Electric Power Systems Research 157 (2018) 168–176

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Performance improvement of photovoltaic power systems using an optimal control strategy based on whale optimization algorithm

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ARTICLE INFO

Article history:
Received 9 August 2017
Received in revised form 6 October 2017
Accepted 19 December 2017

Keywords:
Photovoltaic power systems
Power system control and dynamics
Response surface methodology
Whale optimization algorithm

ABSTRACT

Photovoltaic (PV) installations are consistently increasing all over the world, leading to a high penetration to the electric grid. Tremendous efforts should be exerted to maintain the operation of the PV systems at optimal conditions. This paper introduces an optimal control strategy with the purpose of enhancing the performance of PV systems. This control strategy is based on the proportional-integral (PI) controller, which is designed by using the whale optimization algorithm (WOA). The response surface methodology (RSM) model is established to create the objective function and its constraints. The proposed WOA-based PI controllers are utilized to control the DC chopper and grid-side inverter in order to achieve a maximum power point tracking operation and improve the dynamic voltage response of the PV system, respectively. The effectiveness of the control strategy is tested under different operating conditions of the PV system such as (1) subject the system to symmetrical and unsymmetrical fault conditions, (2) study the system responses under different irradiation and temperature conditions using real data extracted from a field test, and (3) subject the system to a sudden load disturbance in an autonomous operation. This effectiveness is compared with that achieved using the generalized reduced gradient (GRG) algorithm-based PI controller. The validity of the proposed control strategy is extensively verified by the simulation results, which are performed using PSCAD/EMTDC environment.

1. Introduction

Photovoltaic (PV) technology received a great interest worldwide over the last decades. It is expected that the solar PV will be the cheapest renewable power technology in the near future because of the deep cost reduction of the PV components [1]. This reflects the exerted significant efforts to enhance efficiency and develop the manufacturing process of the PV. The statistics of the global PV market state that the total PV installation in Europe can reach up to 156 GW in 2018, which represents a new record of PV installation [2]. This is an indicator to the high penetration of the PV systems into the electric grids. The integration of large scale PV systems with the electric grids can cause many dynamic and operation problems, which should be solved optimally to maintain the power system stability and reliability [3–7].

There are a lot of methods used to investigate and enhance the performance of the PV systems under different operating conditions. In Ref. [8], the reactive power and the terminal voltage of a grid-connected PV system are controlled during a grid disturbance using a neuro-fuzzy control strategy. Although, the neuro-fuzzy controller is efficiently capable of dealing with the system nonlinearity and parameters sensitivity, it depends mainly on the designer experience for selecting the artificial neural network (ANN) design and the fuzzy rules. Moreover, the training of the ANN takes a long time, which affects the dynamic performance. In Refs. [9,10] the low voltage ride through (LVRT) capability of PV systems is proposed using the proportional-integral (PI) controller. The voltage stability of PV systems is improved using a cascaded PI control scheme [11]. In Ref. [12], adaptive or self-tuning PI controllers are revealed to improve the dynamic performance of the PV power plants. However, the fixed-gains PI controllers are still the most commonly used in industry. Several studies have used this type of control to improve the dynamic performance of PV systems, but its design relies on the trial and error method, which is not an accurate method for the controller design [13–15]. Although, the PI controller offers a wide stability margin in modern control systems, it suffers from the system nonlinearity and the system's parameters variation. Therefore, the optimal design of such controllers in heavy nonlinear systems like PV systems is considered a cumbersome problem for the designers of power system control. The principal problem is the difficulty to represent the system model by linear transfer functions. Therefore, several optimization

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https://doi.org/10.1016/j.epsr.2017.12.019
0378-7796/

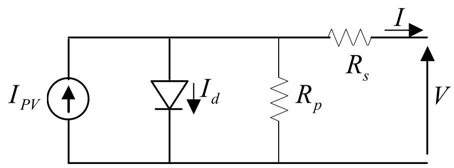

Fig. 1. The equivalent circuit of the single-diode PV model.

methods are used to solve such design problems such as genetic algorithm (GA) [16], the Taguchi approach [17], harmony search algorithm [18], and shuffled frog leaping algorithm [19]. The significant development of the computational evolutionary algorithms and its powerful application to solve complex nonlinear optimization problems represent the main motivation of the author to apply the novel whale optimization algorithm (WOA). It is a novel meta-heuristic optimization algorithm, which is motivated by the social behavior of the humpback whales. This algorithm easily describes the hunting process of the humpback whales to the prey. It was presented by Mirjalili and Lewis in 2016 [20]. The WOA possesses some merits over other swarm optimization algorithms such as its high convergence speed and its lower number of parameters to be designed. Recently, it was successfully applied to many classic mathematical optimization problems and various engineering problems with the purpose of design optimization [20]. To the best of the Author's knowledge, the proposed algorithm has not been reported so far in renewable energy systems literatures.

In this paper, a novel application of the WOA-based PI control strategy is proposed to enhance the dynamic performance of PV systems. The DC boost chopper of the PV system is implemented to extract the maximum power. The grid-side inverter of the PV system is used to control both of the DC-link voltage and the voltage at the point of common coupling (PCC). All power electronic devices are controlled using the proposed control strategy. To perform the optimization process, the objective function and its constraints are established using the response surface methodology (RSM), which is a powerful statistical method that expresses the system response in terms of the design variables through empirical formulas. In this study, the RSM model is a second order to obtain accurate results. The proposed WOA is applied to the RSM model as an offline optimization problem using MATLAB environment [21]. The validity of the proposed control strategy is extensively verified by the simulation results, which are performed using PSCAD/EMTDC environment [22]. The effectiveness of the proposed controller is checked under different operating conditions of the PV system such as (1) subject the system to symmetrical and unsymmetrical fault conditions, (2) study the system responses under different irradiation and temperature conditions using real data extracted from a field test, and (3) subject the system to a sudden load disturbance in an autonomous operation. This effectiveness is compared with that achieved using the GRG-based PI controller. With the WOA-based PI control strategy, the dynamic performance of PV systems should be enhanced.

The paper is structured as follows: Section 2 presents the PV system modeling. In Section 3, the converters control is introduced. Section 4 describes the problem formulation and the WOA. In Section 5, the design procedure is carried out. Section 6 presents the simulation results and discussion. Finally, Section 7 draws the conclusion.

2. PV system modelling

Fig. 1 indicates the equivalent circuit of the single-diode PV model, which is selected to model the PV module due to its accuracy and simplicity. The nonlinear current–voltage characteristic of the PV module can be expressed by the following expression [23,24]:

$$I = I_{PV} - I_o\left[\exp\left(\frac{V + R_s I}{aV_t}\right) - 1\right] - \frac{V + R_s I}{R_p} \tag{1}$$

where I_{PV} is the photovoltaic current, I_o, a are the reverse bias current and ideality factor of the diode, respectively, R_s, R_p are the series and parallel resistances, and V_t is the thermal voltage.

I_{PV} can be written by the following equation:

$$I_{PV} = (I_{PV,n} + K_I \Delta T)\frac{G}{G_n} \tag{2}$$

where $I_{PV,n}$ is the photovoltaic current under the nominal condition, K_I is the short circuit current per temperature factor, ΔT is the temperature difference between the actual and nominal values, G and G_n are the solar irradiation and its nominal value, respectively [23]. The mathematical model of $I_{PV,n}$ and I_o are written in details in Ref. [12]. A Kyocera KC200GT PV module is chosen for this study and its characteristics are demonstrated in Table 1 [25]. All the data of the PV model are depicted in Ref. [23]. For a large scale PV system, series-parallel connections of the PV modules are required [15]. In this study, a 2.5 MW PV system is used and its electrical characteristics are illustrated in Fig. 2a. The data of the PV system are listed in Table 2 [12]. The PV system is connected to the electric grid through a DC boost chopper, a DC-link capacitor of 10 mF, a grid-side inverter, step up transformers, and transmission lines, as shown in Fig. 2b.

Table 1
Characteristics of KC200GT PV module [23].

Short circuit current (I_{sc})	8.21 A
Open circuit voltage (V_{oc})	32.9 V
Current at maximum power point (I_{mp})	7.61 A
Voltage at maximum power point (V_{mp})	26.3 V
Maximum output power (P_{max})	200 W
K_V	−0.123 V/°C
K_I	0.00318 A/°C
Number of series connected cells (N_s)	54

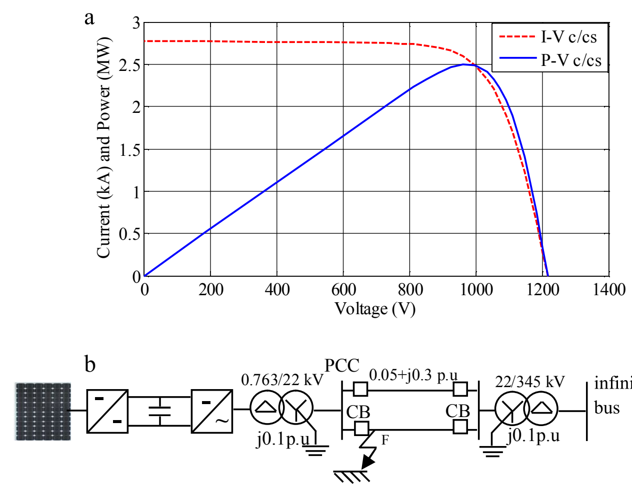

Fig. 2. (a) Electrical characteristics of a 2.5 MW PV system. (b) Grid-connected PV system.

Table 2
Data of a 2.5 MW PV system [12].

P_{max}	2.5 MW
V_{mp}	973.1 V
I_{mp}	2572.18 A