Design of Energy Storage System to Improve Inertial Response for Large Scale PV Generation

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Abstract—With high-penetration levels of renewable generating sources being integrated into the existing electric power grid, conventional generators are being replaced and grid inertial response is deteriorating. This technical challenge is more severe with photovoltaic (PV) generation than with wind generation because PV generation systems cannot provide inertial response unless special countermeasures are adopted. To enhance the inertial response, this paper proposes to use battery energy storage systems (BESS) as the remediation approach to accommodate the degrading inertial response when high penetrations of PV generation are integrated into the existing power grid. A sample power system was adopted and simulated using PSS/E software. Impacts of different penetration levels of PV generation on the system inertial response were investigated and then BESS was incorporated to improve the frequency dynamics.

Index Terms--Battery energy storage system; frequency stability; inertial response; PV generation.

I. INTRODUCTION

Because of the implementation of power electronic devices used to couple renewable generation systems to the existing grid, system inertia provided by conventional generation units cannot be compensated by renewable generation unless special countermeasures are taken [1-10]. This degradation is especially prevalent with large-scale integration of photovoltaic (PV) generation. Unlike wind generation, no rotational mass is present in PV systems; therefore, PV systems contribute no inertial response when disturbances occur on the grid. This situation is becoming even worse considering that some of the existing traditional power plants will be retired and replaced by renewable generation within the next few decades. Not only will the inertia associated with the rotational mass be depleted, but also the power system stabilization capability provided by some existing generators will also vanish with the removal of the synchronous machines [11].

Different approaches to accommodate the degrading inertial response in cases of high penetrations of PV integration have been proposed in the open literature. One possibility is to increase frequency reserve capacities by adding more traditional generators online, but this option is not cost-effective and frequent attempts to accommodate the intermittences from PV generation cause additional wear-and-tear on power plant

components [12]. Another approach is to operate the PV plants at non-maximum power output, i.e., a de-rated generation level. The spare capacity (analog to the spinning reserve in conventional plants) is reserved to provide inertial response in case of a disturbance. Drawbacks of this approach include the complex control system that must be implemented and, most importantly, the suboptimal operation of a PV system so that it can operate as spinning reserve during most of its operation [13].

In this paper, a battery energy storage system (BESS) is adopted to achieve a satisfactory grid inertial response with high penetration levels of renewable generation. The control scheme of the BESS for provision of inertial response was devised and built up based on the control blocks provided by the PSS/E software package. The sample power grid system associated with the PSS/E package, including the steady-state and dynamic models, was adopted and different scenarios with different PV penetration levels were simulated to investigate the impact of high PV penetrations on the system inertial response. For the cases in which the frequency response deteriorated to the point that violations on the grid operation requirements were observed, BESS was integrated to investigate its ability to improve system inertial response.

This paper is arranged as follows: a brief background review of this study is provided in Section I, followed by the system description to be investigated, as given in Section II. The modeling techniques adopted for the PV generation system and BESS are presented in Section III. Simulation results are presented in Section IV. Concluding remarks are given in Section V.

II. SYSTEM DESCRIPTION

The power conditioning system (PCS) for solar power plants (and other types of grid-connected renewable energy sources, such as wind and fuel cells) may have different architectures—for example, a single-stage (grid-connected inverter-only) or a two-stage (a DC-DC converter and a grid-connected inverter) PCS [14, 15]. The latter structure, shown in upper part of Fig. 1, is more popular and was selected to interface a PV power plant with a transmission network because it may provide an extra degree of freedom of control. In this topology, the PV-connected DC-DC converter functions to

continuously track the maximum power point (MPP) of the solar power plant by regulating the PV modules' output voltage. The DC-DC converter steps up the solar DC output voltage to a higher level than that at the point of interconnection (POI) to the grid such that a step-up transformer may not be needed for a voltage source inverter to inject power into the grid. This approach has been proposed in transformer-less PV inverter studies by using emerging power electronic devices with high power capacity (see [16-18]). In this paper, this costly approach is not adopted, and a step-up transformer is utilized. The grid-interfaced inverter is controlled to convert the DC to alternating current and regulates the real and reactive power flowing into the grid instantaneously and independently.

Fig. 1. Overall system diagram of a PV BESS.

In the lower part of Fig. 2, a BESS is shown to be connected to the power grid through a similar PCS configuration as the PV system. From the topology it is seen that the only difference between the two configurations is that a bi-directional DC-DC converter is utilized to manage the two-way power flow into and out of the BESS. The designed BESS can store the excess energy in the existing power system and release energy to support the grid when the system power is deficient. This charging/discharging process is managed by regulating the BESS input current via adjustment of the associated DC-DC converter connected to the BESS to provide various grid support capabilities. This paper focuses on the application of a BESS in inertial response improvement for the large scale integration of PV systems, as will be detailed in the following sections.

Fig. 2. Interaction diagram of PV system modules in PSS/E.

III. MODELING OF PV AND BESS CONVERSION SYSTEMS

The electrical models of the PV system and BESS with their associated control systems in PSS/E will be briefly introduced [19, 20].

A. PV System

As shown in Fig. 2, the PV system dynamic model in PSS/E is developed to simulate the performance of a PV plant connected to the grid through a power electronics based conversion system. This model includes four components.

which are a converter module (PVGU), a converter control module (PVEU), a panel module (PANEL) and an irradiance module (IRRAD).

In Fig. 2 the IRRAD module provides the capability to input an irradiance profile including up to ten (10) data points in terms of time and irradiance values. At each simulation step, the module will calculate the linearized irradiance value. Then the irradiance value is fed to the PANEL module which calculates the DC power from the PV plant at the corresponding irradiance level based on I-V curves from PV manufactures.

The converter module (PVGU) calculates the current injection to the grid based on filtered active and reactive power commands from the electrical control module (PVEU). Both components of the injected current are processed under the high/low voltage conditions by means of the specific logic diagram as shown in Fig. 3, which is re-produced and revised from [19].

Fig. 3. Diagram of PVGU module in PSS/E.

The core component in the converter based conversion system is the associated control system. In PSS/E, the electrical control module for the PV generation system (PVEU) is shown in Fig. 4. The control system consists of decoupled active and reactive power control logics to achieve different regulation objectives.

Fig. 4. Diagram of PVEU module in PSS/E.

B. BESS Modeling and Control System

The BESS model in PSS/E is developed to simulate the dynamic characteristic of the battery system in providing different grid support functions including transient stability, damping and limiting frequency excursions, which is the main task to be investigated in this study. The BESS is also interfaced with the grid via its power converter systems. Therefore, the BESS model in PSS/E includes the converter module and the associated control system. The modeling technique for the voltage source converter in the BESS is to assume it performs as a synchronous generator in terms of the

decoupled active and reactive power control capabilities. The modeling diagram of the BESS is shown in Fig. 5.

As shown in the lower part of Fig. 5, the BESS reactive power control scheme is to emulate the automatic voltage regulator (AVR) function in the synchronous generator for purposes of manipulating the terminal voltage, which is out of scope for this paper and details of the model parameters can be found in [19].

In the upper part of Fig. 5, the BESS active power output, P_{OUT} instantaneously follows its command signal, P_{AUX} together with the initial value with power and current limits set by the BESS ratings. Then the energy extracted from and absorbed into the BESS is calculated based on the discharging and charging efficiencies, respectively. As mentioned above, the main purpose of the BESS in this study is to provide inertial response so that the active current is assigned higher priority and the reactive current is derived from the equation at the lower right corner based on the converter current limit.

Fig. 5. BESS modeling diagram in PSS/E.

The P_{AUX} input signal in Fig. 5 is obtained from the battery control block, which is implemented by an auxiliary signal model manually integrated through an internal PSS/E statement CONEC. In this study, the auxiliary signal module is CPAAUX and it can provide the P_{AUX} signal from the frequency deviations at a designated bus, as shown in Fig. 6.

Fig. 6. Diagram block of auxiliary signal model CPAAUX.

The CPAAUX model attains the frequency deviation signal from the bus ID to be regulated and filters it before feeding it to a proportional gain controller, C_m . With capacity limitations applied, the auxiliary power signal is generated and supplied to the BESS model as the active power reference. Additional analysis has been conducted to evaluate the T_a and T_b values on the dynamic performances of the BESS control system. The details of related findings and the adopted Bode plot approach will be presented in a future publication. Based on those observations, the values of T_a and T_b are assigned to be 0.1 and 100, respectively, to achieve favorable dynamic performance for the interested frequency range around 0.1 Hz.

IV. SIMULATION RESULTS

The one line diagram of the simulated the power system is shown in Fig. 7. In the base case scenario, there are 6 synchronous generators, 23 branch lines, 8 loads and 23 buses existing in the system. The voltage levels range from 13.8 kV to

500 kV and total load capacity is 3.26 GW. Bus 3011 in AREA 5 is assigned to be the swing bus in power flow calculations. For the dynamic models, all the generators are initially equipped with PSS2A type power system stabilizers (PSS). In this sample power grid, the PV plants with various capacities ranging from 100 MW to 1 GW (around 30% of the load capacity) will be integrated into the system and allocated at different buses. Then the frequency profiles at Bus 101 are monitored for reference to compare the impact of the different scale of PV penetration on the frequency performance and the appropriate improvement provided by the associated BESS. Part of the simulation results will be presented in this section. Interested readers can find the controller parameters used in the studies from [19].

A. Case study 1: Impact of different penetration levels of PV on inertial response

In this case study, the PV model depicted in Section III.A is implemented and for the IRRAD module, a fast cloud transient profile observed from Long Island Solar Farm (LISF) located at Brookhaven National Laboratory is adopted as the input. The cloud transient induced irradiance dip lasts for around 10 seconds, as shown in the middle part of Fig. 8 and highlighted by the solid line. For illustration purposes, the irradiance values at other time instants are assumed constant at the original value of 1000 W/m² as indicated by the dotted line sections. It is noted that in this study the temporal and spatial discrepancy between the different PV plants located in the power grid has not been considered such that a unified irradiance profile, such as that shown in Fig. 8, was applied to the IRRAD modules associated with all PV models if multiple PV plants are considered, as mentioned in the following case studies.

The first study starts with replacing the 100MW generator connected at Bus 3018 with a 100MW PV plant. The dynamic simulation is conducted using the irradiance profile shown in Fig. 8. Then the capacity of the PV plant is increased in steps of 100 MW up to 300 MW to re-do the dynamic simulations. With further increments of the PV generation at the single location of Bus 3018, the system cannot handle the large amount of power exportation to the rest of the power grid and the power flow solution will not converge. Therefore, for the cases in which the PV capacity is above 300 MW, different PV plants are incorporated to simulate the distributed PV generation scenarios within the systems. For those cases, there is a 400 MW PV plant connected to Bus 3018 for the 400 MW case and an additional 200 MW connected to Buses 101, 102 and 206 for the 600, 800 and 1000 MW cases, respectively. The monitored frequency deviation at Bus 101 is shown in Fig. 9 in different colors.

From Fig. 9 one can observe that the frequency deviation at Bus 101 increases with the higher PV penetration levels within the grid for the same cloud transient situation. For a low penetration level of PV integration up to 800 MW, the system can endure the transient in terms of frequency stability without triggering under frequency protection devices. However, for the case of 1000 MW PV integration case, the frequency drops more than 0.5 Hz or 0.0083 p.u. during this transient, which may violate the under frequency setting and trip the generator connected to Bus 101, according to NERC requirements. This will significantly impact the power supply to the loads in the system due to the shortage of generation. In the worst case a cascaded event could be induced if the system was not properly designed and operated.

B. Case study 2: Integration of BESS for improvement of the inertial response

After the BESS control system parameters are suitably selected, as described in Section III.B, different capacities of

BESS are connected to Bus 101 to investigate their impact on the frequency deviations. The frequency deviations at Bus 101 for different BESS capacity are monitored and plotted in Fig. 10.

Fig. 7. Sample power system, SAVNW provided in PSS/E [19].

Fig. 8. A typical irradiance profile collected at LISF used in the case studies.

Fig. 9. Frequency deviation at Bus 101 for different penetration levels of PV generation.

In Fig. 10, the frequency deviation profile at Bus 101 for the 1000 MW PV integration is indicated by the dark green line, the nadir of which case drops below the critical setting point of 0.0083 p.u. With 200 MW BESS connected to Bus 101, the frequency deviation is improved and is less than 0.006 p.u. This is sufficient to enable the system to ride through the solar transient event. With incremental additions to the BESS capacity, the frequency performance of the system can be improved further. By implementing different capacities from 200 to 700 MW of BESS, their functions in frequency correction can be as much as 0.38 Hz, i.e., from 0.0085 p.u. to 0.0021 p.u. This shows that by incorporating the BESS into the system, the system frequency stability can be well enhanced under the high penetration level of PV generations. However, it can also be observed that the frequency performance improvement for BESS capacity of 600 against 700 MW is very marginal, as can be seen by comparing the bright green line with the purple line; therefore, it would not be economical to invest more on BESS to improve the inertial response in this case. This demonstrates how this type of analysis can be used to find the optimal size of energy storage.

V. CONCLUSIONS AND FUTURE WORK

As conventional generators are replaced by high-penetration levels of PV generation, the power system inertia will be significantly reduced. A BESS integrated PV

generation system was investigated in this paper for improving system inertial response. Extensive simulations have been conducted to investigate, 1) the impact of high penetration levels of PV generation on the system inertial response, and 2) the benefit of BESS in improving inertial response for high PV penetration levels. The studies showed that the frequency stability may be problematic with high penetrations of PV generation in the system if it is not properly accommodated. A BESS with an appropriate control system can be a potential solution to resolve the challenge. In addition, the investigated system can provide ride through capabilities for other system transients in addition to the ones induced by solar transients. The required BESS capacity to accommodate the combination of such internal system disturbances as loss of generator or sudden increment of loads and solar transients needs to be investigated. This will provide the system operators a fruitful insight on how to use BESS for provision of ancillary services to ride through the more complicate contingencies. Further studies on the reactive power control capability of the BESS can also be conducted.

Fig. 10. Frequency deviation at Bus 101 for different BESS capacities to improve the 1000 MW PV generation case.

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