Nonlinear Differential Flatness Control of a Distributed PV-ES DC Generation System

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Abstract: - To overcome the intermittency problem, this paper proposes a novel nonlinear differential flatness control method for a distributed photovoltaic-energy storage (PV-ES) DC generation system. For high-power applications, four-phase parallel boost converters and four-phase parallel bidirectional converters are implemented as a PV converter and a storage device, respectively. For PV four-phase parallel boost converters, an improved extremum seeking algorithm is designed to achieve maximum power point tracking (MPPT) control and to satisfy the dynamic behavior of the system. For ES four-phase parallel bidirectional converters, an original nonlinear control law based on the flatness principle is proposed, which smoothes the output power and enhances the system stability under a load mutation or control parameter perturbation. To validate the proposed method, simulations are realized by simulation results in MATLAB/Simulink.

Key-Words: - Distributed PV-ES DC generation system, Four-phase parallel converters, Extremum seeking algorithm, Nonlinear differential flatness control, Stabilization analysis

1 Introduction

In recent years, a growing number of distributed photovoltaic (PV) systems are connected to the grid, which plays a positive role in promoting the development of clean energy. The main drawbacks of distributed PV systems lie in high cost and intermittent power output. Along with the continuous improvement of PV permeability, energy storage (ES) devices are very necessary. ES technology has become an effective means to solve the PV output power fluctuation, further enhancing the permeability of PV [1]-[2].

To achieve coordinated control of photovoltaic-energy storage (PV-ES) system, efficient topology and control schemes of converters are essential [3]-[5]. In this paper, low-voltage, high-current (power) converters are needed because of the electrical characteristics of the PV module and the battery. In traditional ways, a boost converter is often used as a PV converter, and a bidirectional converter is often used as a battery converter. However, the classical converters will be limited by the size of filter inductor, capacitor and the duty cycle regulation model [6]-[8]. This paper designs parallel power converters with interleaving, which offer better performance in terms of dynamics, because of smaller inductor and capacitor sizes. A nonlinear dynamic system theory is proposed to analyze interleaved boost converter in [9], analysis shows that the interleaving parallel technology can expand the stable-domain, reduce inductor current ripple and capacitor voltage ripple. In [10]-[11], the interleaving parallel technology has been applied to fuel cells, electric vehicles and other fields, experimental results show it is ideal for dc-bus converters and merchant power applications. Interleaving parallel technology needs to be expanded in the application of distributed dc generation system.

Current work on controlling distributed PV-ES DC generation system is reported in [12]-[13], where a linear control using PI strategy or pole assignment method was proposed to achieve coordinated control of PV-ES system. The design of controller parameters based on linear methods requires a linear approximation, where this is dependent on the operating point. However, the proposed system is nonlinear system in which most of the nonlinearities occur due to the intermittent sunlight and the switching functions of the converters, it is natural to apply nonlinear control strategies that directly compensate for system nonlinearity without requiring a linear approximation. Recently, many nonlinear control, including sliding mode control[14], the exact linearization technique[15], adaptive control, have been extensively studied for nonlinear power electronic applications, but the complexity has limited the engineering application of PV-ES coordinated control.

Flatness control theory was introduced by the authors in 1992 via differential algebraic techniques, which has recently been studied in many applications because it is appropriate for robustness, predictive control. The algorithm can ensure the performance of the control system in a wide stable domain which is simple and robust[16]-[17]. In 2009, Edward Song et al. [18] adopted a flatness-based tracking control for the VSC to achieve reactive power and voltage tracking control, but not to achieve this method to the application of DC/DC converter. In 2011, Phatiphat Thounthong et al. [19] demonstrated the application of flatness control theory to PV-SC system, which obtained good dynamic performance. In 2013, Phatiphat Thounthong et al. [20] further demonstrated the application of such method to fuel cell-supercapacitor system, which was proved to be feasible and effective. However, this control strategy needs to choose capacitive voltage as flat state variable, so that it limits the application of nonlinear differential flatness control in energy storage device such as batteries which adopt inductive current as state variable.

To realize the optimal coordinated control of PV-ES in the proposed system, this paper designs four-phase interleaved converter. For PV four-phase parallel boost converters, an improved extremum seeking algorithm is designed to achieve maximum power output. For ES four-phase parallel bidirectional converters, a nonlinear differential flatness control is proposed, which control the four-phase interleaved converters duty cycle by selecting energy storage battery current as flat state variable, and selecting each phase input power as flat output variable, which is a simple solution to smooth the output power and stabilize the system with a load mutation or control parameter perturbation.

2 Mathematical Brief of Distributed PV-ES DC Generation System

The schematic diagram of the distributed generation system, which is the main focus of this paper, is shown in Fig. 1. The proposed system consists of a PV source, a battery storage device, a dc-link capacitor, input filter inductors and converters. The PV converters combine four-phase parallel boost converters with interleaving, and the PV converters employ four-phase parallel bidirectional converters with interleaving. The mathematical model of the system is presented in the following sections.

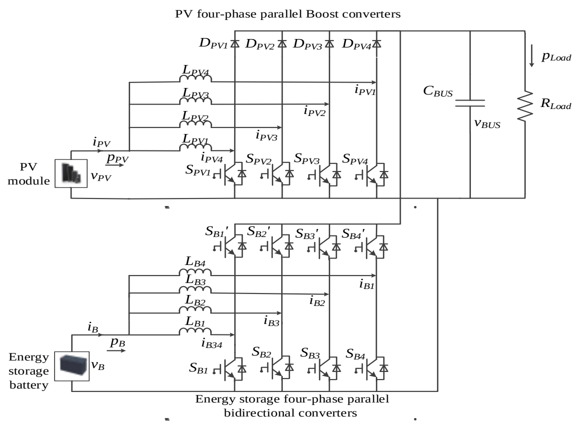


Fig. 1. Proposed circuit diagram of the distributed PV-ES DC generation system

2.1 PV Module Behavioral Model

The output characteristics of PV module is highly nonlinear and dependent on the atmospheric conditions, its behavioral model is:

$$i_{PV} = I_{sc}\left\{1 - C_1\left[\exp\left(\frac{v_{PV}}{C_2 V_{oc}}\right) - 1\right]\right\} \tag{1}$$

where

$$\begin{cases} C_1 = \left(1 - \dfrac{I_m}{I_{sc}}\right)\exp\left(-\dfrac{V_m}{C_2 V_{oc}}\right) \\ C_2 = \left(\dfrac{V_m}{V_{oc}} - 1\right)\left[\ln\left(1 - \dfrac{I_m}{I_{sc}}\right)\right]^{-1} \end{cases}$$

where i_{PV} is PV output current, v_{PV} is PV output voltage, I_{sc} is the short circuit current, V_{oc} is the open circuit voltage, I_m is the maximum power current and V_m is the maximum power voltage, C_1 and C_2 are the correction factors.

Under arbitrary ambient conditions, the four parameters of PV module will fluctuate, namely:

$$\begin{cases} I_{sc} = \Delta I \times I_{scref} \\ I_m = \Delta I \times I_{mref} \end{cases} \quad \begin{cases} V_{oc} = \Delta V \times V_{ocref} \\ V_m = \Delta V \times V_{mref} \end{cases} \tag{2}$$

where

$$\begin{cases} \Delta I = \dfrac{S}{S_{ref}}\left[1 + a\left(T - T_{ref}\right)\right] \\ \Delta V = \left[1 - c\left(T - T_{ref}\right)\right]\ln\left[e + b\left(S - S_{ref}\right)\right] \end{cases}$$

where S_{ref} and T_{ref} represent solar irradiance and temperature, I_{scref}, V_{ocref}, I_{mref}, V_{mref} are PV parameters under standard condition, a, b, c are compensation coefficients, e is the base of natural logarithm.

From (1) and (2), the output power of PV can be expressed as follows:

$$p_{PV} = v_{PV} \times i_{PV}$$

$$= v_{PV} \cdot \left(\Delta I \times I_{scref}\right) \cdot \left\{ 1 - C_1 \left[\exp\left(\frac{v_{PV}}{C_2 \cdot \left(\Delta V \times V_{ocref}\right)} \right) - 1 \right] \right\} \quad (3)$$

2.2 Energy Storage Battery (ESB) Mathematical Model

The mathematical model of ESB can be equivalent to a controlled voltage source and a fixed resistor in series, as is shown in Fig.2. The ESB voltage and current can be expressed as follows:

$$v_B = E - i_B R \quad (4)$$

where v_B is terminal voltage of the ESB, i_B is the ESB current (a positive value represents discharging, a negative value represents charging).

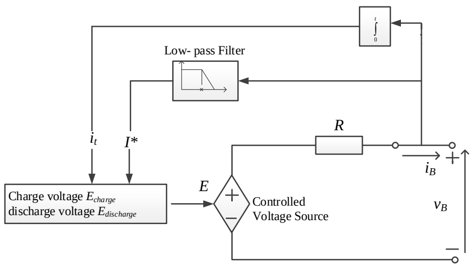


Fig. 2. Storage battery constant resistance model

The ESB discharging process mathematical model is:

$$E = E_0 - K\frac{Q}{Q - i_t} I^* - K\frac{Q}{Q - i_t} i_t + B i_B e^{-B i_t} \quad (5)$$

and the charging process mathematical model is:

$$E = E_0 - K\frac{Q}{0.1Q + i_t} I^* - K\frac{Q}{Q - i_t} i_t + B i_B e^{(A-) B i_t} \quad (6)$$

where E is open circuit voltage, E_0 is constant voltage, Q is the battery capacity, i_t is the integration of ESB current, K is polarization constant, I^* is low frequency current dynamics, A is exponential voltage coefficient, B is exponential capacity factor, R is the ESB internal resistance.

According to (4) and (6), the ESB charging power and discharging power can be expressed as follows:

$$p_{B(discharge)} = v_B \times i_B$$
$$= \left[\left(E_0 - K\frac{Q}{Q - i_t} I^* - K\frac{Q}{Q - i_t} i_t + B i_B e^{-B i_t} \right) - i_B R \right] \times i_B \quad (7)$$

$$p_{B(charge)} = v_B \times i_B$$
$$= \left[\left(E_0 - K\frac{Q}{0.1Q + i_t} I^* - K\frac{Q}{Q - i_t} i_t + B i_B e^{(A-) B i_t} \right) - i_B R \right] \times i_B \quad (8)$$

2.2 ES Four-phase Parallel Bidirectional Converters Average Model

As is portrayed in Fig. 1, when ESB is discharging, the proposed converter works in boost mode, up bridge-arm S_{BK} is shifted with respect to one another by π/2 radians, down bridge-arm S_{BK}'(K=1…4) work as free-wheeling diodes. While ESB is charging, the proposed converter works in buck mode, S_{BK}' is shifted with respect to one another by π/2 radians, S_{BK} works as free-wheeling diodes. Therefore, The nonlinear average mathematical boost model of ES four-phase parallel bidirectional converter is:

$$\begin{cases} L_{BK}\dfrac{di_{BK}}{dt} = v_B - r_{LK} \cdot i_{BK} - (1 - d_{BK}) \cdot v_{Bus} \\ C_{Bus}\dfrac{dv_{Bus}}{dt} = \sum_{K=1}^{4} (1 - d_{BK}) \cdot i_{BK} - \dfrac{v_{Bus}}{R_{Load}} \end{cases} \quad (9)$$

And the nonlinear average mathematical buck model of ES four-phase parallel bidirectional converter is:

$$\begin{cases} L_{BK}\dfrac{di_{BK}}{dt} = v_B - r_{LK} \cdot i_{BK} + d_{BK} \cdot v_{Bus} \\ C_{Bus}\dfrac{dv_{Bus}}{dt} = \sum_{K=1}^{4} d_{BK} \cdot i_{BK} + \dfrac{v_{Bus}}{R_{Load}} \end{cases} \quad (10)$$

where the subscript number K=1,2,3,4 represents the parameters of each ES converters module, i_{BK}(K=1…4) is the K-phase inductor current of ES converters, v_{Bus} is dc bus voltage, d_{BK} is the duty cycle of K-phase converter, C is the dc bus capacitance value, R_{Load} is equivalent resistance of dc load, L_{BK} is the K-phase converter input inductance value, r_{LK} is the series resistance of the K-phase inductance, representing the K-phase converter module static losses.

The input power of ES four-phase parallel bidirectional converter can be expressed as follows:

$$p_{BK} = v_B \cdot i_{BK} (K = 1...4) \quad (11)$$

3 Distributed PV-ES DC Generation System Nonlinear Control

3.1 PV MPPT Control Based on Four-phase Parallel Boost Converters

PV output power characteristic curve can be obtained by the equation (3) as shown in Fig.3. Known from Fig.3, the maximum power point of PV varies with changes in solar irradiance and temperature, and has a significant nonlinear characteristic. To achieve PV maximum power output and satisfy the dynamic behavior of the system during a brutal solar variation, an improved extremum seeking algorithm is designed based on four-phase parallel boost converters. The traditional extremum seeking algorithm checks the sign of PV power derivative permanently to obtain the tracking direction of MPP at each time, which is combined with voltage changes dv_{PV}/dt to determine the current moment change direction of voltage to directly held or the reverse. However, it can be seen from Fig.3 (a) that when the solar irradiance suddenly weakens, the PV output power decreases substantially, and miscalculation will occur by traditional method. Therefore, this paper presents an improved extremum seeking algorithm, by setting a delay link, when the power derivative is negative and the delay is completed, the tracking signal changes, or keep the original tracking method. This improvement ensures accurate tracking of the maximum power point under solar irradiance dramatic changes.

Through traditional extremum seeking algorithm voltage changes dv_{PV}/dt can be obtained, after integrating it generates the output v_{PVmax} near the instantaneous MPP. As PV four-phase parallel boost converters adopt democratic current-sharing, PV current reference value can be expressed as follows:

$$i_{PVref} = \frac{1}{4}\left(i_{PV1} + i_{PV2} + i_{PV3} + i_{PV4}\right) \tag{12}$$

where i_{PVref} is PV current reference value which is also the PV currents average; i_{PVK}(K=1…4) is the K-phase inductor current of PV converters.

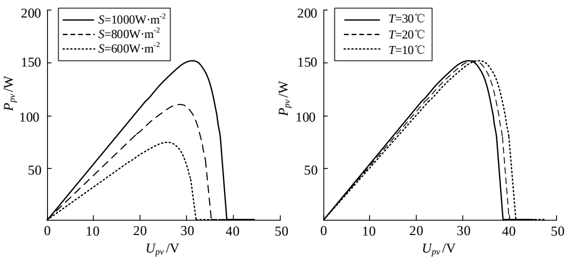


Fig. 3. Photovoltaic output power characteristics
(a) Output characteristics at variable insolation
(b) Output characteristics at variable ambient temperature

Also, different current error signals (ε_1, ε_2, ε_3 and ε_4, corresponding to the respective difference between the reference current i_{PVref} and each converter input current i_{PVK}, are established as follows:

$$\begin{cases} \varepsilon_1 = i_{PVref} - i_{PV1}; \varepsilon_2 = i_{PVref} - i_{PV2} \\ \varepsilon_3 = i_{PVref} - i_{PV3}; \varepsilon_4 = i_{PVref} - i_{PV4} \end{cases} \tag{13}$$

Then, current error signals are added respectively to v_{PVmax} in order to make a minor adjustment of each converter and then generate the different control signals v_{PVK}:

$$\begin{cases} v_{PV1} = v_{PV\max} + \varepsilon_1; v_{PV2} = v_{PV\max} + \varepsilon_2 \\ v_{PV3} = v_{PV\max} + \varepsilon_3; v_{PV4} = v_{PV\max} + \varepsilon_4 \end{cases} \tag{14}$$

As Fig.4 shows, the comparison between the different v_{PVK} converter control signals and the four saw tooth supplies each d_{PVK} duty cycle value. This type of control allows both a perfect track of instantaneous MPP and an optimum share of the photovoltaic current between each switching module.

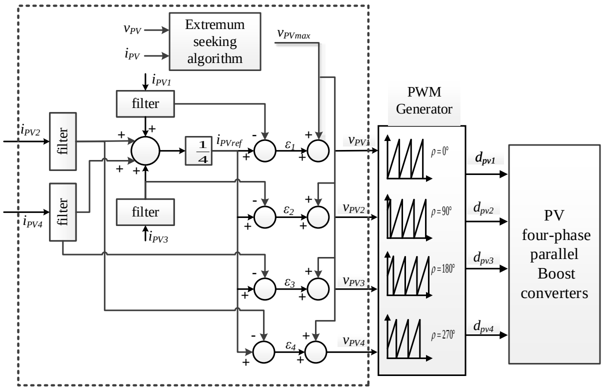


Fig. 4. Improved extremum seeking algorithm MPPT control of PV four-phase parallel Boost converters

3.2 Nonlinear Differential Flatness Control of ES Four-phase Parallel Bidirectional Converters

The intermittent PV generation varies with changes in atmospheric conditions. ES four-phase parallel bidirectional converter is an important control link of distributed PV-ES DC generation system, which can smooth the PV output power and to achieve coordinated control of PV-ES system. Efficient control schemes are essential to maintain the stable operation under disturbances such as changes in atmospheric conditions, changes in load demands, or an external fault within the system.

A nonlinear system is flat if there exists a set of differentially independent variables (equal in number to the number of inputs) such that all state variables and (control) input variables can be expressed in terms of those output variables and a finite number of their time derivatives by endogenous feedback without integrating differential equations. As depicted in Fig. 5, nonlinear flat systems are equivalent to linear controllable systems. Therefore, a dynamical system is naturally differentially flat if it is equivalent to a system without dynamics, i.e., a static system.

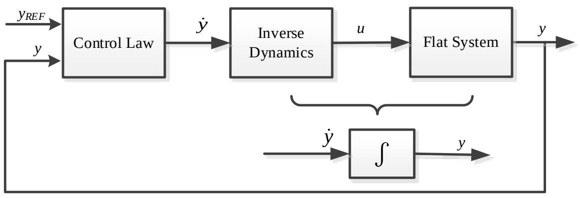


Fig. 5. Concept of control system based on the flatness principle

To prove the ES four-phase parallel bidirectional converter is a flat system, taking ES discharge process for example, from (11), the input power p_{BK} derivatives of each module is given versus v_B and i_{BK} by the following differential equation:

$$\frac{dp_{BK}}{dt} = \frac{d(v_B \cdot i_{BK})}{dt} = i_{BK} \cdot \frac{dv_B}{dt} + v_B \frac{di_{BK}}{dt}, K = 1...4 \quad (15)$$

Considering ESB terminal voltage is approximately constant, equation (15) can be rewritten as:

$$\frac{dp_{BK}}{dt} = v_B \frac{di_{BK}}{dt}\Big|_{v_B = constant}, K = 1...4 \quad (16)$$

Based on the flatness principle introduced above, the flat output $\boldsymbol{y} = [y^1, y^2, y^3, y^4]^T$, control variable $\boldsymbol{u} = [u^1, u^2, u^3, u^4]^T$, and state variable $\boldsymbol{x} = [x^1, x^2, x^3, x^4]^T$ are defined as follows:

$$\boldsymbol{y} = \begin{bmatrix} p_{B1} \\ p_{B2} \\ p_{B3} \\ p_{B4} \end{bmatrix}; \quad \boldsymbol{u} = \begin{bmatrix} d_{B1} \\ d_{B2} \\ d_{B3} \\ d_{B4} \end{bmatrix}; \quad \boldsymbol{x} = \begin{bmatrix} i_{B1} \\ i_{B2} \\ i_{B3} \\ i_{B4} \end{bmatrix} \quad (17)$$

Controlling ESB four-phase parallel bidirectional converters are the same as controlling a single bidirectional converter, from (11), the state variable x can be written as:

$$x_1 = \frac{p_{B1}}{v_B} = \phi(y_1) \quad (18)$$

From (9) and (16), the control variable u can be calculated from the flat output y and its time derivative $y^{\cdot}$, i.e.

$$u_1 = 1 + (\dot{y}_1 \cdot \frac{L_{B1}}{v_B} + r_{L1} \cdot i_{B1} - v_B) \cdot \frac{1}{v_{Bus}} = d_1 = \psi(\dot{y}_1) \quad (19)$$

It is apparent that $x = \phi(y)$ and $u = \psi(y')$ correspond to (18) and (19), respectively. Consequently, the mathematical model of ES four-phase parallel bidirectional converter discharge process can be proved to be flat. Similarly, the mathematical model of charging process can be proved to be flat. So the ES four-phase parallel bidirectional converter is a differentially flat nonlinear systems.

3.3 Control Law and Stability

The input-power reference of each module is represented by y_{1ref} ($=p_{B1ref}$). A linearizing feedback control loop achieving an exponential asymptotic tracking of the trajectory is given by the following expression:

$$(\dot{y}_1 - \dot{y}_{1ref}) + K_{11}(y_1 - y_{1ref}) + K_{12}\int_0^t (y_1 - y_{1ref})d\tau = 0 \quad (20)$$

Then linearizing feedback control law is:

$$\dot{y}_1 = \dot{y}_{1ref} + K_{11}(y_{1ref} - y_1) + K_{12}\int_0^t (y_{1ref} - y_1)d\tau \quad (21)$$

where K_{11} and K_{12} are the controller parameters.
One may set the following as a desired characteristic polynomial:

$$p(s) = s^2 + 2\xi\omega_n s + \omega_n^2 \quad (22)$$

where ζ and ω_n are the desired dominant damping ratio and natural frequency, respectively. Optimum choice of the design controller parameters is obtained by comparing (20) and (22), namely: $K_{11} = 2\zeta\omega_n$, $K_{12} = \omega_n^2$. Replacing the term for $y^{\cdot}$ into (19) gives the equation for the closed-loop static-state feedback duty cycle d_{B1}, i.e.

$$\begin{aligned} u_1 = 1 + ((\dot{y}_{1ref} + K_{11}(y_{1ref} - y_1) + K_{12}\int_0^t (y_{1ref} - y_1)d\tau) \cdot \frac{L_{B1}}{v_B} \\ + r_{L1} \cdot i_{B1} - v_B) \cdot \frac{1}{v_{Bus}} = d_{B1} = \psi(\dot{y}_1) \end{aligned} \quad (23)$$

Fig. 6 depicts nonlinear differential flatness control of distributed PV-ES DC generation system. The MPPT control above generates the PV maximum power p_{PVmax}. This signal is then subtracted by the

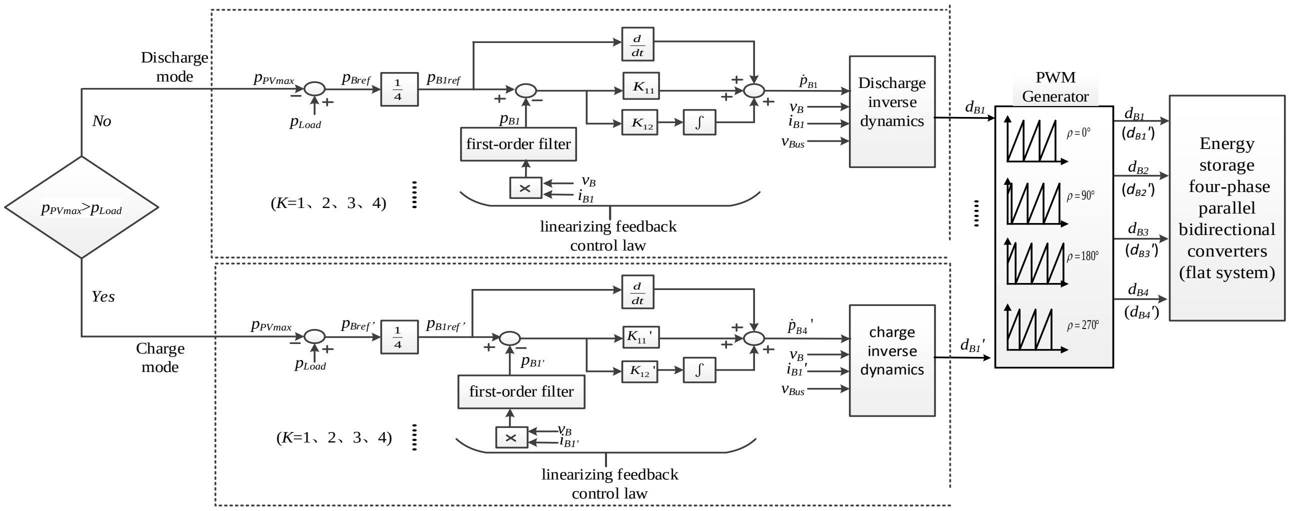


Fig. 6. Differential flatness control of energy storage four-phase parallel bidirectional converters

load reference power p_{Loadref}, which yields a desired reference trajectory of ES four-phase parallel bidirectional converters is represented by p_{B1ref}. Based on the proposed linear feedback control law, the flat nonlinear ES system is proved to control quickly ESB charge and discharge by tracking vary of PV module and load power so that smoothing PV output power and satisfying load power.

ES nonlinear system stability can be determined by controller parameter and system control frequency. Clearly, the control system is stable for K_{11}、K_{12}>0 (ζ, ω_n > 0).To reduce harmonics due to power-electronic switching, the measured input powers of each module are associated to a first-order filter used. Based on the power-electronic constant switching frequency ω_S (PWM) and the cascade control structure, the input power control must operate at a cutoff frequency $\omega_P << \omega_F$ (a cutoff frequency of the first-order filter) $<< \omega_S$. Once the flat outputs are stabilized, the whole system is exponentially stable because all the variables of the system are expressed in terms of the flat outputs.

4 Simulation Validation

To authenticate the proposed control algorithm and control laws, the simulation study is carried out in MATLAB/Simulink. Specifications of the PV module are detailed in Table I. Parameters associated with ESB and control system can be seen in Tables II. As Fig.3 (a) and (b) show, the effect of solar irradiation on the output power is greater than the temperature effect. Thus this work ignores the impact of temperature, focuses on the analysis of the PV system output power change under dramatic changes of solar irradiation.

Table 1. PV module parameters

V_{oc}	I_{sc}	V_m	I_m	a	b	c
66 V	25.4A	54.2V	23.3A	0.002 5	0.000 5	0.002 8

Table 2. Energy storage battery and system parameters

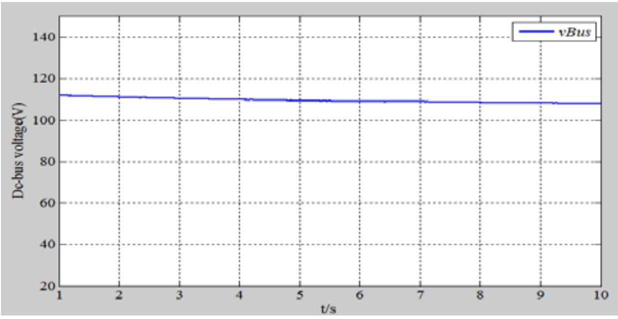
E_0	Q	C_{Bus}	L_{PV}	L_B	r_L
60V	25Ah	0.1F	1 e-3H	4e-2H	2e-2Ω
ω_S	ω_E	ω_P	K_{11}	K_{12}	
15 700	1 000	100	283 rd·s-1	1e4 rd2·s-2	

In this work, the initial condition is the standard atmospheric condition in which the solar irradiation is considered as 1000W/m^2 and the temperature is 25 ℃. At t=4s, solar irradiation suddenly increases to 1300W/m^2. At t=8s, solar irradiation drop sharply to 600W/m^2 by the effect of clouds. The performance of the designed control strategy is evaluated through the following case studies.

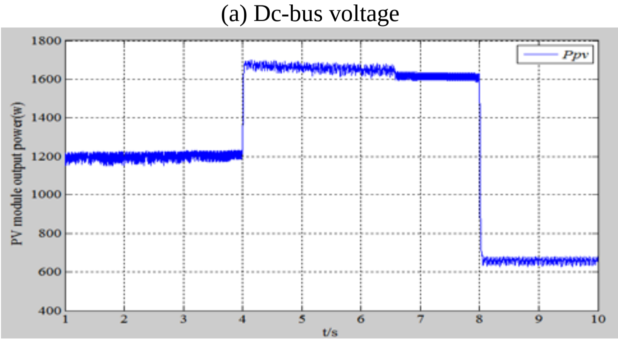
Case 1: load power increases (or decreases) when PV module output power increases (or decreases). The waveforms of dc-bus voltage, PV module output power, ESB power and the load power are shown in Fig. 7 from where it can be seen that initial load power setpoint is equal to 600W, and PV module output power is equal to 1200W, as a result, ES system works in charging mode, which charging power $P_{B(\text{charge})}$ is equal to 600W.

1) At t=4s, the load power setpoint steps to the constant power of 1200W, and PV module output power steps to 1600W by the effect of solar irradiation. ESB fast responses system power changes, controlling the converter current to adjust the charging power $P_{B(\text{charge})}$ of 400W.

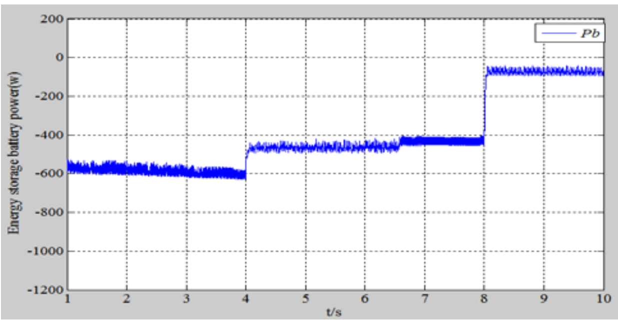
2) At t=8s, the load power setpoint steps from 1200W to 600W, and PV module output power steps from 1600W to 600W. Obviously, PV output power just meet the load demand, and ES system is mainly used for smoothing PV power fluctuations.



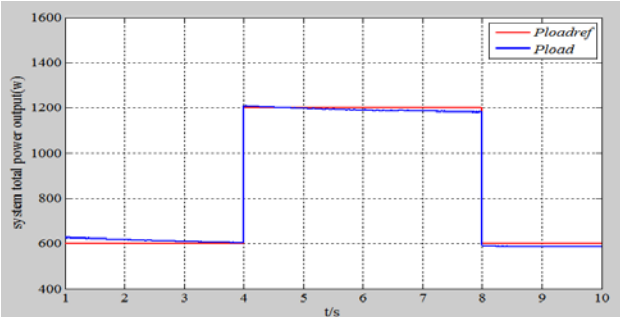
(a) Dc-bus voltage



(b) PV module output power



(c) Energy storage battery power



(d) Load power setpoint（red line）and system total power output (blue line)

Fig. 7. Differential flatness control of distributed Photovoltaic-energy storage dc generation system dynamic response under Case 1

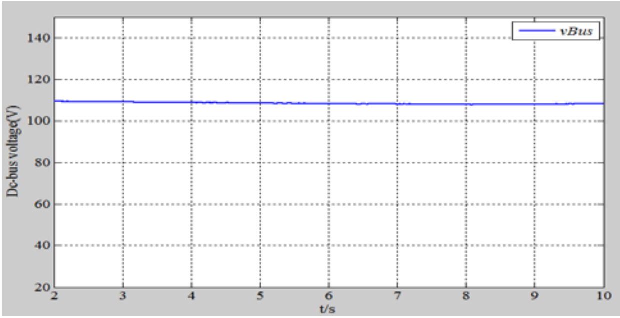
The results in case 1 reveal that differential flatness control of distributed PV-ES DC generation system can complete fast charging of energy storage system, realizing coordinated control of PV-ES system and compensating gap of PV power-load power demand, which can also smooth the output power and stabilize the system with a load mutation or control parameter perturbation.

Case 2: load power increases (or decreases) when PV module output power decreases (or increases). The waveforms of dc-bus voltage, PV module output power, energy storage battery power and the load power are shown in Fig. 8 from where it can be seen that initial load power setpoint is equal to 1200*W*, and PV module output power is equal to 1200*W* which meets perfectly the load power demand. So the target of ES system is to smooth PV output power and to achieve high quality power supply.

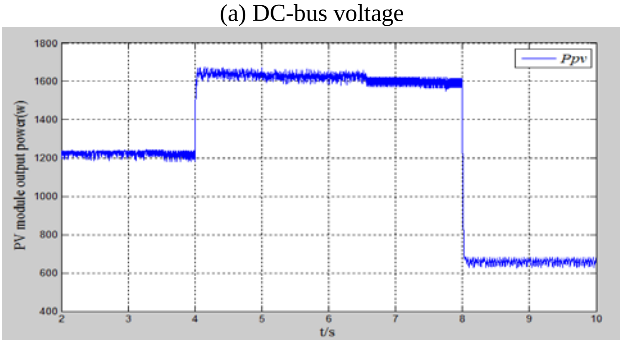
1) At t=4*s*, the load power setpoint steps from 1200*W* to 600*W*, and PV module output power steps to 1600*W*. ES system fast responses and change to charging mode, charging power $P_{B(\mathrm{charge})}$ is equal to 1000*W*.

2) At t=8*s*, the load power setpoint steps from 600*W* to 1200*W*, and PV module output power steps from 1600*W* to 600*W*. ES system fast switches to discharge model, discharging power $P_{B(\mathrm{discharge})}$ is equal 600*W*.

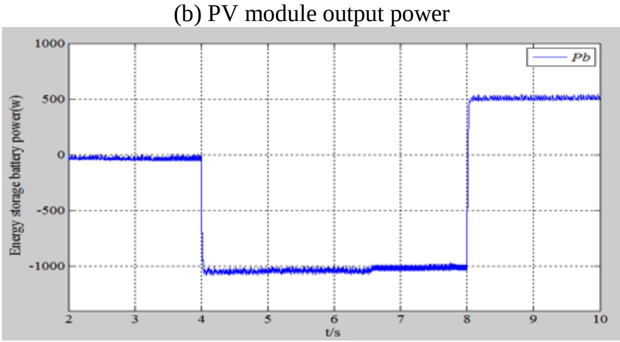
The results in case 2 reveal that differential flatness control of distributed PV-ES DC generation system can complete fast discharging control and switching between charging and discharging of S system. Not only can realize the reliable power supply in the steady state, but can still maintain power smooth, achieving high reliability and high quality power supply in the extreme situations of PV output drops at the same time load demand rises.



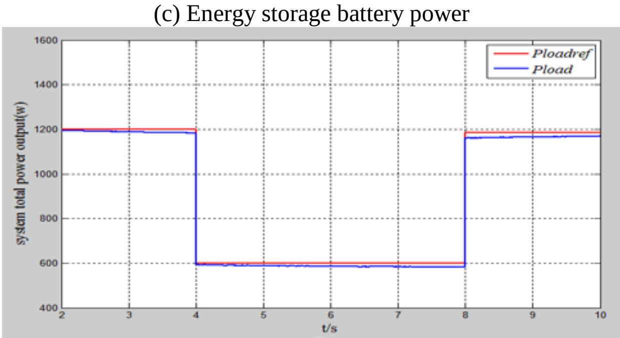
(a) DC-bus voltage



(b) PV module output power



(c) Energy storage battery power



(d) Load power setpoint（red line）and system total power output (blue line)

Fig. 8. Differential flatness control of distributed photovoltaic-energy storage dc generation system dynamic response under Case 2

This paper compared the performance of the flatness-based control with a traditional linear PI control method. To give a reasonable comparison between the methods, the parameters of the linear PI controller K_P and K_I were tuned to obtain the best possible performance, and this result is compared with the flatness-based control. Tab. 3 shows the simulation results obtained for both controllers under the situation the same as case 1, we conclude that the flatness-based control provides a better performance than the traditional PI control.

Table 3. Performance comparison between pi and differential flatness approach

Control methods	Overshoot σ	Adjustment time t_s	Steady-state error e_{ss}
Traditional PI control.	12%	1*s*	0.033
Flatness-based control	0	0.5*s*	0.017

5 Conclusion

The main contribution of this brief is to model and control distributed PV-ES DC generation system. According to the proposed the system topology, for PV four-phase parallel boost converters, an improved extremum seeking algorithm is designed to achieve maximum power point tracking (MPPT) control, to widen the range of PV module output voltage and to lessen current ripple. From the perspective of stability, a novel nonlinear differential flatness control based on ES four-phase parallel bidirectional converters is proposed, which effectively solve the problem of traditional control method based on small signal model, such as narrow stability margin, small freedom degree. Moreover, the proposed control method has a strong anti-interference ability under sudden change or control parameter perturbation, which provides a simple solution to coordinated control of renewable energy-ES device and stability control of nonlinear converters.

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