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A Control Method for Grid-friendly Photovoltaic Systems with Hybrid Energy Storage Units

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Abstract—This paper proposed a systematic control strategy to make the interconnected photovoltaic (PV) systems more grid-friendly. The investigated PV system comprises PV arrays, lead-acid battery, super-capacitor, DC/DC and DC/AC power converters. In order to make this system work as a classical generator to participate in grid regulation, the constant active/reactive power control is implemented in the controller of the DC/AC converter which connects the DC bus of the PV system and the main grid. The DC bus voltage is coordinately controlled by super-capacitor and battery. The maximum power point tracking (MPPT) control is applied to extract maximum power from PV panels. The power management scenarios for the interconnected PV system were discussed and the experiment results were given to validate the feasibility of the proposed control strategy as well.

Keywords—Photovoltaic; grid-connected; super-capacitor; battery; power management

I. INTRODUCTION

Grid-connected photovoltaic (PV) generation has been developed dramatically in recent years and gradually forms a considerable part of the main grid. However, the intermittent nature of PV power makes it contribute little to the stability and economic operation of the grid and even brings adverse effect to the grid's power quality [1-2]. One of the solutions proposed to overcome the above shortcoming of the PV generation is to utilize energy storage [3]. The optimal design of PV-storage systems is receiving more and more attention for interconnected PV application [4-5]. The well operated PV-storage system can be constructive to the main grid power by supplying the designated active and reactive power required by the grid.

The utilization of energy storage units in power systems can be classified into two categories. One is in response to fast transients and the other is related to steady-state energy exchanging. Flywheels and super-capacitors are good candidates for the former application and large capacity batteries are suitable for the latter one. Currently, the mixed use of fast and slow energy storage units is gaining popularity for interconnection of renewable generation [6-8].

This paper proposed a systematic control strategy to make the interconnected PV systems more grid-friendly. The investigated PV system comprises PV arrays, lead-acid battery, super-capacitor, DC/DC and DC/AC power converters. In order to make this system work as a classical generator to participate in grid regulation, the constant active/reactive

power control is implemented in the controller of the DC/AC converter which connects the DC bus of the PV system and the main grid. The DC bus voltage is coordinately controlled by super-capacitor and battery. The maximum power point tracking (MPPT) control strategy is applied to extract maximum power from PV panels. The power management scenarios for the interconnected PV system were discussed in the paper. The experiment platform for the investigated PV system was setup and the feasibility of the proposed control method has been validated through laboratory experiments.

The paper is organized as follows. In Section II, the studied PV system is introduced and the control strategies for each part of the system are also presented. The experiment results are given in Section III and Section V summarizes the conclusions.

II. PV SYSTEM AND CONTROL STRATEGY

The interconnected PV system studied in this paper is shown in Fig. 1. It consists of PV panel, hybrid energy storage unit, DC bus capacitor, DC/AC converter and DC load. The PV panel is connected to the DC bus through a boost DC/DC converter. The hybrid energy storage unit is composed of lead-acid batteries and super capacitor. The batteries and the super capacitor are connected to the DC bus through two bi-directional (buck-boost) DC/DC converters. The DC bus voltage U_{dc} is maintained as constant. The three-phase DC/AC converter links the DC bus and the main grid (50Hz). The resistive load is employed to be connected to the DC bus.

Figure 1. Schematic diagram of the investigated PV system.

A control strategy of the above PV system is proposed to make this system friendly to the grid. In the proposed control strategy, the PV array is maximum power point tracking (MPPT) controlled by the boost converter. The DC bus voltage

is maintained as constant by the batteries and the super capacitor through buck-boost converters. The inverter controller is designed as the constant power controller which needs the power references inputted from the energy management system of the grid. The system operator makes the inverter generation plan based on the conditions of the PV array and the load requirements. The detailed control schemes of each part of the PV system are described as follows.

A. MPPT control of PV array

An improved variable-step perturb and observe (P&O) method is utilized to realize MPPT of the PV panel. This method has the characteristics of simple controlling, quick tracking, and small steady-state power oscillations.

Figure 2. PV control flowchart

For the PV array, the small-signal variation of output power ΔP and the variation of duty ratio Δd around the maximum power point (MPP) have the following approximate relationship [9]:

$$\Delta P = -\frac{\Delta U_{pv}^2}{R_{MPP}} \approx -\frac{\mu^2 \Delta d^2}{R_{MPP}} f(T_a) \quad (1)$$

where R_{MPP} is the equivalent resistance of the PV array at MPP; $f(T_a)$ is the function of sample time T_a ; $-\mu$ is output voltage of boost converter. Appropriate Δd and T_a can be selected to carry on power tracking. Meanwhile, in order to accelerate the speed of tracking, a variable-step control is

added. When the output voltage of PV array U_{pv} shown in Fig.1 is in a certain range (U_{low} , U_{high}) a short step is used for the disturbance. Instead, a larger step is employed if U_{pv} is out of this range. The open-circuit voltage of the PV array U_{oc} multiplied by 0.78 is the intermediate value of U_{low} and U_{high} . The corresponding control diagram for PV array is shown in Fig. 2.

Two main parameters, Δd and T_a , are essential to this MPPT control algorithm. A small Δd can reduce power loss around the steady-state working point caused by oscillation. However, the small Δd may lead to algorithm failure when the weather condition changes fast, e.g. a cloudy day. Sample time T_a should be greater than a given threshold in order to avoid algorithm instability. Otherwise the MPP maybe missed due to the whole system's transient response. Both PV array's and converter's dynamic performance should be considered in the determination of the values of Δd and T_a .

B. Hybrid energy-storage control

Battery has high energy density whereas it has relatively slow charging and discharging speed. On the other hand, super capacitor has high power density and fast response. The mixed use of these energy storage units can make them complimentary to each other. Based on the above characteristics of battery and super capacitor, a hybrid energy-storage control scheme is proposed and shown in Fig. 3.

Figure 3. Hybrid energy storage control scheme

In this scheme, the DC bus voltage is coordinately controlled by battery and super capacitor. First, the measured DC bus voltage U_{dc} is compared with the reference DC bus voltage U_{dc-ref} and the difference is sent to a proportional-integration (PI) controller to get the current reference I_{ref} . Then I_{ref} is split into two parts. One is the battery current reference $I_{bat-ref}$ which is obtained by applying a low pass filter (LPF) and a coefficient K to I_{ref} . The other one I_{sc-ref} is the difference between I_{ref} and $I_{bat-ref}$. By this means, the high frequency part of the DC bus disturbance will be mitigated by super capacitor and the low frequency part of the disturbance is smoothed by battery. The current references I_{sc-ref} and $I_{bat-ref}$ will be used in the constant current control of the buck-boost converters shown in Figure 1. The illustration of the buck-boost converter control when battery is in discharging state is shown in Fig. 4.

Figure 4. Battery buck-boost converter control

C. Three phase inverter control scheme

Three-phase grid-connected inverter generates designated active and reactive power by using constant power (PQ) control. The schematic diagram of the inverter controller is shown in Fig. 5.

Figure 5. Three-phase inverter PQ control

The three-phase inverter output instantaneous active power and reactive power are given as follows:

$$P = \frac{3}{2} (u_d i_d + u_q i_q) \quad (2)$$

$$Q = \frac{3}{2} (u_d i_q - u_q i_d)$$

where u_d, u_q are the dq forms of u_a, u_b and u_c shown in Fig. 1; i_d, i_q are the dq forms of i_a, i_b and i_c . The corresponding inverter current references are calculated as follows:

$$i_{dref} = \frac{2}{3} \left(\frac{P_{ref} u_d - Q_{ref} u_q}{u_d^2 + u_q^2} \right) \quad (3)$$

$$i_{qref} = \frac{2}{3} \left(\frac{P_{ref} u_q + Q_{ref} u_d}{u_d^2 + u_q^2} \right)$$

The current control equations are as follows:

$$u_{sd} = (K_p + K_i / s)(i_{dref} - i_d) - \omega L i_q + u_d \quad (4)$$

$$u_{sq} = (K_p + K_i / s)(i_{qref} - i_q) + \omega L i_d + u_q$$

where L is the inverter filter inductance; K_p and K_i are the parameters of the PI controller; s is the Laplace operator.

III. EXPERIMENT RESULTS

The proposed control strategy has been validated by the laboratory experiments. The system parameters for the system shown in Fig. 1 are summarized in Table I.

TABLE I PARAMETERS OF PV SYSTEM

DC side	PV array	1kW
	Batteries (6 in series)	12V, 65Ah
	Super Capacitor	72V, 70F
	Inductors (L_1, L_2, L_3)	5mh
	DC bus capacitor (C)	2200μF, 400V
	DC bus voltage (U_{dc})	150V
	DC load (R_{load})	200Ω
AC side	Inductor (L)	5mh
	AC voltage (U_{ab})	35V

A. PV array experiment

There are six panels divided into two groups in the PV array. Each group has three panels in series and the two groups are in parallel. The parameters of a single solar panel (under conditions of $S=1000W/m^2$, $T=25^\circ C$) are given as follows:

TABLE II PARAMETERS OF SOLAR PANEL	
Maximum power current(I_{MPP})	5.0 A
Maximum power voltage(V_{MPP})	36 V
Short-circuit current(I_{SC})	5.30 A
Open-circuit voltage(V_{OC})	43.9 V

Fig. 6 shows the MPPT experiment results at 5:00 pm of one day. As shown in the figure, at about 1.6s the MPP is tracked and the steady-state oscillation is relatively small. $T_a=0.01s$, $\Delta d=0.005$ and $\Delta d'=0.02$ in the control algorithm.

Figure 6. PV Maximum power point tracking experiment results

B. Hybrid energy-storage control

The validation of the hybrid energy-storage control scheme is illustrated in Fig. 7. In this experiment, the AC part of the system is not connected. The battery current I_{bat} , the capacitor current I_{sc} and the DC bus voltage U_{dc} are shown from top to bottom, respectively. At an intermediate time instant, the DC load decreases from 200Ω to 60Ω, and then increased from 60Ω to 200Ω. One can see in the figure that the super capacitor is responsible for absorbing and releasing high frequency energy. I_{sc} changes rapidly and I_{bat} changes relatively slow compared with I_{sc} . Through the cooperation of the two energy storage units, U_{dc} is recovered smoothly to the reference value during load fluctuation. The gain K in the control scheme shown in Fig. 3 is 0.8 and the cut-off frequency of the LPF is 50Hz.

C. Experiment results on the overall system

The verification results of the overall system performance are presented in this section. Fig. 8 shows experimental curves of the PV array output current I_{pv} , the battery current I_{bat} , the capacitor current I_{sc} and the DC bus voltage U_{dc} . In the figure, during the period of t_1 , the control algorithms of the PV array, the batteries and the super capacitor begin running. In this time segment, the PV array has not yet reached MPP and the energy needed to maintain the stability of the DC bus is provided by the energy storage devices. The super capacitor provides most

of the instantaneous energy and the DC bus voltage gets to the constant value quickly. When the PV array is approaching MPP, the DC bus voltage begins to increase and soon becomes higher than the reference value. The super capacitor rapidly switches to a charging status at this time. As a result, the excessive energy in the DC bus is absorbed by the super capacitor. While during the whole process, the battery current changes slowly, and the over-charge or the over-discharge state does not appear.

Figure 7. Experiment results of the hybrid energy storage system.

Figure 8. Operation of the overall PV system.

The PQ control algorithm of the inverter is tested during the period of t_2 . The active power reference is stepped from 0 to 50W at the beginning of the t_2 segment and the reactive power reference is set as 0. Before this instant, the PV energy is consumed by the DC load and no power is delivered to the grid. When the inverter reference power steps up, the super capacitor responds to this power requirement in a fast time and the batteries react in a relatively slow time. The PV array has invisible change due to its generation limitation at that time. The DC bus voltage is still controlled as constant. The output voltage and current waveforms of the inverter are shown in Fig. 9.

Figure 9. Output voltage and current waveforms of the inverter

IV. CONCLUSION

This paper proposed a control strategy for an interconnected PV system. Battery and super capacitor are mixed used to maintain the stability of the DC bus voltage. The grid-tie inverter is controlled as constant power to interact with the main grid in a friend way. The MPPT control is applied to the PV array. The experiment results show that the proposed control strategy is effective to provide the designated power commanded from the main grid.

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