Distributed primary frequency regulation of grid-connected photovoltaic power station with battery storage

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Abstract. Large-scale renewable energy connects with power system has posed great challenges to the safe and stable operation of power system, in order to solve the problem of frequency stability caused by large-scale photovoltaic connects with grid, a method of distributed frequency regulation by meanings of distributed battery energy storage system (DBESS) in grid-connected photovoltaic power station is proposed. By the way of paralleling a small capacity battery pack into the inverter DC side, fast active support is provided by battery pack when the system frequency is disturbed. Meanwhile, the inverter can adaptively determine the inverter permanent speed droop of itself according to the state of charge (SOC) of the battery pack during primary frequency regulation, to meet the system needs in different situations. Simulation result shows that the distributed frequency regulation proposed in this paper increases rapidity, accuracy and controllability of active control in the photovoltaic power station when system frequency disturbs, and it can meet the demand of the power system primary frequency regulation.

1. Introduction
A record 157 gigawatts of renewable power was commissioned in 2017, up from 143GW in 2016 and far out-stripping the 70GW of net fossil fuel generating capacity added last year, solar alone accounted for 98GW, or 38% of the net new power capacity coming on stream during 2017 [1]. The proportion of world electricity generated by wind, solar, biomass and waste-to-energy, geothermal, marine and small hydro rose from 11% in 2016 to 12.1% in 2017 [2]. With the maturity of technology, policy support and cost reduction, installed capacity and scale of renewable energy especially photovoltaic (PV) maintain rapid growth [3].

However, the sun radiation has the characteristics of randomness, intermittence and unstorable, it will exert a certain impact on the safe and stable operation of the power grid when photovoltaic (PV) generation installed capacity accounts for a large ratio of total grid installed capacity [4], such as when large scale photovoltaic connects with grid it will exert an influence on power system stability [5], power quality [6], system frequency [7], power generation plan and scheduling [8], system reserve capacity [9] and other fields. At present, due to domestic large scale grid-connected photovoltaic station is not equipped with ability of primary frequency regulation, large scale grid-connected photovoltaic can reduce the frequency stability of the system. Therefore, the photovoltaic power station needs to realize the primary frequency regulation by means of active power reserve or equip with energy storage device, and use the corresponding active control system or configure independent control device to realize function of primary frequency regulation [10,11].
At present, there are many kinds of researches on wind power participate in primary frequency regulation at home and abroad, which mainly focus on two methods, one is adding the additional energy storage system, such as flywheel energy storage (FES) [12], battery energy storage system (BESS) [13], superconductor magnetics energy storage (SMES) [14], the other is utilizing the wind power unit’s own active power control [15], such as rotor kinetic control (RKC) [16] and power reserve control (PRC) [17]. However, there are few studies on the primary frequency regulation of photovoltaic and on account of there are no inertias on photovoltaic power stations without considering the capacitance on DC side, photovoltaic power stations can hardly provide active support during system frequency disturbance. Most of the present methods is to install energy storage devices at photovoltaic power stations point of common coupling (PCC), to compensate the active support of photovoltaic power station through the quickly adjust ability of energy storage device, but this will add additional inverters, filter, and boosting transformer and increase the cost [18,19].

In this paper, a method of distributed primary frequency regulation of grid-connected photovoltaic power station is proposed, by means of equipped with the distributed battery energy storage system (DBESS). In the case of keep present hardware facilities in photovoltaic power stations, a small battery pack is paralleled with the DC side of the inverter. It can provide fast active support during system frequency disturbs. At the same time, it can reduce the fluctuation of PV system caused by weather, and improve the stability and controllability of photovoltaic power station in the circumstances of reducing modification cost of PV station. The rest of paper is organized as follows. Section 2 presents the control strategy of the battery pack and Section 3 gives the control strategy of the grid-connected inverter. In Section 4 two cases using DBESS are presented. The paper ends with the conclusion in Section 5. The calculations presented in the paper are done in PSCAD/EMTDC.

2. Control strategy of the battery pack
As figure 1 shows, battery pack is paralleled with the DC side of the inverter in grid-connected photovoltaic power station. In consideration of each inverter is designed with certain redundancy, and in most of time the inverter will not run at full load during the actual operation, the DC side of the inverter can be paralleled with the appropriate capacity battery pack. The battery pack is normally operated to maintain DC voltage, restrains the fluctuations of photovoltaic power stations caused by weather change, and aims to provide primary frequency regulation when the frequency disturbance of the system occurs, to provide active support to the system.

![Figure 1. Schematic diagram of photovoltaic power station structure.](image-url)
2.1. Variable definitions
Some variables used in this paper are defined at first. SOC is the state of charge, \( Q_t \) is residual capacity, \( Q_c \) is nominal capacity. \( SOC_{\text{min}} \) is the minimum of SOC when the battery is discharging and \( SOC_{\text{max}} \) is the maximum of SOC when the battery is charging. \( Q_1 \) is available capacity, \( Q_2 \) is the residual minimum capacity without affecting battery life and the DOD is the depth of discharge. The expression for \( Q_1 \) is as follows, at the end of each charging and discharging step, \( Q_{10} \) represents \( Q_1 \) at the beginning of the current step, \( Q_0 \) represents the total charge at the beginning, \( a, b \) and \( c \) are constants, \( a \) represents proportionality coefficient and its unit is \( h^{-1} \), \( I \) is the charge or discharge current of battery [20].

\[
SOC = Q / Q_c \tag{1}
\]

\[
SOC \in [SOC_{\text{min}}, SOC_{\text{max}}] \tag{2}
\]

\[
Q_t = Q_0 + Q_2 \tag{3}
\]

\[
DOD = 1 - Q_t / Q_c = 1 - SOC \tag{4}
\]

\[
Q_t = Q_{10}e^{-\Delta t/a} + \left(Q_0 + c - l(1-e^{-\Delta t/b}) \right) - Ic(a\Delta t - b) \tag{5}
\]

2.2. Charge and discharge strategy of the battery pack
Battery pack control circuit is as figure 2 shows, control flow chart of battery pack is as figure 3 shows, EN_buck is the enable signal to charge the battery and EN_boost is the enable signal to discharge the battery. When the DC side voltage of the inverter exceeds the deadband, at the same time, SOC of battery pack is in \([SOC_{\text{min}}, SOC_{\text{max}}]\), by charging or discharging the battery in order that the DC side voltage of the inverter is restored into the deadband. In consideration of the possibility when the battery is discharging, in the meantime, the active power of photovoltaic array increases or inverter power decreases, \( U_{dc} \) appears greater than \( U_{dc\text{ref}} \), it will cause the battery pack to start to charge and both two IGBT turn on at the same time, circulating current come into being and even damage components. Similarly, when the battery pack is charging, it may appear \( U_{dc\text{ref}} \) is greater than \( U_{dc} \), in order to prevent these cases from happening, the rules of EN_buck and EN_boost are determined as follows, \( Ds \) is the output value of PI controller.

\[
\begin{cases} 
Ds < 0 \text{ and } SOC < SOC_{\text{max}} & EN_{\text{-Buck}} = 1 \\
Ds > 0 \text{ and } SOC > SOC_{\text{min}} & EN_{\text{-Boost}} = 1 
\end{cases} \tag{6}
\]

![Figure 2. Battery pack control circuit.](image-url)
3. **Control strategy of the grid-connected inverter**

3.1. **Inverter control strategy**

Inverter control strategy is shown in figure 4. The inverter runs in the state of constant active and constant reactive power, active power reference value $P_{ref}$ and reactive power reference value $Q_{ref}$ is determined by upper control system on the basis of ultra short-term forecast power of photovoltaic power station, real-time active power of photovoltaic power station and the real-time SOC state of battery pack. In figure 4, $U_s$ is the AC side voltage of the inverter, $(I_a, I_b, I_c)$ is inverter AC side three phase current, $f_s$ is AC system frequency, $U_{dc}$ is the DC side voltage of the inverter, EN_avr and EN_pfc are the enable signal of automatic voltage regulation and primary frequency control respectively. The current feedforward control generates a compensating signal which impacts on the PWM modulation wave to neutralize the difference between the grid-connected current and the current instruction. Repetitive control is to eliminate the instruction error and disturbance error of grid-connected current and provide high quality steady state waveform.

![Figure 4. Control strategy of grid-connected inverter.](image)

![Figure 5. Adaptive adjustment strategy of k.](image)
3.2. Adaptive parameter control strategy

When the PCC frequency of photovoltaic power station exceeds the deadband, by reading the current PCC frequency and the SOC of battery pack, control system can adaptively adjust the value inverter permanent speed droop $k$ in the condition that the whole station power adjustment has met the power requirement. The adjustment strategy is shown in figure 5 and the calculation method of $k_i$ is shown as follows.

$$\Delta P_i = k_i P_{iN}$$  \hspace{2cm} (7)

$$k_i = \begin{cases} 
0 & \text{SOC}_i \leq \text{SOC}_0 \\
\frac{k_p}{\text{SOC}_m - \text{SOC}_0} & \text{SOC}_m > \text{SOC}_i > \text{SOC}_0 \\
\frac{1}{k_p} & \text{SOC}_i \leq \text{SOC}_m 
\end{cases}$$  \hspace{2cm} (8)

Where $\Delta P_i$ is the active power increment instruction of inverter $i$ during the frequency disturbs, $k_p$ and $\text{SOC}_m$ are constants, The DOD is the maximum depth of discharge which can not affect the battery life, $\text{SOC}_0$ is the SOC in correspondence with the maximum discharge depth DOD.

$$\text{DOD}_c = 1 - \frac{Q_i}{Q_c}$$  \hspace{2cm} (9)

$$\text{SOC}_0 = 1 - \text{DOD}$$  \hspace{2cm} (10)

At the same time equation (7) needs to satisfy

$$\sum k_i P_{iN} = k_N P_N$$  \hspace{2cm} (11)

Where $k_N$ is photovoltaic station permanent speed droop, it is numerically equal to generator units adjustment coefficient $\sigma$, according to the selection principle of thermal power units and hydroelectric units, $k_N$ is set to 0.04 in this paper, $P_{iN}$ is the rated power of the inverter $i$, $P_N$ is the rated power of the whole photovoltaic power station. The relationship between $P_{iN}$ and $P_N$ is

$$P_{iN} + P_{2N} + \ldots P_{iN} \ldots + P_{nN} = P_N$$  \hspace{2cm} (12)

In the case that each set of inverter satisfies the formula(8), it might not satisfy the constraint (11), the solution to this is that the largest $\text{SOC}_{\text{max}}$ in the current whole SOC of each battery pack is selected as the balance battery pack, and the corresponding $k_m$ is determined by the constraint conditions. The rules of primary frequency regulation enable signal $\text{EN}_{\text{pfc}}$ is determined as follows.

$$\begin{align*}
\text{EN}_{\text{pfc}} &= 1 & |\Delta f| > \Delta f_{\text{deadband}} \text{ and } t < t + t_p \\
\text{EN}_{\text{pfc}} &= 0 & |\Delta f| \leq \Delta f_{\text{deadband}} \text{ or } t \geq t + t_p
\end{align*}$$  \hspace{2cm} (13)

Where $\Delta f_{\text{deadband}}$ is primary frequency regulation deadband, the set value of primary frequency regulation deadband has not yet been determined at present, some scholars at home and abroad believe that the primary frequency regulation deadband of renewable energy power station should be greater than conventional power supply [21,22], fast active support is provided when large frequency disturbance and the small frequency disturbance is regulated by conventional unit. Considering the primary frequency regulation deadband of thermal power unit is 0.033Hz at domestic and hydropower unit is 0.05Hz, renewable energy unit primary frequency regulation deadband can be set to 0.06Hz. $t_p$ is the duration time of primary frequency regulation, $t_p$ is set to 10s in this paper in consideration of the regulation ability of photovoltaic power station.

4. Simulation and result

4.1. Frequency step response simulation

The structure of photovoltaic power station shown in figure 1 is selected for simulation, the open circuit voltage of PV array is 38.1V, the short circuit current is 8.95A, and maximum power voltage is 31.1V, maximum power current is 8.38A. The inverter 1 is equipped with four sets of photovoltaic arrays in series and its rated capacity is 100kW, the inverter 2 is equipped with eight sets of...
photovoltaic arrays in series and its rated capacity is 200kW, the capacity of battery pack is 12V10Ah. The system runs steadily before the frequency disturbs, and frequency step occurs after 5 seconds to verify the feasibility of the strategy proposed in this paper. \(SOC_0\) is set to 0.2, \(SOC_m\) is set to 0.5 and \(k_p\) is set to 0.04, the first battery pack \(SOC_1\) is set to 0.3 before the disturbance and the second battery pack \(SOC_2\) is set to 0.6. According to the adjustment strategy of \(k_i\) proposed in section 3, the second battery pack is used as the balance battery pack, \(k_i\) is 0.033 of inverter 1 and \(k_2\) is 0.073 of inverter 2. The primary frequency regulation deadband of photovoltaic power station is set to 0.06Hz, and the DC voltage control deadband of the battery pack is set to 0.005 p.u. The simulation result is shown as following.

As it is shown in figure 6, system frequency steps after 5 seconds, the power electronic converters response quickly at millisecond level. According to the analysis above, active power of inverter 1
should increase 3.33kW in correspondence with that inverter 1 $k_1$ is 0.033, similarly, active power of inverter 2 should increase 14.67kW in correspondence with that inverter 2 $k_2$ is 0.073. Figure 7 shows the change of the SOC of two battery packs, and it will change with the active power and time. Figure 8 and figure 9 shows inverter DC side voltage, When the active power of inverter increases rapidly, inverter DC side voltage drops, the battery pack quickly releases energy to maintain the DC bus voltage, DC bus voltage transient disturbance will affect the active power of the photovoltaic array, moreover, the larger the DC voltage fluctuates, the greater the active power of the photovoltaic array fluctuates. Active power of inverter 1 and inverter 2 are shown in figure 10 and figure 11.

4.2. Main grid simulation

The classic three-machine nine-node system is adopted in this paper to verify the DBESS in main grid, the system shown in figure 12 is built in PSCAD for simulation. Where G1 and G2 are thermal units, installed capacities are 330MW and 200MW respectively, G3 consists of three photovoltaic power stations and the total installed capacity is 65MW. Before the failure occurs, the active power of G1 is 65.7MW and the active power of G2 is 71.4MW, the active power of photovoltaic power station is 46MW and the load is 180MW. According to the standard of China, the response lag time of thermal unit primary frequency regulation should be less than 3s [23], and it was set to 1s in the simulation in this paper.

![Figure 12. Test system with PV station.](image1)

![Figure 13. System frequency.](image2)

![Figure 14. Active power of PV station.](image3)

![Figure 15. Active power of thermal units.](image4)

It was supposed that the load suddenly increases by 45MW at time t=2s, the simulation results are shown from figure 12 to figure 15. The lowest frequency is up to 49.25Hz when the photovoltaic power station is unable to participate in primary frequency regulation, and in contrast, the lowest frequency is 49.33Hz when the photovoltaic power station is able to provide the ability of primary frequency regulation. However, when the photovoltaic power station exits the primary frequency regulation after 10s, the secondary drop of frequency occurs and the frequency is reduced by 0.05Hz.
Figure 13 and figure 15 show that the secondary drop of frequency will affect the active power of the thermal power unit at the same time.

5. Conclusions
In this paper, a method of distributed frequency regulation of grid-connected photovoltaic power station is proposed. Through the way that small capacity battery is paralleled with the inverter DC side on the basis of the original hardware facilities, and reform the control strategy of photovoltaic inverter, it can reduce the improvement cost of photovoltaic power station. At the same time, due to the rapid response ability of the inverter, it can satisfy the rapidity, and accuracy of primary frequency regulation and restrain the active power fluctuation of photovoltaic station because of the weather change. Meanwhile, according to the SOC of the battery pack, the adaptive adjustment strategy of permanent speed droop can determine the power change of each inverter during primary frequency regulation, it can improve the reliability of primary frequency regulation of photovoltaic power station. Simulation result shows that the strategy proposed in this paper can provide fast active power support when system frequency disturbs, and improve the stability and controllability of photovoltaic power station in the case of reducing the cost of photovoltaic power station renovation.

As we proved DBESS technically feasible in this paper, the cost of it is not detailed calculated, our another goal is to prove it economically better than traditional BESS, this work will be done in the future research, and the methods to eliminate the influence of the secondary drop of frequency on power grid is also a research direction in the future.

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