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A Power Optimizer utilizing Nonlinear Adaptive Control for Distributed Photovoltaic Systems

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Abstract. In order to improve the utilization of the solar energy,a PV power optimizer was investigated in this paper. According to the distributed maximum power point(DMPP) architecture, each of the PV cells is equipped with a power optimizer. The power optimizer utilizing nonlinear adaptive control, which is based on a nonlinear model describing the dynamics of the buck-boost converter. Theoretical analysis and the simulation results indicate that the proposed nonlinear adaptive control technique achieves fast and accurate MPPT under varying irradiance conditions. Compared with PID control method,the nonlinear adaptive control method takes less time to achieve MPPT. The simulation is performed by simpowersystem toolbox of MATLAB.

Introduction

Photovoltaic(PV) cells have nonlinear voltage-current characteristics, and the output of the PV cells is dependent upon the solar radiation and temperature[1]. In order to improve the utilization rate of the renewable energy and to harvest the maximum power from the PV cell, it is necessary to implement a control strategy to identify the PV cell operating point characterized by the maximum power point(MPP)[2]. Leonor Linares et al proposed an improved distributed maximum power point (DMPP) architecture[3]. Each of the PV cells is equipped with a power optimizer which ensure the each of the PV cells operates independently at the MPP in the current environment so as to achieve the overall maximum power output.

Many studies have been undertaken to track the MPP from the output of PV systems. The most common maximum power tracking(MPPT) methods are perturbation and observation(P&O)[4], incremental conductance[5] and hill climbing[6]. However, these MPPT methods ignore the dynamics of the PV cells and converter.

From the above, this paper proposed a power optimizer utilizing nonlinear adaptive control for the distributed PV system which is based on a DMPP structure as shown in Fig.1. The power optimizer consists of a MPPT algorithm module and a DC-DC converter module. Using buck-boost converter as DC-DC converter, the output voltage can be lower or higher than the input[7]. The MPPT algorithm module uses a nonlinear adaptive algorithm. The nonlinear adaptive algorithm is based on the nonlinear model of the buck-boost converter and the PV cell. For the proposed method, simulations in MATLAB/Simulink are performed and a comparative analysis with PID control method is illustrated. The simulation results revealed that the proposed power optimizer provides a fast and accurate MPPT method of the PV cell under rapidly changing solar radiation.

Power Optimization Principles of the Photovoltaic Systems

Photovoltaic cell modelling

The equivalent circuit of the photovoltaic(PV) cell can be represented by a single diode equivalent circuit shown in Fig.2[1,8]. In ideal situations, R_s=0, $R_{sh}=\infty$, the output current of PV cell can be expressed as:

$$I_{pv} = I_{ph} - I_o[\exp(BV_{pv}) - 1] \tag{1a}$$

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$$B=\frac{q}{AKT} \tag{1b}$$

$$I_o=I_{or}[\frac{T}{T_r}]^3\exp\left[\frac{qE_g}{\gamma K}\left(\frac{1}{T_r}-\frac{1}{T}\right)\right] \tag{1c}$$

$$I_{ph}=[I_{SCR}+K_I(T-T_r)]\frac{\lambda}{1000} \tag{1d}$$

Where K is Boltzman's constant, 1.38×10^{-23} J/K; q is the electron charge, 1.6×10^{-19}C; A is diode factor; T_r is the reference temperature; T is the PV cell temperature; I_o is the PV cell reverse saturation current; I_{or} is the PV cell saturation current at T_r; γ is the ideality factor; E_g is the band gap for silicon; I_{ph} is the photocurrent; I_{SCR} is the short circuit current at 289.15K and 1kW/m^2; λ is the solar radiation.

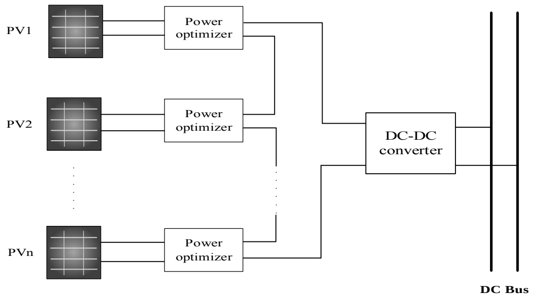


Fig.1 Power optimizer DMPP structure topology

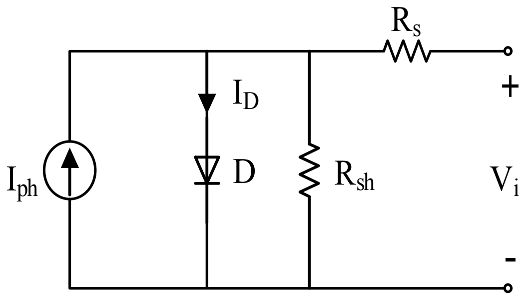


Fig.2 equivalent circuit of photovoltaic cells

DC-DC converter modelling

As shown in Fig.3, the state variables of buck-boost converter are $x=[i_L \quad v_{pv}]^T$. The state space-averaged model of buck-boost converter is given as follows[9]:

$$\frac{di_L}{dt}=\frac{Dv_{pv}}{L}-\frac{(1-D)v_{out}}{L} \tag{2a}$$

$$\frac{dv_{pv}}{dt}=\frac{i_{pv}}{C}-\frac{Di_L}{C} \tag{2b}$$

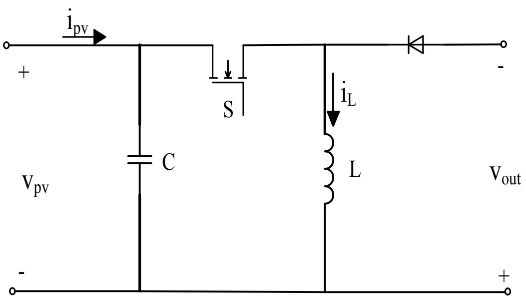


Fig.3 Circuit diagram of buck-boost converter

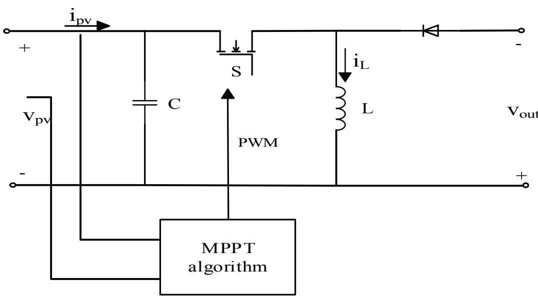


Fig.4 schematic of the power optimizer

Power optimizer analysis

As shown in Fig.4, a photovoltaic power optimizer consists of a MPPT algorithm module and a buck-boost converter module. PV cell can be used in the photovoltatic/thermal(PV/T) integrated system[10] to control the temperature of the PV cell at around 25°C. So the power optimization controller proposed in this paper mainly consider the influence of solar radiation on the output power of the PV cell.

Then, substitute Eqs. (1a), (1c), (1d) into (2b):

$$\frac{dx_2}{dt}=\frac{\alpha(\lambda)}{C}-\frac{I_{or}\omega(x_2)}{C}-\frac{Dx_1}{C} \tag{3a}$$

$$\alpha(\lambda) = I_{SCR}\frac{\lambda}{1000} \tag{3b}$$

$$\omega(x_2) = \exp(Bx_2) - 1 \tag{3c}$$

Maximum power point tracking(MPPT) can be achieved when:

$$\frac{\partial P}{\partial V_{pv}}\Big|_{V_{pv}=V_m} = 0 \tag{4a}$$

$$P = V_{pv}I_{pv} \tag{4b}$$

$$\frac{\partial P}{\partial V_{pv}}\Big|_{V_{pv}=V_m} = I_{pv} + V_m\frac{\partial I_{pv}}{\partial V_m} = 0 \tag{4c}$$

Substitute Eqs. (1a), (3b) into (4c):

$$\alpha(\lambda) - I_{or}[(1+BV_m)\exp(BV_m) - 1] = 0 \tag{5}$$

Power optimization controller design

The power optimization controller adopts a nonlinear adaptive algorithm to achieved MPPT of the PV cell. Firstly, the goal of the controller is to make the voltage x_2 tracking MPP voltage V_m, so define tracking error z_1:

$$z_1 = x_2 - V_m \tag{6}$$

From Eq. (3a), the dynamics of tracking error z_1 can be expressed as:

$$\dot{z}_1 = \dot{x}_2 - \dot{V}_m = \frac{\alpha(\lambda)}{C} - \frac{I_{or}}{C}\omega(x_2) - \frac{Dx_1}{C} - \dot{V}_m \tag{7}$$

The Lyapunov function is defined as:

$$V_1 = \frac{z_1^2}{2} + \frac{\tilde{\alpha}(\lambda)^2}{2k} \quad (k > 0) \tag{8}$$

$$\dot{V}_1 = z_1\dot{z}_1 + \frac{\tilde{\alpha}(\lambda)}{k}\dot{\tilde{\alpha}}(\lambda) = z_1\left(\frac{\hat{\alpha}(\lambda)}{C} - \frac{I_{or}}{C}\omega(x_2) - \frac{Dx_1}{C} - \dot{V}_m\right) + \frac{\tilde{\alpha}(\lambda)}{k}\left(\frac{kz_1}{C} - \dot{\hat{\alpha}}(\lambda)\right) \tag{9}$$

Where $\alpha(\lambda)$ is uncertain parameter, $\hat{\alpha}(\lambda)$ is estimates of $\alpha(\lambda)$, $\tilde{\alpha}(\lambda)$ is parameter error:

$$\tilde{\alpha}(\lambda) = \alpha(\lambda) - \hat{\alpha}(\lambda) \tag{10}$$

According to Eq. (12), it can eliminate $\tilde{\alpha}(\lambda)$ with the update laws:

$$\dot{\hat{\alpha}} = k\frac{z_1}{C} \tag{11}$$

$$-\frac{Dx_1}{C} = -\frac{\hat{\alpha}(\lambda)}{C} + \frac{I_{or}}{C}\omega(x_2) + \dot{V}_m - mz_1 \quad (m > 0) \tag{12}$$

If satisfied Eq. (12), $\dot{V}_1 = -mz_1^2 < 0$, z_1 can be regulated to zero. So, the control law can be expressed as:

$$D = \frac{\hat{\alpha}(\lambda)}{x_1} - \frac{I_{or}\omega(x_2)}{x_1} - \frac{CV_m}{x_1} + \frac{mCz_1}{x_1} \tag{13}$$

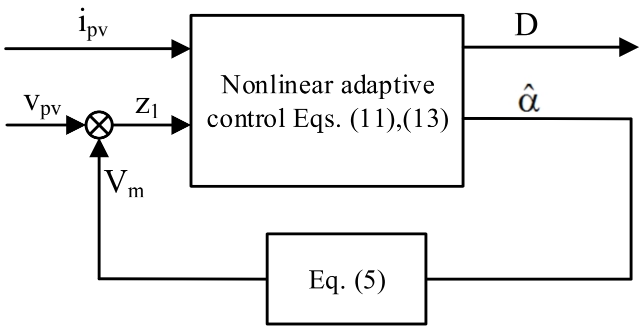


Fig.5 Closed-loop control structure diagram

From Eqs. (5), (11), (13), the power optimization closed-loop control system can be shown in Fig.5. As shown in Fig.5, the power optimization controller steer $\frac{\partial P}{\partial v_{pv}}$ to zero, by adjusting the duty cycle D, which can achieved accurate maximum power point tracking of the PV cell.

Simulation results

In this paper,the PV cell's electrical characteristics are described as follows: Maximum Power, P_m=123W; short circuit current, I_{SCR}=7.80A; open circuit voltage, V_{oc}=36V; voltage at MPP,V_m=29V; current at MPP, I_m=7.35A.

The Fig.6 shows the simulation model of the PV cell. And the Fig. 7 shows the I-V and P-V characteris for the PV cell under varying solar radiation and constant temperature(25°C) conditions. The simulation results show that the output current and power decreases with the irradiation when the temperature is 25°C.

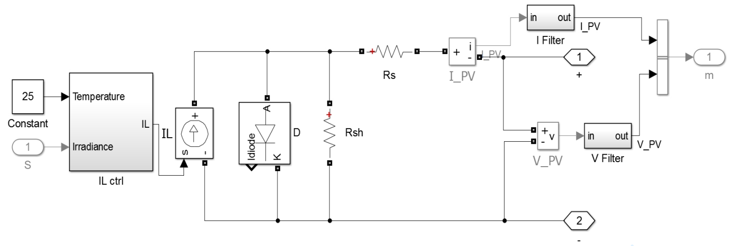


Fig.6 Simulation model of the PV cell

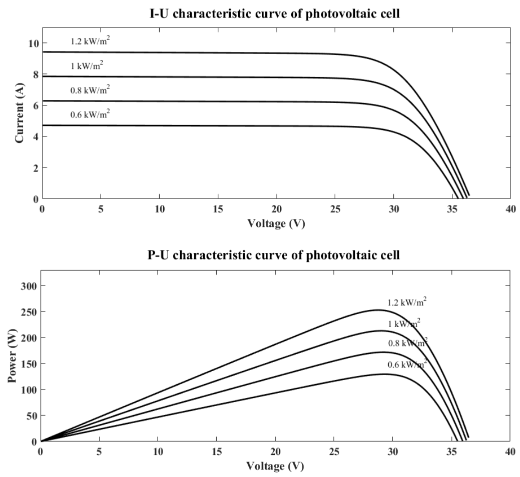


Fig.7 Simulated curves for the model of PV cell

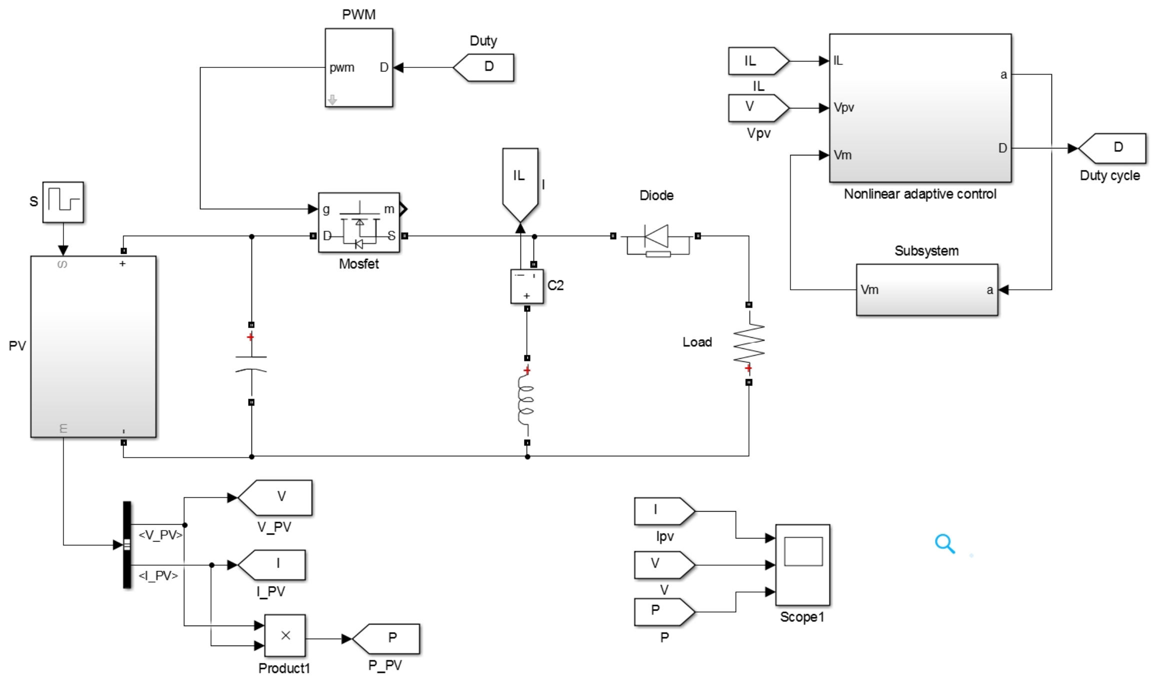
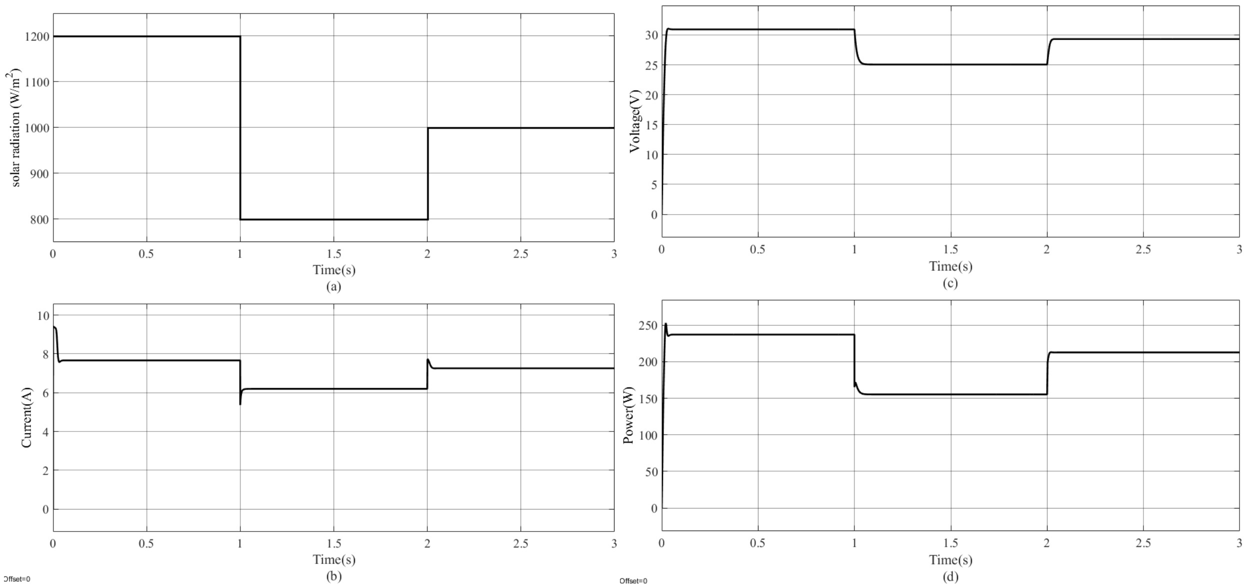


Fig.8 Simulation model of power optimizer with nonlinear adaptive control

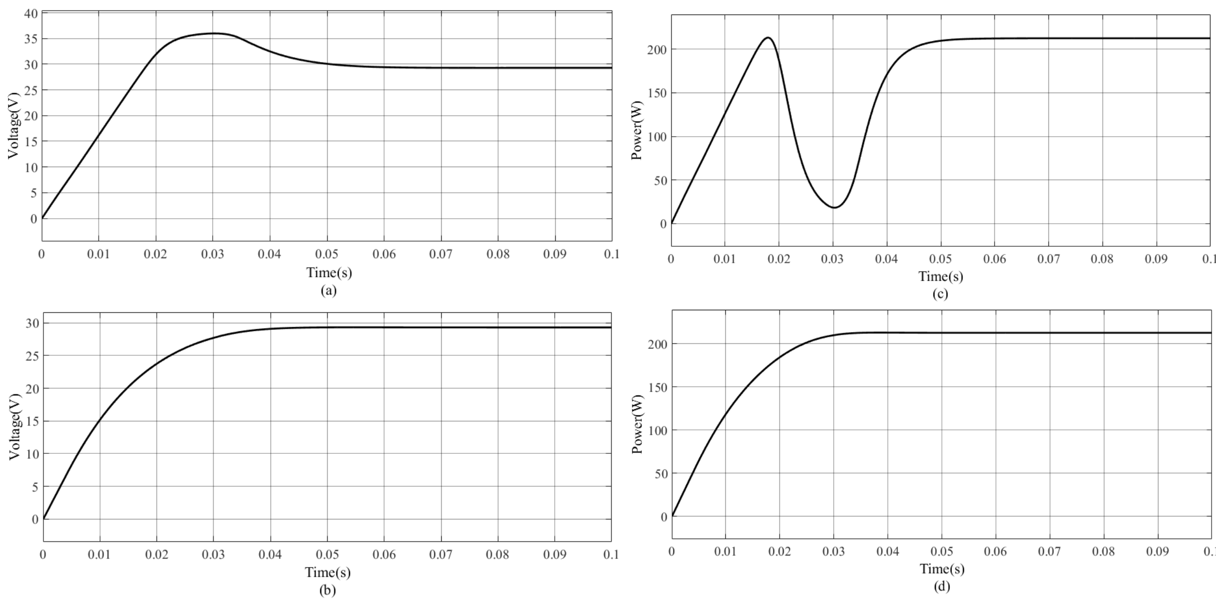
The simulation model of power optimizer with nonlinear adaptive control has been implemented in Matlab/Simulink as shown in Fig.8, which includes the PV cell module, the buck-boost converter module and the MPPT algorithm module. The characteristics of the power optimizer are illustrated as follows: Inductance, $L = 10^{-3}H$; Capacity, $C = 4700\times10^{-6}F$; Load resistance, R_o=10Ω; PWM frequency, 50KHz. And the desigen parameters are given as follows:m=20; k=1000.

The Fig.9 shows the Simulation waveform of the power optimizer with nonlinear adaptive control in presence of solar radiation changes. The solar radiation changes are carried out between 1200W/m^2 and 800W/m^2, between 800W/m^2 and 1000W/m^2. The temperature is kept at 25°C.The simulation waveform shows that the proposed power optimizer provides stable output with fast and accurate MPPT of the PV cell under rapidly changing solar radiation conditions.



(a) solar radiation(λ) (b)PV cell current(A) (c)PV cell voltage(V) (d)PV cell power(W)
Fig.9 Simulation waveform of the power optimizer with nonlinear adaptive control

The Fig.10 shows the Simulation waveform of the power optimizer with PID control and nonlinear adaptive control under the condition of solar radiation varies from 0W/m^2 to 1000W/m^2 and constant temperature at 25°C. Compared with PID control method, the nonlinear adaptive control method takes less time to achieve MPPT and has better robustness.



(a)PV cell voltage with PID control (b)PV cell voltage with nonlinear adaptive control
(c)PV cell power with PID control (d)PV cell power with nonlinear adaptive control
Fig.10 Simulation waveform of the power optimizer with PID control and nonlinear adaptive control

Conclusions

In this paper, a power optimizer utilizing nonlinear adaptive for distributed photocoltaic systems is proposed. Theoretical analysis and the simulation results confirm that the proposed power optimizer achieves fast and accurate MPPT of the PV cell under rapidly changing solar radiation and constant tenperature(25°C) conditions. Compared to PID control method, the proposed nonlinear adaptive control method has better performances such as faster MPPT speed and better robustness.

Acknowledgements

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