Tie-Line Bias Control of a Power System with Large PV Plants Using PMU Information

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SUMMARY

The increasing penetration of uncertain and variable renewable energy into the transmission grid introduces challenges in real-time power system operation. A photovoltaic (PV) system’s power output fluctuation due to weather conditions (irradiance and temperature) causes the system’s frequency to fluctuate. The power and frequency fluctuations in systems with large MW PV plants raise dynamic and transient stability concerns. In this study, a two-area power system with large MW PV plants was considered, in which Area 1 provided power support to Area 2. To minimize power fluctuations and maintain the desired system frequency while concurrently maximizing the penetration of PV power into Area 2, automatic generation control (AGC) with tie-line bias control was implemented. The objective was to increase/decrease generations in Area 1, thus varying the tie-line power flow to balance out the PV power variability. Furthermore, phasor measurement unit (PMU) data were used in the AGC to drive the tie-line bias control. Typical results are shown for the steady state, variable PV generation and large tie-line disturbance conditions.

KEYWORDS

Large PV plants, phasor measurement units, tie-line bias control, tie-line power flow and frequency control
1. Introduction

The penetration levels of photovoltaic (PV) systems in Japan, Germany, Spain and many other countries are rising because of both the improved generation efficiency of PV modules and government subsidies. Concerns exist regarding the reliability and security of operating power systems with a high penetration of renewable energy resources. High photovoltaic (PV) penetration levels can significantly affect both the steady state and transient stability of the systems because the sun does not shine on demand [1]. In order to maximize the penetration of renewable energy, alternative power or demand side management technologies are needed. These sources could include energy storage, a tie to a neighboring power system with excess generation (preferably from clean sources), etc. PV power is difficult to predict and depends primarily on weather conditions and cloud movements. Cloud cover passing over a PV plant is as serious as the loss of a generator the size of the plant.

Furthermore, unlike conventional generators, PV plants usually are connected to the grid through power electronic converters, which reduces the system’s inertia [2]. The power and frequency fluctuations in systems with large MW PV plants raise dynamic and transient stability concerns [3, 4], even more so than in the case of systems with wind turbines, which actually have some kinetic energy available, because solar panels are virtually inertialess. The rate of change of frequency (ROCOF) increases as a result. When a frequency event occurs, the conventional synchronous machines will inject or absorb kinetic energy into or from the grid to counteract the frequency deviation. It is therefore critical to utilize power and energy sources that have fast charge and discharge characteristics. Battery energy storage units and supercapacitors, while ideal, are only feasible for smaller power systems. For bulk power systems, these storage technologies are expensive. On the other hand, in multi-area interconnected power systems, it is possible to identify potential areas for the integration of large PV plants, as well as areas with appropriate control technologies for balancing power and frequency fluctuations in the system caused by large variable and uncertain PV penetration.

In this study, a two-area interconnected power system, in which Area 1 provided power support to Area 2 and which had large MW PV plants, was considered. To minimize power fluctuations and maintain the desired system frequency while concurrently maximizing the penetration of PV power into Area 2, a secondary control, automatic generation control (AGC) with tie-line power flow control, was implemented [5, 6]. The objective was to increase/decrease generations in Area 1, thus varying the tie-line power flow to balance out the PV power variability. Furthermore, synchrophasor data obtained from the phasor measurement unit (PMU) were used in the AGC to drive the tie-line bias control. A real-time model of a 200MW PV plant and a two-area, four-machine power system was developed using the real-time digital simulator (RTDS) [7]. Typical results are shown for steady state, variable PV generation and large disturbance conditions.

The remainder of the paper is organized as follows. Section II describes the real-time model of a power system with large PV plants. Section III discusses the real-time monitoring of the tie-line frequency using PMUs. The real-time control of the tie-line bias is discussed in Section IV, while Section V presents the typical results under steady state, variable and large disturbance conditions. Finally, some conclusions and directions for future work are offered in Section VI.

2. Real-Time Modeling of the Power System

A 200 MW PV plant made up of four 50 MW PV plants was connected to a two-area, four-machine system [6], as shown in Figure 1 [8]. The power system consisted of two areas connected by two parallel transmission lines; each area had two synchronous generators. The generators (G1, G2, G3 and G4) were rated at 900 MVA. All of the generators were equipped with their primary controllers, including turbine governors, automatic voltage regulators and power system stabilizers. Under normal operating conditions, a 400 MW power flow from Area 1 to Area 2 was observed [6]. Phasor measurement units were placed at the ends of the tie-lines at buses 7 and 9.
The 50 MW PV plants were connected to a 230 kV utility transmission grid through a double converter and transformer stage, as shown in Figure 2. The first conversion stage converted from dc to dc using a boost converter, and the second converted from dc to ac. Maximum power point tracking (MPPT) was associated with the dc/dc converter. In the inverter controller design, the simple principle that active power corresponds to the phase angle difference and reactive power corresponds to the voltage magnitude difference was utilized. The inverter was bi-directional, meaning that it supplied ac power to the transmission grid and could supply instantaneous dc power to the dc bus, if necessary. There were three PI regulators, the first of which was for the dc/dc converter. The objective of this PI regulator was to moderate the duty ratio of the dc/dc converter with the reference coming from the MPPT algorithm, which was based on an incremental conductance algorithm. The second regulator moderated the phase angle with the objective of maintaining the dc capacitor voltage, while the third moderated the voltage magnitude in order to maintain a unity power factor. The second and third PI regulators both controlled the dc/ac converter.

To study large PV integration into the transmission grid, the assumption was made that a PV plant will contain a number of smaller plants, each consisting of several PV modules. In this study, as noted previously, there were four 50 MW PV plants. The entire system, which consisted of the power system, the PV plants (integrated into Area 2), frequency monitoring using PMUs, and the controls, was modeled in real-time using the Real-Time Digital Simulator (RTDS) for power systems. The 200MW distributed PV model (area of 2.65 miles by 1.13 miles) was represented by four 50 MW PV plant equivalents in the RTDS simulation.

Furthermore, actual solar irradiance and temperature profiles from Clemson, SC, USA were integrated into the RTDS simulation for the PV plant power generation. Typical profiles for two different days are shown in Figures 3 and 4.

Figure 1. 200 MW PV plant integrated into a two-area power system.
Figure 2. Four 50 MW PV plants connected to bus 12 of the power system in Figure 1.

Figure 3. Actual solar irradiance and temperature recorded in Clemson, SC, USA on October 2, 2013 by the Real-Time Power and Intelligent Systems (RTPIS) Laboratory [9].

Figure 4. Solar irradiance and temperature recorded in Clemson, SC, USA on February 5, 2014 by the RTPIS Lab.

3. Tie-Line Frequency Monitoring Using PMUs

PMUs were placed in the test system in Figure 1 at buses 7, 9 and 12. At 30Hz, the PMU network gathered information about the power system, in particular, the tie-line frequency, PV plant output and actual interchange between the areas. The tie-line bias was monitored; this is usually the accepted standard operating constraint for controlling the area control error (ACE), which typically is done using the SCADA network that polls the system roughly every four seconds.
Figure 5 shows the frequencies of Areas 1 and 2 provided by the PMUs at buses 7 and 9, respectively. Correspondingly, Figures 6 and 7 show the PV plant generation at bus 12 and the tie-line power, respectively. The PV plant output was approximately 162MW, and the tie-line power was approximately 138MW.

Figure 5. Frequencies of Areas 1 and 2 provided by PMUs at buses 7 and 9 in the power system shown in Figure 1.

Figure 6. PV plant generation output at bus 12 in the power system shown in Figure 1.

Figure 7. Tie-line power flow in the power system shown in Figure 1.
4. Tie-Line Bias Control Using PMUs

In order to maintain the system’s frequency and tie-line flows, a secondary control, AGC, was implemented such that each area had its own regulator. The block diagrams of the AGCs in Areas 1 and 2 appear in Figures 8 and 9, respectively [9]. The objective of each area regulator was to maintain the frequency at 60Hz. In addition, the AGC of Area 1 also regulated the tie-line power. The regulation of both the tie-line power flow and frequency is referred to as tie-line bias control. The ACE was calculated, with the objective of adjusting the generation of G1 and G2 to make ACE equal zero (Figure 8). This study demonstrated that it is possible to compensate for the lower frequency changes in the PV plant generation using AGC and the real-time PV plant generation information. The PV plant generation in Area 2 offset the outputs of generators G1 and G2 in Area 1, thus enabling maximum PV plant generation utilization in supplying the load demand in Area 2. The outputs of the AGCs provided the primary control reference to the respective generators.

\[
\begin{align*}
\Delta P_{tie} & = f_{PMU} - \lambda_{ref} \cdot \Delta f \\
\Delta P_{ref, G1} & = \alpha_1 \cdot \Delta P_{tie} \\
\Delta P_{ref, G2} & = \alpha_2 \cdot \Delta P_{tie} \\
\Delta P_{ref, G3} & = \alpha_3 \cdot \Delta f \\
\Delta P_{ref, G4} & = \alpha_4 \cdot \Delta f
\end{align*}
\]

Figure 8. Area 1 AGC functional diagram for the power system shown in Figure 1.

Figure 9. Area 2 AGC functional diagram for the power system shown in Figure 1.

5. Real-Time Simulation Results

Two case studies are presented in this section. The first presents a case in which cloud cover passed over the PV plant, causing a rapid drop in the PV generation, and thus a frequency drop. The second case study presents a large system disturbance on the tie-line.

5.1. Variable PV Plant Generation

Figures 10 and 11 show a drop in the solar irradiance to approximately 20% of the initial value for a period of 100s, and the corresponding PV plant output, respectively. The tie-line power flow reference was set to 400MW. Figures 12 and 13 show the tie-line power variations and respective generator outputs in Areas 1 and 2, respectively. During this study, the temperature variations were not significant. \( \alpha_1 \) and \( \alpha_2 \) were set to be equal for generators G1 and G2, whereas \( \alpha_3 \) was slightly higher than \( \alpha_4 \) in the case of generators G3 and G4. The figures illustrate that the tie-line bias control compensated for the PV plant power variation within the AGC’s frequency bandwidth.
Figure 10. Solar irradiance reflected on the 200 MW PV plant shown in Figure 1.

Figure 11. Actual 200 MW PV plant power generation.

Figure 12. Tie-line power flow variation for the PV plant generation in Figure 9.
5.2. Large Disturbance on the Tie-Line

A three-phase short circuit of 100 ms in duration was placed at bus 8 in the power system shown in Figure 1 for the system operating under a steady state PV plant generation of approximately 162 MW (Fig. 4), tie-line power reference ($P_{\text{ref}}$ in Fig. 6) of 300MW, and tie-line power flow of approximately 138MW (Fig. 5). Figures 14 and 15 show the tie-line power variations and respective generator outputs in Areas 1 and 2, respectively. The system resumed its steady state power flow in approximately 40 seconds.

Figure 14. Tie-line power flow variation during a 100ms three-phase short circuit fault at bus 8 in the power system shown in Figure 1.
6. Conclusions and future work

Power and frequency fluctuations caused by the large-scale integration of PV plants into bulk power systems raise concerns about the security and reliability of such systems. To minimize power fluctuations and maintain the desired system frequency while concurrently maximizing the penetration of PV power into the system, automatic generation control with tie-line bias control was implemented. AGC studies were carried out on a real-time digital simulator with a PMU network providing information about the power system, in particular, the tie-line frequency, PV plant output and actual interchange between the areas. The results obtained demonstrate that it is possible to use tie-line bias control to compensate for the lower frequency changes in PV plant generation. Future work will involve predicting the PV plant generation and replacing the real-time PV plant generation value with the predicted value in the tie-line bias control. The optimal frequency bandwidth of the AGC must be determined, and the prediction time step synchronized to it, in order to fully realize the potential of this strategy.


