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Novel high-efficient large-scale stand-alone solar/wind hybrid power source equipped with battery bank used as storage device

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ABSTRACT

In this study, a novel large-scale stand-alone solar/wind/battery hybrid power generation system is designed and constructed. It consists of a photovoltaic (PV) array, a wind energy conversion system (WECS), a battery bank, a bidirectional DC/DC converter, two unidirectional DC/DC converters, a unified maximum power point tracking (MPPT) controller, a control unit, and a DC/AC inverter. The stand-alone solar/wind/battery hybrid system presented in this study combines two renewable resources (solar and wind) with a back-up battery bank used as a standby power source to produce electric energy. Moreover, it maximally converts solar and wind energies into electric energy because it uses a novel fast and highly accurate unified MPPT technique that concurrently tracks the maximum power points of both PV system and WECS. Other works reported in the literature are mostly simulation based works (models), and moreover, there is not any new MPPT consideration in them. It is experimentally verified that the large-scale constructed system is a high-efficient stand-alone solar/wind/battery hybrid power generation system that produces electric energy under different environmental conditions such as cloudy sky, so it can be widely used in remote areas.

1. Introduction

The stand-alone solar/wind/battery hybrid power generation system designed and constructed in this study consists of a PV system and a WECS both controlled by a proposed novel proposed unified MPPT controller, so a concise survey is first performed about different MPPT methods applicable to PV systems and WECSs. In a PV system, a MPPT controller tracks the maximum power point (MPP) of the PV panel/array used in the system, and so enhances the energy efficiency [1]. Various MPPT techniques applicable to PV systems are available [2]. Open-circuit voltage technique estimates the MPP voltage using the open-circuit voltage of a PV array [3]. In temperature technique, the open-circuit voltage itself is estimated using the temperature of the PV cells located on the PV array's surface [4]. Similarly, in short-circuit current method, the short-circuit current is used to track MPP [5,6]. MPPT fuzzy based techniques produce some fuzzy variables based on the instant operating point of a PV array, and MPP is then found using fuzzy logic [7,8]. There is also an adaptive version of fuzzy technique having better performance such as shorter convergence time [9]. MPPT can be also performed using neural networks, so that, a trained multi-layer neural network is utilized to track MPP, the neural network is first trained using real data related to the MPP such as the MPP voltage or power [10]. In perturb and observe (P&O) method, a parameter of the PV system such as voltage or current is perturbed to track MPP. The step-size of the perturbation may be fixed or variable [11–13]. PSO-ANFIS and P&O-ANFIS are two hybrid MPPT methods the performances of which were analyzed in [14]. Incremental conductance MPPT technique uses *P-V* curve slope to find MPP [15–17]. There is a modified version of this method that utilizes auto-scaling variable step-size distances on a *P-V* curve to track MPP [18]. In extremum seeking control MPPT technique, a feedback with nonlinear parameters is used to find MPP [19–21], a version of this method appropriate for the PV systems connected to grids is called "ripple-based" [22]. Power management technique applicable to shaded situations [23] and scanning algorithm which finds MPP by scanning output power [24] are the two other MPPT methods. Some MPPT algorithms use a sensor to measure solar irradiance, and then, the MPP associated to the measured irradiance is estimated [25]. A MPPT method that uses the direct-prediction and P&O algorithms to find MPP was reported in [26]. In a PV system, MPPT can be also performed using the cuckoo search algorithm [27], field program gate array [28], genetic algorithm [29], and predictive model [30].

A WECS applicable to industrial applications includes a wind turbine, a three-phase electric generator, a rectifier, and a MPPT controller [31,32]. A wind turbine converts wind power to mechanical power [33], so that, the turbine output mechanical power gets to maximum at an optimum turbine speed [34]. A MPPT unit regulates the speed of a turbine to its optimum speed, and similar to PV systems, various MPPT

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techniques applicable to WECSs are available [35]. Tip speed ratio (TSR) method computes the wind turbine's TSR, and then, regulates the instant TSR of the turbine to its optimum value by varying the turbine speed [36,37]. Power signal feedback (PSF) method uses power equations/curves to find the maximum output powers of a turbine at different speeds [38,39], and then, regulates the turbine power to the obtained reference values [40]. The TSR and PSF methods require sensors to measure the TSR or speed of the turbine, so the accuracy of the sensorless versions is low [41]. Hill-climbing search (HCS) and P&O techniques perturb different parameters of a WECS to track MPP, and are also applicable to PV systems [42,43]. Optimal sizing of hybrid power sources is another important issue that has been addressed in some recently published research works [44,45].

Different types of hybrid power sources have been reported in the literature that most of them are only simulation based works (models), and moreover, there is not any new MPPT consideration in them [46–50]. But, there is not any stand-alone solar/wind/battery hybrid power generation system equipped with a high-efficient unified MPPT unit. In this work, a stand-alone solar/wind/battery hybrid power generation system is designed and constructed. It combines solar and wind energies with a back-up battery bank to produce electric energy to supply power needs of a remote area. It is demonstrated that the constructed system is a very perfect stand-alone solar/wind/battery hybrid power generation system that maximally converts solar and wind energies into electric energy because of using a novel fast and highly accurate unified MPPT technique that concurrently tracks the MPPs of both PV system and WECS. The unified MPPT technique implemented in the hybrid power source does not need any sensor, and only uses the output voltages and currents of the PV array and WECS. It is also demonstrated that the solar/wind/battery hybrid power generation system produces enough electric energy to supply power needs under different environmental conditions such as cloudy air. The rest of this paper is organized as follows. The design and implementation of the stand-alone solar/wind/battery hybrid power generation system is explained in detail in Section 2. Constructed system and experimental verifications are presented in Section 3, and Section 4 concludes the paper.

2. Stand-alone solar/wind/battery power generation system: Design and implementation

The stand-alone solar/wind/battery hybrid power generation system has been designed, constructed, and located in a remote coastal area where on-shore wind blows with an average speed of 41.6 km/h almost during the whole of the year. The constructed power generation system produces electric power to supply power needs of a manufacturer factory. The configuration of the stand-alone solar/wind/battery hybrid power generation system is shown in Fig. 1. As shown in Fig. 1, the hybrid system consists of a PV array, a WECS, two unidirectional DC/DC converters dedicated to the PV array and WECS, a bidirectional DC/DC converter connected to a battery bank, a unified MPPT and control unit, and a single-phase DC/AC inverter. Supplementary electric energy needed under unavoidable environmental conditions such as cloudy air is produced by the battery bank used as a standby power source. A 36 kW PV array has been chosen for the PV system, and by noting the availability of wind blow with the average speed of 41.6 km/h, a 10 kW vertical wind turbine with the rated wind speed of 12 m/s has been chosen for the WECS. A battery bank with the capacity of 30 kWh has been considered to provide supplementary electric energy needed under inevitable environmental conditions when the captured solar and wind energies are not enough to supply power needs. The PV array and WECS have been connected to the DC bus through the two similar unidirectional DC/DC converters, and the MPPT controller concurrently tracks the maximum power points of the PV array and WECS. To track the two maximum power points, the DC link voltage is used as a reference voltage by the MPPT controller. The circuit of the two similar unidirectional DC/DC converters dedicated to the PV array and WECS is shown in Fig. 2 [51]. The switching frequency and duty cycle of the switch N-MOSFET S_1 are respectively denoted by f_s and $D_S = {}^{t_{on}}/_{T_S}$, where $T_s = {}^{1}/_{f_s}$ is the switching period, and t_{on} is the on-time of the switching. The converter's gain is expressed as [51]:

$$\frac{V_{dc}}{V_{in}} = \frac{n}{1 - D_S} \tag{1}$$

where n and V_{in} are respectively the transformer ratio and the converter input voltage, and V_{dc} is the converter output voltage as shown in Fig. 2. The implementation of the stand-alone solar/wind/battery hybrid power generation system is shown in detail in Fig. 3. The outputs of the two unidirectional DC/DC converters dedicated to the PV array and WECS are connected to the DC bus, so in fact, V_{dc} is the DC link voltage provided by the two unidirectional DC/DC converters. The different parts of the hybrid system are explained and analyzed in detail in separate sub-sections as follows.

2.1. PV system and MPPT process

As shown in Fig. 3, the PV system consists of the PV array and its associated unidirectional DC/DC converter. The PV array output power (P_{pv}) is obtained as:

$$P_{pv} = V_{pv}\, I_{pv} \tag{2}$$

where V_{pv} and I_{pv} are the PV array voltage and current, respectively. The P-V characteristic of the PV array used in this study is shown in Fig. 4. The derivative of P_{pv} is zero at the MPP, so:

$$\frac{dP_{pv}}{dV_{pv}} = 0 \tag{3}$$

As shown in Fig. 4, the derivative is positive at the left side of the MPP, so:

$$\frac{dP_{pv}}{dV_{pv}} > 0 \tag{4}$$

Similarly, at the right side, the derivative is negative, so:

$$\frac{dP_{pv}}{dV_{pv}} < 0 \tag{5}$$

The PV power derivative is approximated by defining power slope α_{pv} as:

$$\frac{dP_{pv}}{dV_{pv}} \approx \frac{\Delta P_{pv}}{\Delta V_{pv}} = \frac{P_{pv}(k) - P_{pv}(k-1)}{V_{pv}(k) - V_{pv}(k-1)} = \alpha_{pv} \tag{6}$$

where $V_{pv}(k)$ is the kth sample of the PV voltage measured by the unified MPPT control unit, $k = 1, 2, 3, \ldots$, and $P_{pv}(k)$ is the kth sample of the PV output power which is computed by the MPPT unit as:

$$P_{pv}(k) = V_{pv}(k) I_{pv}(k) \tag{7}$$

where $I_{pv}(k)$ is the kth sample of the PV current measured by the MPPT unit. The relationship between the DC link voltage and the PV voltage can be expressed using Eq. (1) as:

$$V_{pv} = \frac{(1 - D_{pv})\, V_{dc}}{n} \tag{8}$$

where D_{pv} is the duty cycle of the DC/DC unidirectional DC/DC converter connected to the PV array. Since the DC link voltage is constant, the PV voltage V_{pv} can be regulated to the PV voltage at the MPP (V_{pv-mpp}) by varying the duty cycle D_{pv}, so that, V_{pv} is increased by deceasing D_{pv}, and similarly, V_{pv} is decreased by increasing D_{pv}. Thus, MPPT can be performed in the PV system by only varying the duty cycle D_{pv}. The flowchart indicating the MPPT process in the PV system performed by the MPPT controller is shown in Fig. 5. The PV voltage