

# Integrated control of photovoltaic-energy storage system for power oscillation damping enhancement

Xiangyu Zhang, Li Yang, Xiaorong Zhu

State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources  
North China Electric Power University  
Bao Ding, China  
zh.xy.sq@163.com

**Abstract**—Due to the lack of damping regulator, the power oscillation in the power system with high penetration of photovoltaic-energy storage devices will threaten the dynamic stability of the system. Based on the analysis of the operation characteristics and control scheme of the photovoltaic-energy storage system, the relationships between the active and reactive power regulation and the power oscillation damping are discussed, and the novel additional active and reactive power modulations are proposed respectively for improved system damping. The proposed strategy switches the control mode of the PV grid connected inverter and the battery energy storage during power oscillations according to the frequency deviation and State-of-Charge(SOC) of Battery which avoids the deep charge and discharge of energy storage device. Finally, a typical power system with photovoltaic penetration of around 30% is used to validate the proposed control strategies. Simulation results show that the power oscillations can be significantly damped with the power regulations of photovoltaic-energy storage system.

**Keywords**—battery storage; damping; photovoltaic; power oscillation

## I. INTRODUCTION

As photovoltaic generation achieves higher penetration levels, and becomes a more and more substantial portion of our electric energy supply, the reduced system dynamic stability has attracted increased attentions from manufactures and system operators. As a variable and intermittent power source, the rapid increase of photovoltaic generation in power system has brought in new technical issues, such as frequency regulation, power oscillation, voltage stability, etc. Among these technical issues, the system power oscillation become significant particularly in solar energy resource rich areas where the regional grids may have very high photovoltaic penetration and thus face more serious challenges for the lack of damping regulator [1]. Thus, the ability of controlling the power oscillation is important for the photovoltaic station to maintain the stability and reliability of the regional network.

The inter-area power oscillation of the power system always threatens the safe operation of the network. At present, there are various methods for suppressing low frequency oscillations in power system. Many kinds of controllers such as power system stabilizers (PSS), static var compensators (SVC) and static compensators (STATCOM) are commonly

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used for oscillation damping [2-3]. The large-scale PV stations are geographically far away from load centers and connected to relatively weak transmission networks. Reference [4] analyzed the impacts of large-scale grid-connected PV generation on small-signal oscillation stability in power system, and the result represents the stability limit of PV operation. Given the structure of a photovoltaic (PV) system, which is dominated by controllers, the controllers of PV system may be employed for improving the oscillation damping. Similar to the variable speed wind turbine, which is connected through the power electronic converter, it can significantly damp the system power oscillation after faults [5-6]. Reference [7] further indicates that the PV generation system has an adverse impact on oscillation damping, especially with high penetration level. Generally, in order to smooth the intermittent power fluctuation, the energy storage devices have been widely implemented to PV generation system, such as battery energy storage [8]. Therefore, in this paper, the dynamic characteristics of the photovoltaic-energy storage system and its capability to damp the power oscillations will be deeply investigated.

The paper is organized as follows. Section II presents the principle of photovoltaic-energy storage system. Section III presents a control method for damping the low frequency oscillation used by photovoltaic-energy storage system. The proposed strategy can realize the control mode switching of the PV grid connected inverter and the battery energy storage system during power oscillations according to the frequency variation and State-of-Charge of Storage Battery. Then simulation studies based on a typical power grid with photovoltaic penetration of around 30% are presented in Section IV to demonstrate the effectiveness of the proposed schemes on providing oscillation damping. And finally, section V draws the main conclusions.

## II. PRINCIPLE OF PHOTOVOLTAIC-ENERGY STORAGE SYSTEM

### A. Model Analysis

The proposed control methods are developed considering the power regulation of photovoltaic-energy storage system. The structure and conventional control of photovoltaic-energy storage system are illustrated in Fig. 1. The electromagnetic power of the PV system can be controlled using the boost

converter for maximum power point tracking (MPPT) operation. The grid side converter is used to maintain a constant dc-link voltage. In this paper, Bi-directional DC/DC converter is used in battery for damping the fluctuations in the PV because of the necessity of the bidirectional flow of energy. The PV fluctuation power is detected by energy storage system. The battery will have a response to the PV power fluctuation when the fluctuation of the PV power reaches the control cycle of the battery  $T_{Bs}$  [9]. Then by using  $\Delta P_{pv}$  and the coefficient  $\tau$ , the reference power of battery  $P_{B\_ref}$  is calculated as following [9].

$$P_{B\_ref}(k+1) = \frac{\tau_B}{\tau_B + T_{Bs}} (P_{B\_ref}(k) - \Delta P_{pv}(k)) \quad (1)$$

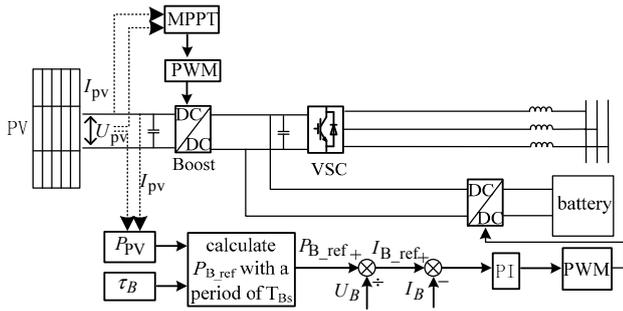


Fig. 1. Topological structure diagram of photovoltaic-energy storage system

### III. THE DAMPING CONTROL OF THE PHOTOVOLTAIC-ENERGY STORAGE SYSTEM

Under the basic control scheme, PV systems cannot automatically provide dynamic support for the grid. During power oscillations, the DC voltage fluctuation as the result of imbalanced power on the DC side can be found due to the grid voltage change. In order to achieve the security of PV system and the damping capacity, this paper investigates the coordinated power modulation between the photovoltaic and the energy storage for improving system damping.

#### A. Control Principle

An equivalent circuit of three-machine power network with photovoltaic-energy storage system, as shown in Fig. 2, is used for the theoretical evaluation of the effect on damping capability.  $U_G$  is the grid connection point voltage of the PV station.  $E'$  is the q-axis transient electric potential.  $U$  is the terminal voltage of  $G_2$ .  $\delta$  is the phase angle between  $E'$  and  $U$ .  $x_1, x_2$  are the line reactance, respectively.

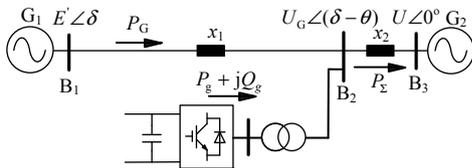


Fig. 2. The structure of three machine system

The active and reactive power output of the synchronous generator  $G_1$  can be expressed as

$$P_G = \frac{E'U_G}{x_1} \sin \theta \quad (2)$$

$$Q_G = \frac{E'U_G}{x_1} \cos \theta - \frac{U_G^2}{x_1} \quad (3)$$

If the impact of generator excitation system and the governor is not considered, the small perturbation equation of the classical two order model of generator can be expressed as

$$H_G p^2 \Delta \delta + D p \Delta \delta + \Delta P_G = 0 \quad (4)$$

where  $D$  is the damping coefficient,  $\Delta P_G$  is the active power variation of  $G_1$ .

As shown in Fig. 2, the power balance equation is given by

$$\frac{E'U_G}{x_1} \sin \theta + P_g = \frac{U_G U}{x_2} \sin(\delta - \theta) \quad (5)$$

where  $P_g$  is the injection power from the PV system.

Then the (5) developed by the small perturbation method is expressed as

$$\frac{U_G U \cos(\delta_0 - \theta_0)}{x_2} (\Delta \delta - \Delta \theta) + \frac{U \sin(\delta_0 - \theta_0)}{x_2} \Delta U_G = \Delta P_G + \Delta P_g \quad (6)$$

In the proposed scheme, the small perturbation quantities of the active and reactive power responses are controlled as follows:

$$\Delta P_g = -k_p p \Delta \delta = -k_p \Delta \omega \quad (7)$$

$$\Delta Q_g = -k_w p \Delta \delta = -k_w \Delta \omega \quad (8)$$

where  $k_p, k_w$  is proportional coefficient,  $\Delta \omega$  is speed variation.

Substituting (7) and (8) into (6),  $\Delta \theta$  is obtained as

$$\Delta \theta = a_0 \Delta \delta + a_1 \Delta U_G + a_2 k_p p \Delta \delta \quad (9)$$

where

$$a_1 = \frac{x_1 U \sin(\delta_0 - \theta_0) - x_2 E' \sin \theta_0}{x_2 E' U_{G0} \cos \theta_0 + x_1 U U_{G0} \cos(\delta_0 - \theta_0)}$$

$$a_2 = \frac{x_1 x_2}{x_2 E' U_{G0} + x_1 U U_{G0} \cos(\delta_0 - \theta_0)}$$

where  $\delta_0, \theta_0, U_{G0}$  are the initial values of  $\delta, \theta, U_G$ .

Then, the linear differential equations of the rotor motion can be expressed as

$$H_G p^2 \Delta \delta + \left( D + \frac{E' U_{G0} a_2 k_p}{x_1} \cos \theta_0 + \frac{a_3 x_1 k_w}{2U_{G0} - E' \cos \delta_0} \right) \Delta \delta + \frac{a_0 E' U_{G0}}{x_1} \cos \theta_0 \Delta \delta = 0 \quad (10)$$

$$\text{where } a_3 = \frac{E' U \sin \delta_0}{x_2 E' \cos \theta_0 + x_1 U \cos(\delta_0 - \theta_0)}$$

It is found from (10) that the eigenvalue moves left toward the left half plane for the additional power control coefficient  $k_p$  and  $k_w$ . That means an increased damping is derived from the supplementary power control.

### B. Damping Controller Design

The reasonable power coordination between the battery and photovoltaic inverter under different operating modes is carried out by detecting the frequency deviation. For the purpose of avoiding the frequent switching of the working mode, the hysteresis control is used in the switching point. The variation  $S=1, 2$ , which is shown in Fig. 3, indicate that PV inverter cooperate with battery in the first working mode and the second mode.

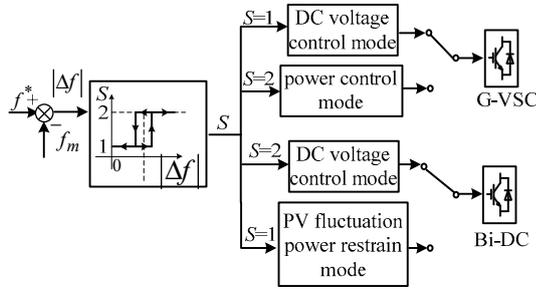


Fig. 3. The coordinate control strategy

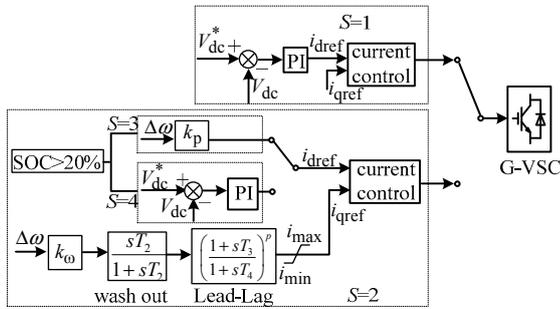


Fig. 4. The control strategy of the inverter

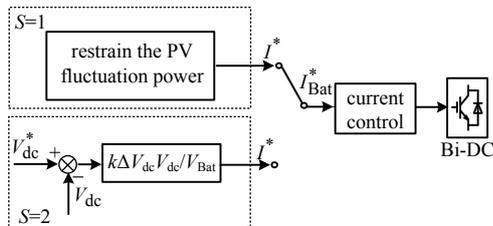


Fig. 5. The control strategy of battery

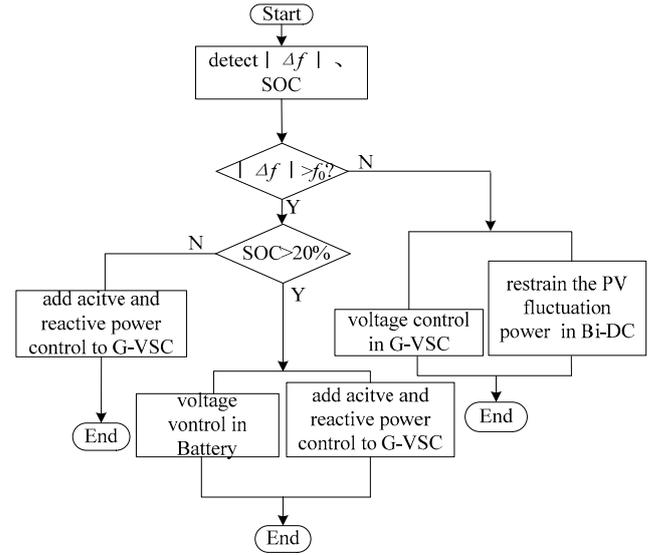


Fig. 6. Flowchart of coordinate control strategy

If  $|\Delta f| < f_0$ , the grid connected photovoltaic inverter and battery work in the first mode of operation. Meanwhile, battery is only used to smooth the power oscillation stemming from the external environment. If  $|\Delta f| > f_0$ , the power control strategy is adopted in the grid connected photovoltaic inverter and the reactive power control is added to restrain the power oscillation. Then the active power control is added into the system by detecting the State-of-Charge (SOC) of Storage Battery. If the value of the SOC is more than 20%, the stability of the DC bus voltage is maintained by the battery and the active power can also be attached to the grid connected photovoltaic inverter. Furthermore, the active and reactive damping control, which is added to the grid connected inverter, injects active and reactive power into the power grid based on the system frequency deviation. In summary, the coordination control strategy is illustrated in Fig. 4, 5 and 6.

## IV. EXPERIMENTAL SETUP AND RESULTS

Simulations using Matlab/Simulink have been carried out to validate the impacts of the power regulation from photovoltaic-energy storage stations. A typical power system shown in Fig. 7 is used, which consists a photovoltaic-energy storage system, two synchronous generators and two aggregated loads (L1, L2). The conventional power plants and the photovoltaic power station are rated at 160 MVA, 70 MVA and 100 MW. The loads of the system are L1 and L2 respectively, and their capacities of the system are 75 MW, and 150 MW. Comparative studies of inter-area power oscillations with and without the proposed control strategy are carried out following a single-phase short circuit fault at bus B<sub>2</sub>. In the simulations, irradiation intensity is assumed to be 800W/m<sup>2</sup>, and the fault duration is 0.1s.

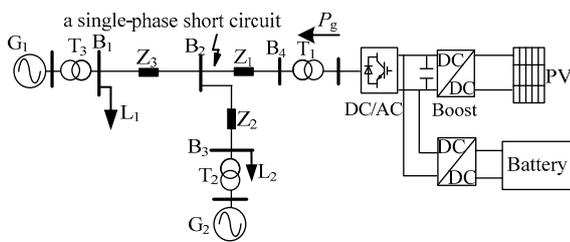
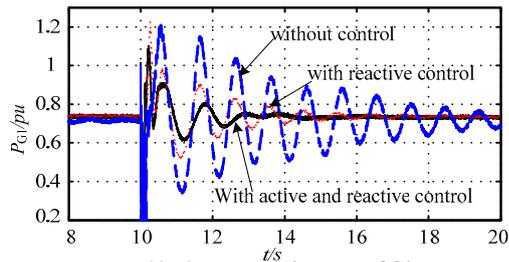
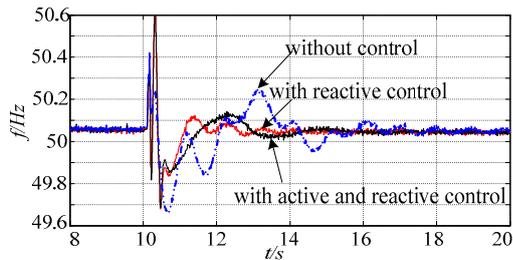


Fig. 7. The simulation system diagram

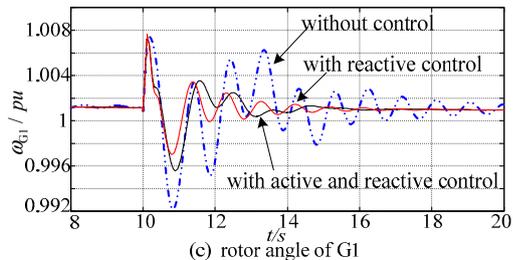
Three modes are considered to test the effectiveness of the proposed controller by the comparison of active and reactive damping control and without damping control. In view of the State-of-Charge of Battery, the simulations are under the circumstance of  $SOC > 20\%$  and  $SOC < 20\%$ .



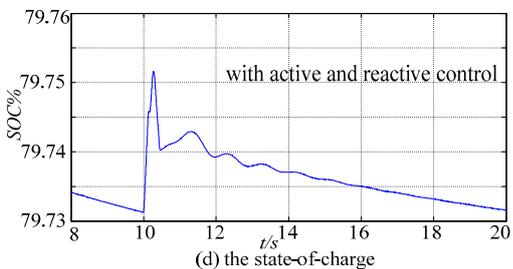
(a) electromagnetic power of G1



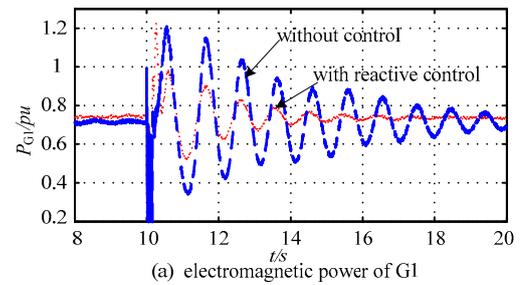
(b) system frequency



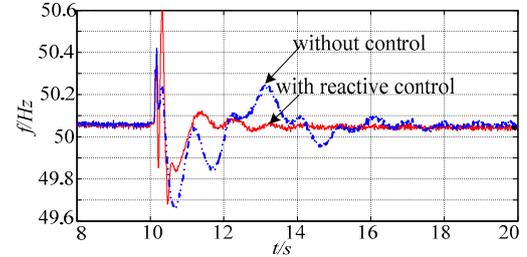
(c) rotor angle of G1



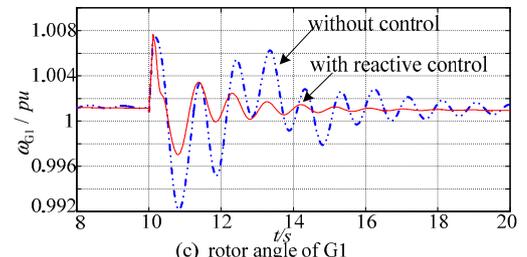
(d) the state-of-charge

Fig. 8. Dynamic response under the  $SOC > 20\%$ 

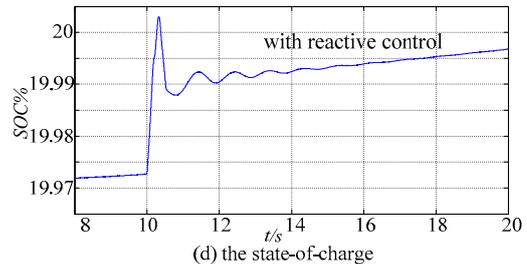
(a) electromagnetic power of G1



(b) system frequency



(c) rotor angle of G1



(d) the state-of-charge

Fig. 9. Dynamic response under the  $SOC < 20\%$ 

PV system was operated in different control mode and corresponding impact on time domain behavior was observed. In the condition of the normal value of the SOC, the dynamic response was observed in Fig. 8. As can be seen in Fig. 8, the electromagnetic power of G1 tends to be stable after 5s with reactive power control. By contrast, the recovery time of electromagnetic power with active and reactive power control is three seconds less than the active power control. It can be observed that the oscillation is better controlled through the control method. At the same time, the frequency of the system come to stable under the action of the damping control. As the SOC is less than 20%, the inverter can only add reactive power control. The result is shown in Fig. 9.

## V. CONCLUSION

This paper investigates the power regulation method of PV generation during transient events for enhancing the grid

damping capability. A novel integrated control is proposed. In this scheme, according to the frequency variation and the SOC of battery, the PV grid connected inverter and the battery energy storage system can switch the control mode to regulate the active and reactive power independently for improving system damping. As evident from the analysis and test results, the reactive damping controller can be activated immediately after grid faults. In order to avoid the excessive charge and discharge, the SOC of battery should be detected, Then the photovoltaic-energy storage system can provide additional active power support for grid damping as well. Thus, the system damping characteristic is further improved.

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