21, rue dArtois, F-75008 PARIS
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CIGRE US National Committee
2019 Grid of the Future Symposium

Modeling of BESS for Blackstart System Restoration Studies

S. SANKAR, N. SHARMA
Black & Veatch
USA

SUMMARY

Transmission System Operators and Owners are required to maintain a Black Start and System Restoration Plan that has been thoroughly verified with studies. Combustion turbines are typically used as Black Start generators, which then are used to start larger coal and combined cycle plants. Steady state and transient studies are normally performed to verify whether voltage and frequency are within limits so as not to interrupt the restoration process, and to ensure large induction motors associated with the power plants can be started. In recent times, Battery Energy Storage Systems (BESS) are being considered for black start system restoration, in lieu of combustion turbines. The models that are currently available for BESS in transmission planning software are meant to study synchronized operation of BESS, rather than an islanded operation. In this paper, a modeling technique is presented for evaluating BESS for black start system restoration. The performance of BESS for black start system restoration is compared with the performance of a combustion turbine.

KEYWORDS

Battery Energy Storage, Black Start unit, Induction motor, Isochronous mode, Frequency and Voltage control

sankars@bv.com

1 INTRODUCTION

Emergency System Restoration plans define the sequence of steps needed to restore critical transmission lines, loads and generation facilities using black start generating resources [1–3]. The black start unit(s) themselves can only supply a small fraction of the system load, hence these units are used to assist in the starting of larger generating units, which need their station service loads to be supplied by off-site power sources. In addition to generating plants auxiliary system loads, other priority loads that need quick restoration may include law enforcement facilities, hospitals and other public health facilities, and communication facilities.

The load picked up during restoration process may include small and large motor loads, lighting load etc. The key concerns during restoration process are the control of voltage and frequency. Both voltage and frequency must be kept within a tight band around nominal values to guard against damage to equipment, and to ensure progress in the restoration process. System protection operations may also occur if voltage or frequency goes outside acceptable ranges. Studies are required to verify voltages and frequency during system restoration process, and two types of analysis are usually performed [4, 5].

1.1 Steady State Analysis

The objective of steady state analysis is to evaluate the following:

- Steady state voltages following line energization.
- Capability of the black starting unit to absorb reactive power produced by the overhead and cable transmission system upon energization.
- Black Start generator capacity adequacy to supply system restoration load.

1.2 Dynamic Analysis

Dynamic analysis is required to verify frequency and voltage deviations during line energization, load pick up and motor start, and make sure they are within acceptable limits. One important evaluation in dynamic analysis is the verification of the largest motor start associated with power plant auxiliary system. This verifies that the voltage supply is strong enough to start the motor so that the voltage dip does not stall motor or cause the motor contactors to drop out. The objective of dynamic analysis is to evaluate the following:

- Load-frequency control - It is important that the system frequency regains its reference value following the start-up of motors or pick up of any system load. The preferred control mode for speed governors associated with black start unit is isochronous or constant frequency control mode. When additional generating units are synchronized, the preferred control mode for speed governors would be droop control mode.

- Voltage control - The black start unit terminal voltage is controlled through the generator automatic excitation system. As load is picked up, proper coordination of generator terminal voltage and transmission/ distribution substation voltages with the aid of capacitors and reactors.

- Large induction motor starting within power plant - Large number of small and medium size motors, and a few large motors constitute auxiliary load of generating units. Fuel and feed-water pump motors, and forced and induced draft fan motors are examples of large motors. The starting of these large motors is often across direct on line. The voltage dip caused during the starting of these large induction motors must be evaluated because magnetic contactors of other motors may drop off if the motor terminal voltage is below 80%.

- System stability - Frequency and voltage stability of the generator in electrical island needs to be evaluated. This will be helpful to assess how much load generator can pick up during the restoration process. The impact of loss of load on frequency and voltage also needs to be evaluated.

- Switching transient overvoltages - Energizing equipment during restoration conditions can result in switching overvoltages. These overvoltages may lead to equipment failure or damage that may hinder system restoration process.

Dynamic simulation such as transient stability study can help in estimating the fundamental frequency voltage and frequency excursions caused during the load pick up, however an electromagnetic transient simulation is required to estimate switching transient over voltages.

2 BESS TECHNOLOGY

2.1 Batteries

The popular battery technologies are flow battery, lithium-ion, vanadium redox flow and lead acid [6]. For the purposes of black-start, the flow battery technology may not provide the high-power requirements needed to address the in-rush requirements of large motor starts associated with coal and combined cycle plants.

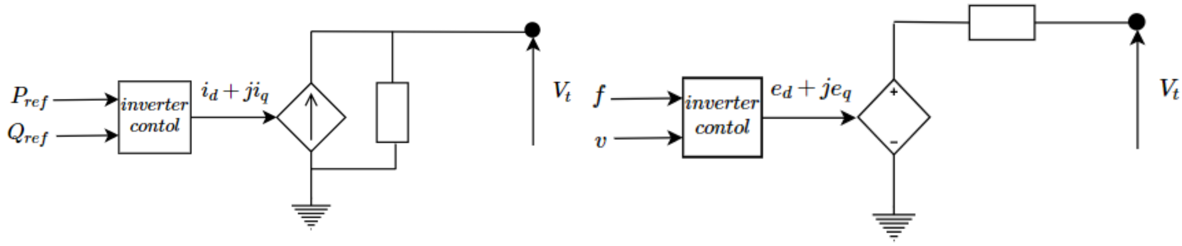
Lead acid batteries are matured and commercially accessible technology, as their design has undergone considerable development. Although lead acid batteries require relatively low capital cost, this technology has inherently high maintenance costs, handling issues associated with toxicity and low energy capability.

Lithium-ion technology has seen a resurgence of development in recent years due to its high energy density, low self-discharge, and cycling tolerance density. The life cycle of Li-ion batteries can range from 2,000 to 3,000 cycles (at high discharge rates) up to 7,000 cycles (at very low discharge rates). Many Lithium-ion manufacturers currently offer 5-15 year warranties or performance guarantees. Lithium-ion battery prices are trending downward, and continued development and investment by battery manufacturers are expected to further reduce production costs.

In this paper, no particular battery technology has been assumed for the modeling and the model presented is applicable for any battery technology.

2.2 BESS Inverter Modeling

The most important aspect of Battery Energy Storage System (BESS) modeling is its converter modeling. Grid connected converters are generally current controlled devices and inject current phase shifted to the grid voltage phase angle such as to provide the required power. These types of converters are called *Grid Following*. On the other hand, islanded inverters (converters) or inverters used for black start purposes need to form its own grid functionality, and they are called *Grid Forming*.



(a) Grid Following Inverter

(b) Grid Forming Inverter

Figure 1: Grid Following and Grid Forming Inverter representation of BESS inverter

The main differences between these two types of converters are:

- *Grid-following inverters* are controlled current sources. Inverter (converter) is controlled to inject a current into the grid that tracks the sinusoidal terminal voltage. The current controlled inverter works under the presumption that a stiff ac voltage is maintained at the terminal and it simply follows the local voltage and inject a controlled current. This type of inverter can only work in grid-connected mode, not in an islanded mode.

- *Grid-forming inverters* are controlled voltage sources. Controller maintains a controlled voltage source and the active and reactive power delivered by the power converter is a function of the ac voltage. These converters can regulate the amplitude and frequency of the grid voltage and can work both in islanded mode and grid connected mode.

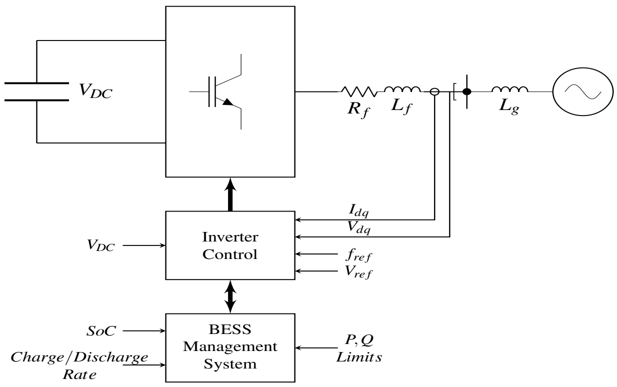


Figure 2: BESS Connected to a grid through VSC

Grid following converter is modeled in transient stability studies as an ideal ac controlled current source in parallel with a shunt impedance as shown in Figure 1a, whereas a grid forming converter should be modeled as an ideal ac voltage source in series with impedance as shown in Figure 1b. A BESS used as a black start unit needs to be modeled as a grid forming converter supplying constant voltage amplitude and frequency in transient stability studies. A general architecture of a BESS is shown in Figure 2. The power conversion unit consists of three phase voltage source converters connected to grid through converter transformer and filter bank. R_f and X_f represent resistance and inductance of combined converter transformer and filter. VDC represents battery and bidirectional DC-DC converter.

BESS is presently modeled as a controlled current source in transient stability programs such as PSS/E and PSLF, and this model is called REGC_A in these programs. A block diagram of this model is shown in Figure 3. The P_{ref} and Q_{ref} from plant controller are used to calculate the inputs to REGC_A block. In response to real and reactive current commands the model injects real and reactive components of inverter current into the external network during the network solution.

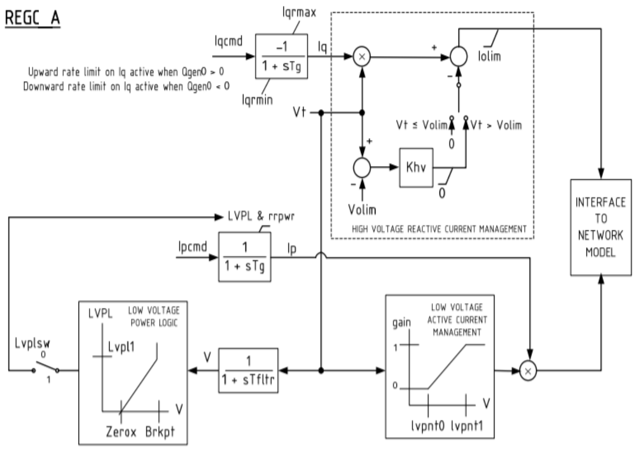


Figure 3: Generic REGC_A Model

The Grid Forming converter is proposed to be modeled as a voltage source and the required output power is obtained by controlling the angle difference between inverters internal voltage and grid voltage [7]. The real power controller as shown in Figure 4 mimics the governor of a synchronous generator. Any imbalance in load will be responded by the controller by changing the voltage angle of the inverter. Here ω^* is the nominal frequency of the inverter. Similarly, the reactive power controller as shown in Figure 4 controls the magnitude of voltage. Here, E^* is nominal set point of d-axis output voltage. The control strategy is chosen such that the output voltage magnitude reference is aligned to $d-$axis magnitude of the inverter reference frame. The current references obtained from reactive power controller, namely I_{p1} and I_{q1}, as shown in Figure 5 along with feed-forward terms are used to obtain internal voltages of the converter. A modulation index of the order of 0.8 was used to calculate the internal voltages of the converter. E_d and E_q are dq axis components of the converter voltage, whereas V_{tdi} and V_{tqi} are the steady state dq-axis components of inverter terminal voltage. This representation of BESS is suitable for both grid and islanded mode. The BESS converter dynamics and DC link dynamics is neglected in modeling as these will have minor impact on fundamental frequency model.

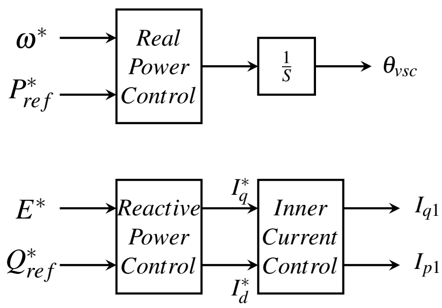


Figure 4: Real power and reactive power control

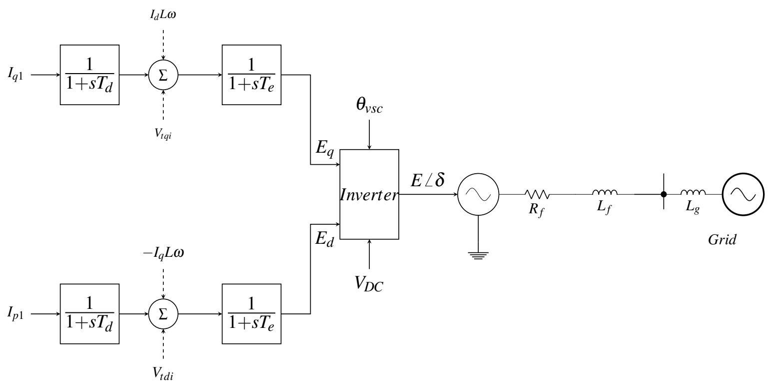


Figure 5: Voltage source representation of BESS

3 SAMPLE STUDY

The application of the proposed model is illustrated using an example system shown in Figure 6. In this example, a BESS is evaluated as a black start generator and its performance is compared with a comparable combustion turbine. The black start generator is considered to be located inside a power plant that requires to be started with the help of black start generator. The largest induction motor rating associated with the generating plant is considered to be 3 MW. In addition to providing the power plant auxiliary system load, the black start generator is also considered to assist system restoration by supplying some critical loads.

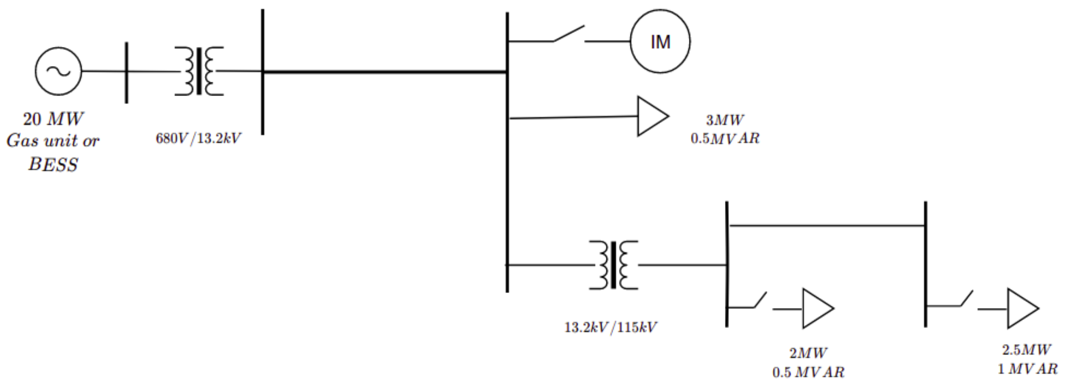
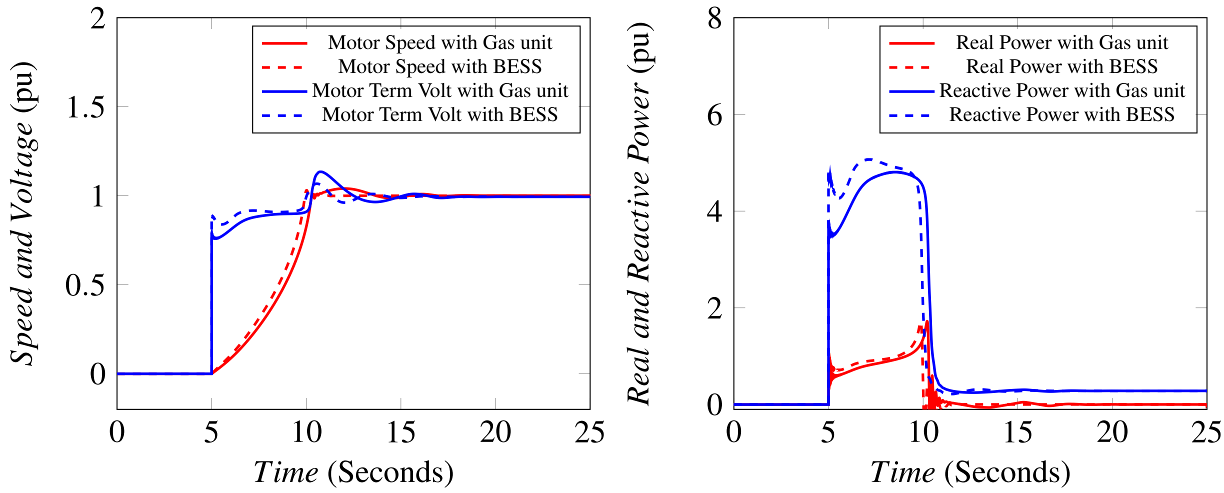


Figure 6: Test System

The BESS model described in Section 2 was implemented in GE PSLF transient stability program. The following sequence of black start system restoration steps were simulated:

1. Black Start BESS or combustion turbine started and stabilized
2. Switch in auxiliary load associated with generator start-up
3. Start the largest motor such as Induced Draft Fan
4. Energize EHV transformer
5. Supply some critical loads
6. Energize a transmission line
7. Supply critical loads

Figure 7 shows the motor terminal voltage and electrical power during motor starting. For comparison purposes, the plots are shown for both BESS and combustion turbine as black start units. As can be seen in Figure 7, the ability to handle in-rush and start-up duration with BESS is comparable to the performance with a combustion turbine generator.

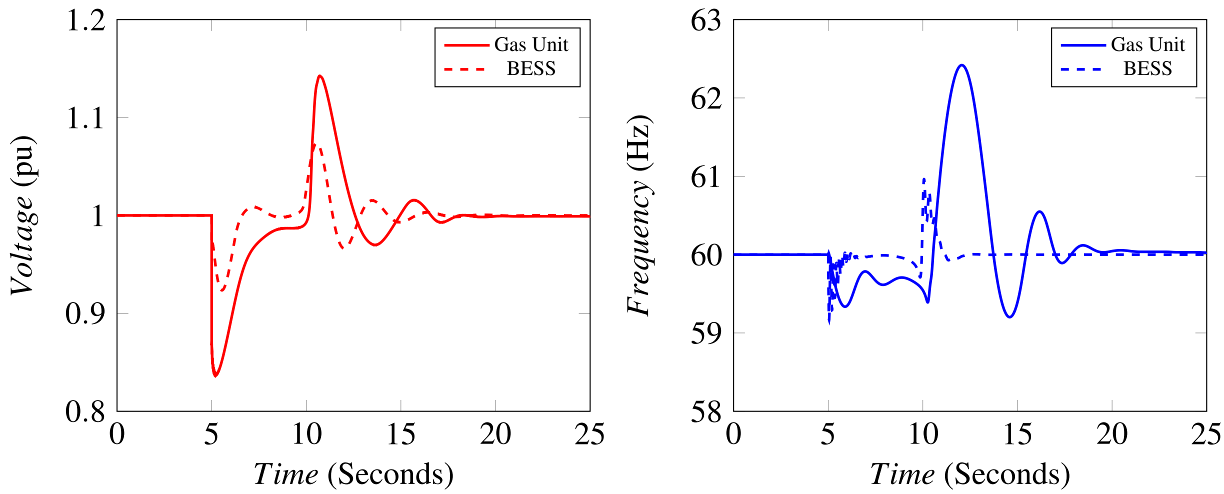


(a) Motor Speed and Terminal Voltage

(b) Motor Real and Reactive Power

Figure 7: Motor Response Comparison with Gas unit and BESS

Figure 8a shows power plants medium voltage bus voltage during motor start. In order for successful system restoration, voltage dip during motor start should not go below 80% of nominal value. Otherwise, it is possible that other motors that are already on-line may drop off, in addition the motor that that is being started. It can be seen from Figure 8a that the transient voltage dip with BESS is lower compared to combustion turbine generator. This is due to the fact that the exciter response of combustion turbine generator is slower than BESSs reactive power controller.



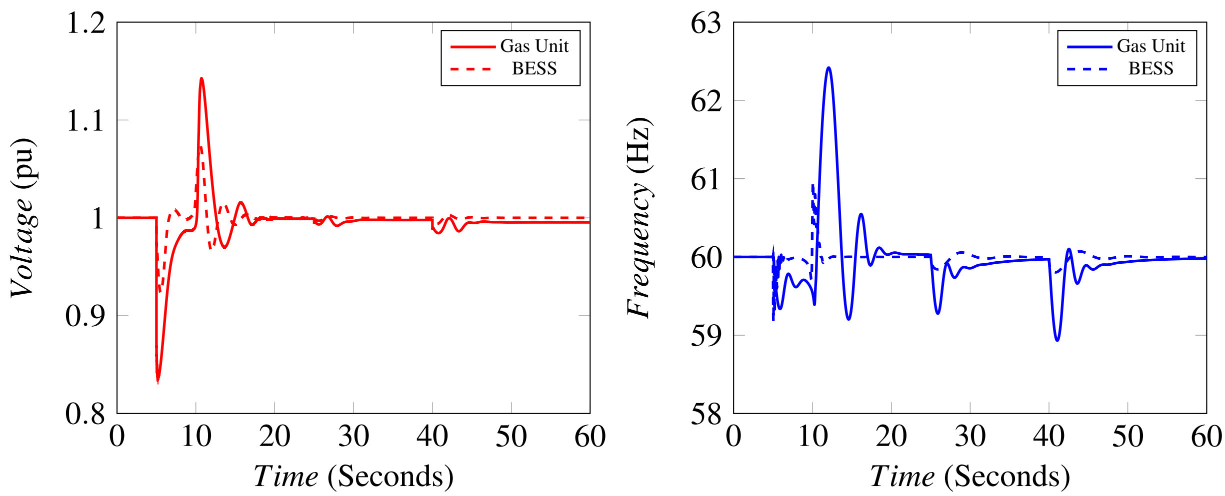
(a) Generator Terminal Voltage

(b) Generator Bus Frequency

Figure 8: Generator terminal voltage and frequency comparison during induction motor starting

Figure 8b shows medium voltage bus frequency during motor start for BESS and combustion turbine generator scenarios. During the motor in-rush period, high current is drawn which causes frequency to drop and then it recovers back once the motor reaches its rated speed. With combustion turbine, there is relatively large overshoot of frequency due to inertia compared to BESS scenario.

Figure 9 shows voltage and frequency during the entire system restoration process including initial motor start, line energization and load pickup. As can be seen in these figures, the performance of BESS as a black start unit is comparable to a combustion turbine. In some aspects, such as voltage and frequency excursions, BESS presents as a better candidate.



(a) Generator Terminal Voltage *(b) Generator Bus Frequency*

Figure 9: Generator Terminal Voltage and Frequency Comparison

4 CONCLUSION

Emergency System Restoration plans define the sequence of steps needed to restore critical transmission lines, loads and generation facilities using black start generating resources. The load picked up during restoration process may include small and large motor loads, lighting load etc. The key concerns during restoration process are the control of voltage and frequency. Both voltage and frequency must be kept within a tight band around nominal values to guard against damage to equipment, and to ensure progress in the restoration process. Dynamic analysis is required to verify frequency and voltage deviations during line energization, load pick up and motor start, and make sure they are within acceptable limits. In recent times, Battery Energy Storage Systems (BESS) are being considered for black start system restoration, in lieu of combustion turbines. The models that are currently available for BESS in transmission planning software are meant to study synchronized operation of BESS, rather than an islanded operation. In this paper, a modeling technique was presented for evaluating BESS for black start system restoration. The performance of BESS for black start system restoration was compared with the performance of a combustion turbine.

BIBLIOGRAPHY

[1] Power System Restoration Dynamics (Issues, Techniques, Planning, Training & Special Considerations) IEEE Power & Energy Society, Power System Dynamic Performance Committee, Power System Stability Controls Subcommittee, Restoration Dynamics Task Force, 2014.

[2] Report on the FERC-NERC-Regional Entity Joint Review of Restoration and Recovery Plans (January 2018) (Restoration and Recovery Report), https://www.ferc.gov/legal/staff-reports/2018/bsr-report.pdf
[3] ISO New England - 2017 Black Start Study, https://sandbox.iso-ne.com/static-assets/documents/2018/08/a4.0_rc_tc_2018_08_07_08_2017_black_start_study.pdf
[4] J. Feltes and C. Grande-Moran, "Down, but Not Out: A Brief Overview of Restoration Issues," in IEEE Power and Energy Magazine, vol. 12, no. 1, pp. 34-43, Jan.-Feb. 2014
[5] M. M. Adibi, Power system restoration, methodologies, and implementation strategies, IEEE Series on Power Engineering, Ed., 2000.
[6] IRENA , Battery Storage : Case Studies, https://www.irena.org/documentdownloads/publications/irena_battery_storage_case_studies_2015.pdf
[7] N. Sharma and S. Sankar, "Modeling and Control of Battery Energy Storage System for Providing Grid Support Services,"2018 Clemson University Power Systems Conference (PSC), Charleston, SC, USA, 2018, pp. 1-5.