in Figure 1. Irradiance conditions are specified with the IRRADU1 model for up to ten data points in Watts per square meter units. The data points are connected with a linear slope. The efficiency of the PV plant is modified with PANELU1 model by specifying the DC power available for several irradiance levels. The PVEU1 controller of the inverter, which interfaces with the PVGU1 generator model, is capable of constant reactive power injection, constant power factor regulation, or voltage regulation schemes. These control settings only impact the reactive power commands to the model; Active power control cannot be modified. The active power control strategy developed with Python API is outlined in IV(b) for frequency regulation considering a curtailment-based or battery storage method.

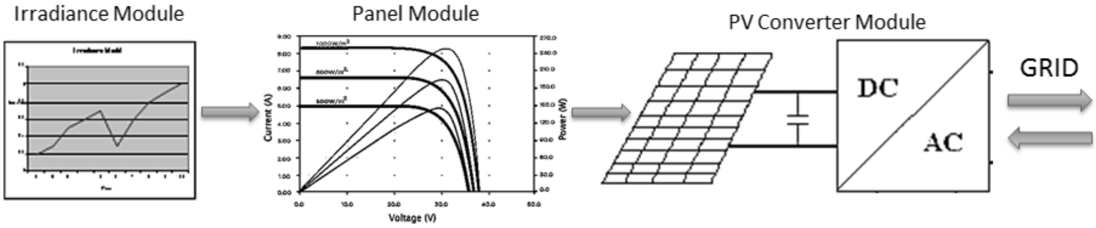


Figure 1. PSSE PV dynamic model diagram

III. Blackstart Cranking Path Dynamic Study

Blackstart paths in the system restoration plan are guides to provide power to critical loads. The definition of critical load can vary by utility and balancing authority but usually, nuclear station service is included. The restoration plan also details the lines that are feasible to energize by taking into account the charging capacitance of the line. The system operations center at Dominion regularly conducts blackstart drills and training for the operators. To aid the training, they have requested dynamic study of several blackstart cranking paths to observe the potential impact to frequency, bus voltage, and generation VAR output. One of Dominion’s current blackstart cranking paths is illustrated in Figure 2. The blackstart generator, roughly 100 MW in capacity, is located close to the nuclear station load. Additional loads are available and are picked up to balance frequency and voltage. Frequency must be maintained between 59.75 Hz and 61 Hz, according to PJM requirements. The voltage should be kept within 90% to 105% of nominal. A 20 MW PV site is located within a short electrical distance to bus C but is not considered in this section. Eventually, as the restoration path grows, the next step is to energize the 500 kV transmission lines. Besides increased line capacity, the 500 kV lines in Dominion are host to large, gas-fired generators that are being considered for next-start generation in future blackstart restoration paths. It is crucial and challenging to energize these lines during the early stages of restoration due to overvoltage and thus is studied in this paper.

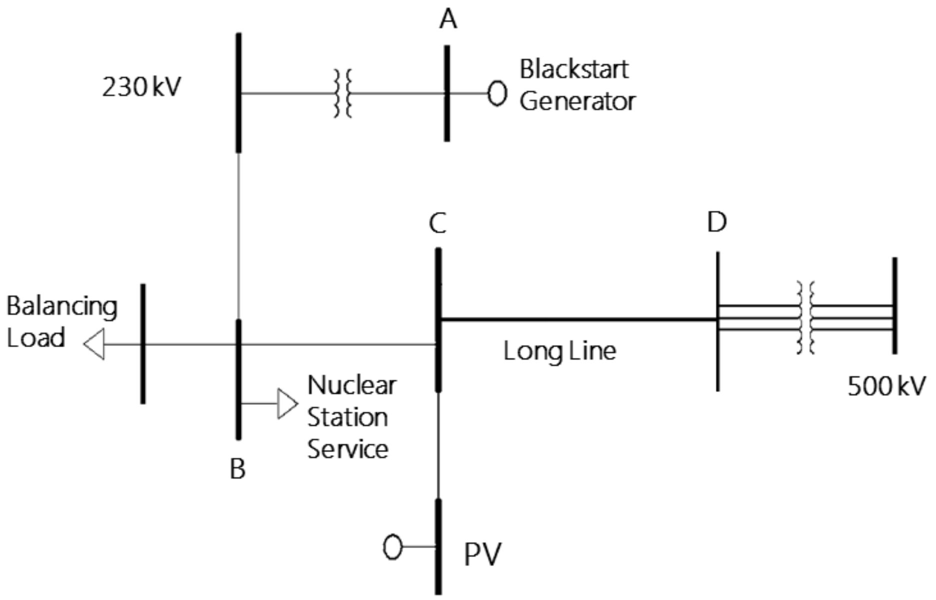
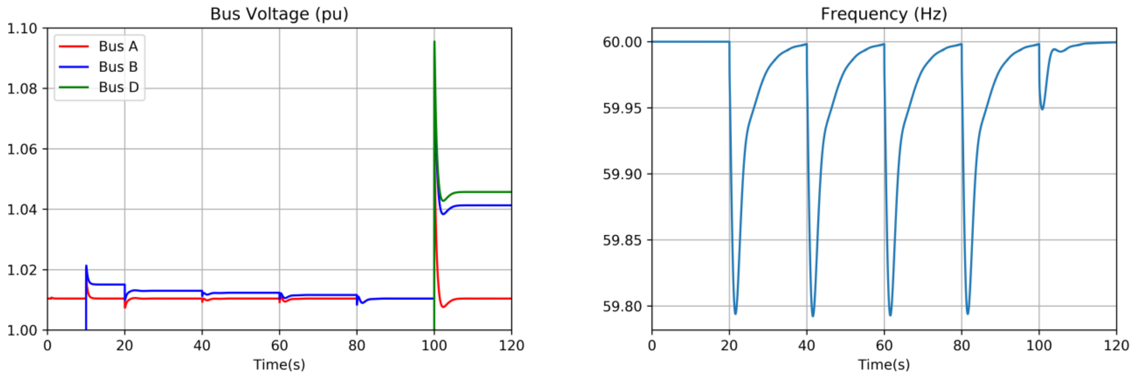


Figure 2. Test case topology



(a) Bus voltage (b) System frequency

Figure 3. Blackstart restoration events

Using the system from Figure 2, several events are studied from a blackstart and are shown in Figure 3. The first event at 10 seconds is the power restoration to the nuclear station service by energizing the 230 kV line between bus A and bus B. It can be seen that neither voltage nor frequency are cause for concern and are within limits. The next event is to energize the line between bus B and bus D although, due to the lightly loaded system, some load needs to be picked up to mitigate potential voltage issues. Dominion Energy system operators are limited on the amount of load picked up in a single step to 5% of the total generation capacity online. In this scenario, only 5 MW load increments are picked up starting at 20 seconds and ending at 80 seconds. Note that this is not a realistic timeframe for restoration events as it usually takes hours longer. The voltage is reduced during each load pickup but the system frequency deviates, within the limit, to around 59.8 Hz. In this scenario, only the blackstart unit is online and operates in isochronous mode. Thus it is able to return the frequency to nominal. It should be noted that this simulation does not represent accurate time duration; it can take hours to energize lines and several loads.

After the system is sufficiently loaded, the long line from bus B to bus D is energized at 100 seconds. Even though this line is a 230 kV line, a large over-voltage transient occurs; despite this, only a minor impact to frequency is observed compared to the previous load pickup events. Overall, this path study scenario represents ideal conditions that could be encountered in blackstart restoration. Since overvoltage occurs in the last step, more balancing load may be picked up prior to energizing the line. The generally accepted guideline within Dominion Energy is to keep voltage at 1% to 2.5% below nominal. A similar study to the one shown in this section has been conducted on several blackstart paths within Dominion's restoration plan. This process has helped identify improvements that can be made for more accurate generator modeling as well as the need for secondary software to study the transients in higher detail.

IV. PV Impact During Restoration

In the future, with fewer traditional generators capable of providing inertia and an increase in renewable generation on the grid, frequency fluctuations may begin to encroach on load shedding thresholds. During fragile grid conditions that can be anticipated for blackstart and restoration, the impact to frequency is amplified due to a smaller system with only one or two generators online. This section discusses the impact of using PV generation during restoration for the test case in Figure 2 after several next-start generators are online and the system load is 150 MW.

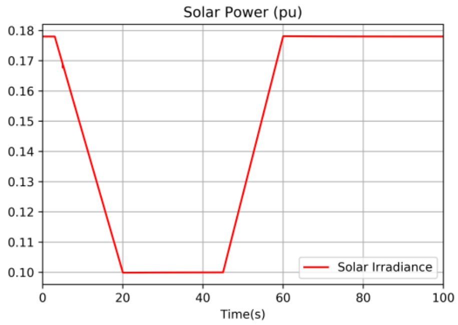
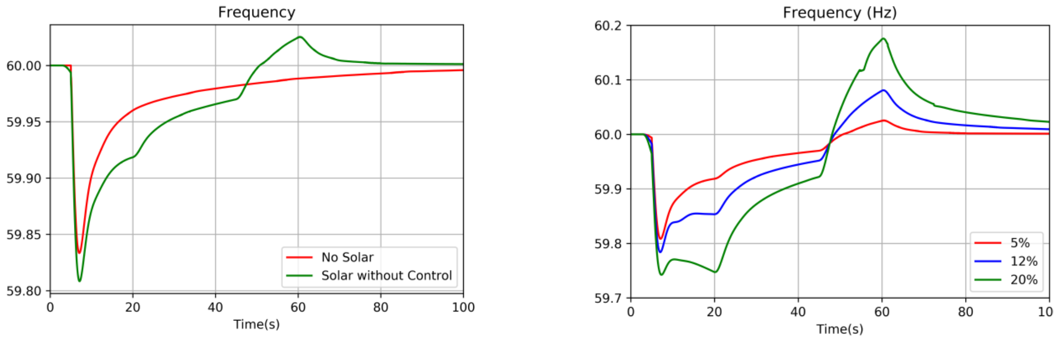


Figure 4. Solar irradiance curve



(a) PV operating at maximum available power (b) Impact of increasing PV penetration

Figure 5. PV impact on load pickup during restoration

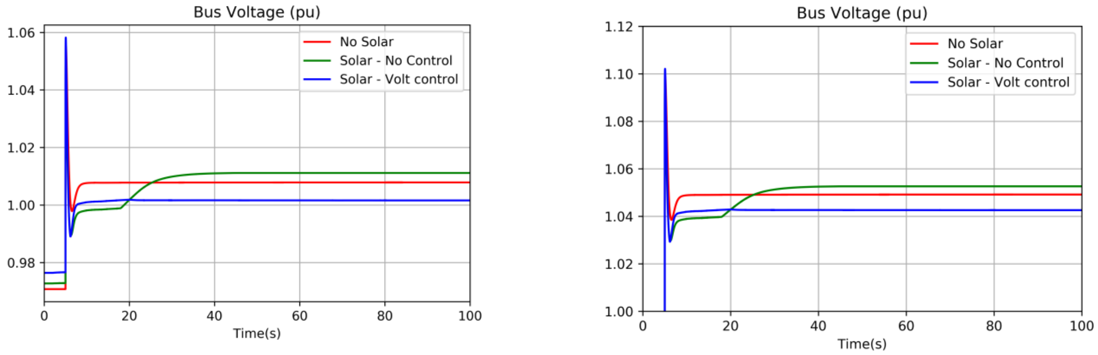
The solar irradiance of the 20 MW PV plant, based on real, historical PV generation data, is shown in Figure 4. A load pickup of 10 MW is simulated at 5 seconds when the solar irradiance is decreasing; the results are shown in Figure 5. If PV operates without any control (i.e. tracking its maximum power available), which is the default mode for PV, then frequency fluctuations when a load is picked up may become worse compared to a scenario without solar as shown in Figure 5(a). This scenario is meant to be a conservative approach for a 20 MW capacity PV farm. If future scenarios are considered with higher renewable penetration, then the effects on the blackstart path can be seen in Figure 5(b) for 5%, 12%, and 20% solar penetration based on capacity. This is a growing concern for utilities since lower inertia grids require faster response times for corrective actions. At 20% penetration, the frequency reaches the under-frequency limit of 59.75 Hz as outlined in the system restoration plan. It is likely for higher penetrations of solar the under-frequency load shedding (UFLS) threshold of 59.3 Hz is reached. During the early stages of blackstart restoration, UFLS is disabled to avoid unnecessary tripping since large frequency deviations may occur when intentionally picking up new load. As the system grows with more lines and loads connected, UFLS is re-enabled and therefore is considered in this scenario with PV online. It should be noted that using PV without any advanced control algorithm is highly unlikely since variances may be challenging to predict and the effects would be worsened in a low-inertia grid. Nonetheless, it is worth considering the advancements in inverter technology and standards that enable PV to provide frequency and voltage control at the interconnection level, such as IEEE 1547-2018. This is discussed in the following subsections.

a. PV to Provide Voltage Support

Energizing high voltage lines during blackstart restoration can be problematic due to overvoltage occurring. The blackstart unit and any other generators online may not have enough reactive power capability to counteract the charging capacitance on lightly-loaded long lines or 500 kV lines. Furthermore, voltage issues usually require a local solution for corrective actions such as static reactors or compensators. Load can be used to reduce the bus voltage but there is scarce availability on extra-high voltage lines, if any. However, it is desirable to reach extra-high voltage lines to help speed up the restoration process since the system can grow at a faster rate, have increased capacity, and yield the possibility for synchronizing to other islands. Dominion Energy has seen the retirement of several generators located on 115 kV and 230 kV lines that served as next-start generators to provided much needed capacity and voltage regulation services during restoration events. This fact forced the consideration of the natural gas generators located on the 500 kV system, which are ideal for restoration due to their large capacity and fast start-up and ramping characteristics; but the challenge remains on how to successfully reach them.

Figure 6 shows the simulation results from energizing a 500 kV line on the blackstart system considered in Figure 2. Three scenarios are studied considering no solar online, solar without control (i.e. in maximum power point tracking (MPPT) operation), and solar with voltage control. This last method is the only one of the three options that absorbs reactive power to mitigate bus voltage changes at the PV site. A constant Q-control method was not investigated since voltage control is able to dynamically vary the reactive power of the inverter as needed for any scenario including injecting reactive power for load pickup events without any additional user input.

The change in voltage due to energizing a 500 kV line for each scenario is shown in Table 1. The percent change is calculated at bus D (230 kV) shown in Figure 6(a). The variation in steady-state bus voltage seen in the ‘no control’ scenario is due to the changing irradiance of PV. These variations do not impact the scenario using a voltage control method due to the available PV reactive power capacity. As is expected, the voltage control method has the best performance at reducing the change in steady-state voltage from pre- to post-event. A similar performance from each of the scenarios was seen when picking up a 10 MW load although on a smaller scale since voltage issues are not as common with load pickup. The transient voltage that occurs when the line is closed does not vary for any of the scenarios, according to PSSE results. This may be due to PSSE limitations for studying transients and consequently, the scenario should also be studied in an electromagnetic transient program.



(a) 230 kV bus voltage

(b) 500 kV bus voltage

Figure 6. Voltage impacts due to energizing 500 kV line

Table 1. Change in voltage at 230 kV bus for energizing 500 kV line

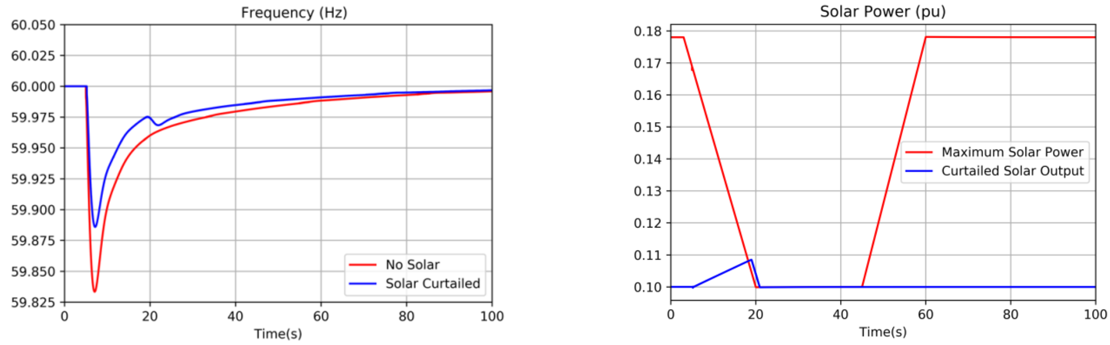
Solar Scenario	**ΔV (%)**
No Solar	3.82
No Control	3.95
Volt Control	**2.58**

b. PV to Assist Frequency Regulation

A change in active power has an inverse relationship to the power system frequency. When load is picked up, the system frequency decreases until generators respond by producing more power. The rate at which it decreases depends on the system inertia. Therefore, in future grid scenarios with higher penetration of renewable energy, fast control algorithms will be necessary to keep frequency within limits.

Due to limitations of the PV dynamic model used in PSSE, the active power control algorithm is implemented using Python API. Two control scenarios are considered: active power curtailment with dynamic headroom and battery storage to regulate frequency. A 3% droop frequency control is implemented to determine the necessary amount of active power injection. The droop control in the curtailment-based method is then limited based on a 20% capacity per minute ramping rate. Lastly, a 17 mHz deadband is implemented based on IEEE recommendations to help mitigate any control issues that may arise due to multiple generators regulating frequency to near nominal.

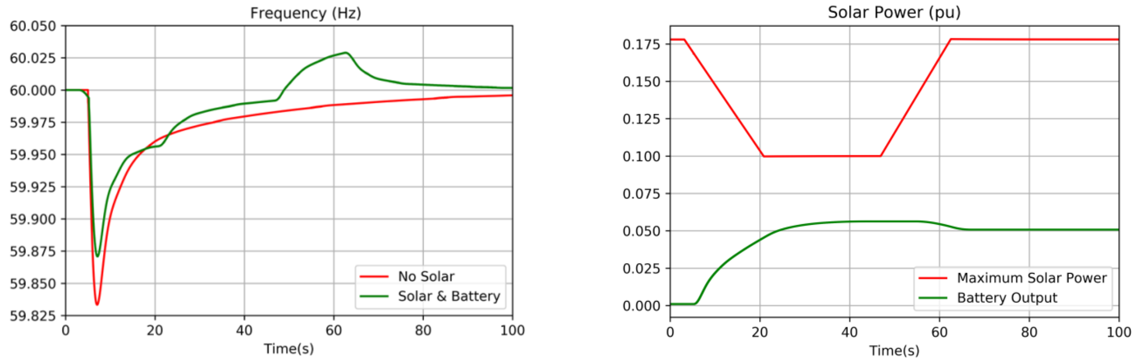
The active power curtailment method keeps track of the maximum irradiance available from the curve in Figure 4 and only provides upward frequency regulation if headroom is available. The PV source is curtailed to 10 MW and has full ramping capability up to the maximum power available, shown in Figure 7(b). The results in Figure 7(a) show a 29.4% improvement to the frequency nadir due to a 10 MW load pickup. Curtailing PV provides a steadier output and therefore reduces and, at times, completely eliminates frequency fluctuations. Although blackstart restoration is a critical process for utilities and may sometimes call for unconventional means to stabilize the system, it may still be difficult to justify discarding available renewable energy via curtailment.



(a) Frequency response (b) Curtailed solar output and max available

Figure 7. Active power control via curtailing PV for 10 MW load pickup

If PV operates using MPPT control to eliminate discarded renewable energy, a battery energy storage system (BESS) can be used to provide frequency regulation. Assuming the battery was successfully charged prior to the event, Figure 8 shows the results of using a 10 MW capacity BESS to provide frequency regulation using a droop control without ramping limitations. The improvement to frequency nadir is about 23.5%. Battery storage is a popular method for peak shifting as its main operation to charge during excess energy and discharge during peak demand, resulting in one or two cycles of the battery during a day. However, to use battery for frequency regulation requires many more charging and discharging cycles based on the number of load pickup events that are performed and thus, deteriorate the lifespan. This is concerning for investors but it should also be noted that blackstart restoration is a critical process that will strain the entire power system and using any and all resources available to reduce the outage duration can be of higher benefit than the lifespan of individual components.



(a) Frequency response (b) Active power injection from solar and battery

Figure 8. Active power control via BESS for 10 MW load pickup

V. Conclusion

Overall, the use of voltage control is successful at mitigating changes in bus voltage due to a 500 kV line energization. The transients were not accurately captured due to the minimum time constant in PSSE therefore software with a smaller time constant, such as PSCAD or RSCAD, should be used to capture the electromagnetic transient. The RTDS platform that interfaces with RSCAD has already been used in many studies related to Dominion's system restoration plan [4]-[8]. The active power control schemes are able to improve minimum frequency from load pickup events but have challenging aspects to overcome such as changes to infrastructure needed for improving communications to PV sites or the cost of a BESS.

Currently, PV is not considered during any blackstart planning due to the relatively small penetration and difficulties in controllability. This paper focuses on the control algorithms for PV that can aid restoration events. However, the goal of this paper is not to justify the use of PV for future restoration but rather to explore the benefits and challenges PV may have to blackstart restoration. Future works include implementing an adaptable control scheme that can switch between reactive power control and active power control depending on the restoration event. Additionally, the impact to system protection settings from the use of PV during restoration should be analyzed to identify if any changes or improvements would be needed.

BIBLIOGRAPHY

[1] M. M. Adibi, *Power System Restoration: Methodologies & Implementation Strategies*. Potomac, MD: John Wiley & Sons. Topic 3, pp. 3

[2] “Virginia Electric and Power Company’s Report of Its Integrated Resource Plan,” *Dominion Energy*, Case No. PUR-2018-00065, Docket No. E-100, Sub 157, May 1, 2018.

[3] M. Gonzalez, H.M. Chou, R. Liu, and K. Thomas, “Blackstart Studies for Future Scenarios.” CIGRE US National Committee – 2018 Grid of the Future Symposium; Reston, VA, 2018, Page(s): 1 – 5

[4] R. Liu, R. Sun, and M. Tania, “Blackstart Hardware-in-the-loop Relay Testing Platform.” CIGRE US National Committee – 2016 Grid of the Future Symposium; Philadelphia, PA, 2016, Page(s): 1 – 5

[5] R. Liu, R. Sun, and M. Tania. "Hardware-in-the-loop relay testing in dominion's blackstart plan." In Power & Energy Society General Meeting, 2017 IEEE, pp. 1-5. IEEE, 2017.

[6] Y. Wang, H.M. Chou, R. Sun et al., “Dynamic study of Dominion’s system restoration plan in RTDS”, IEEE Conference on Innovative Smart Grid Technologies, Washington, DC, Feb. 2019.

[7] Y. Wang, H. Chou, R. Sun et al., “Dominion’s blackstart restoration plan study”, 2017 Grid of the Future Symposium, Cleveland, OH, May 2017.

[8] H.M. Chou, C. Mishra, Y. Wang et al., “Application of RTDS as real-time decision support tool”, 2017 Grid of the Future Symposium, Cleveland, OH, May 2017.