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Novel solar powered electric vehicle charging station with the capability of vehicle-to-grid

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ABSTRACT

In this study, a novel grid-connected solar powered electric vehicle (EV) charging station with vehicle-to-grid (V2G) technology is designed and constructed. The solar powered EV charging station consists of a photovoltaic (PV) array, a DC/DC converter dedicated to the PV array, a maximum power point tracking (MPPT) controller, 15 bidirectional DC/DC converters dedicated to the 15 charging stations provided for charging EVs, and a bidirectional DC/AC inverter connected between the charging station and grid. The contribution of this work is that the grid-connected solar powered EV charging station presented in this work optimally converts solar energy into electric energy because it uses a novel proposed fast and highly accurate MPPT technique. Furthermore, this work includes experimental results obtained from the daily operation of the constructed EV charging station, while other works are only simulation based. It is experimentally verified that the EV charging station not only produces enough electric energy to charge EVs during sunny days but also balances load demand in the local grid during cloudy days.

1. Introduction

The solar powered EV charging station presented in this work consists of a PV system controlled by a MPPT controller, so a concise survey is performed about different MPPT methods. A MPPT controller tracks the maximum power point (MPP) of a PV panel/array used in a PV system, and so enhances the energy efficiency (Fathabadi, 2015a). Different MPPT methods have been reported in the literature (Rezk and Eltamaly, 2015). Open-circuit voltage (OCV) first measures the open-circuit voltage of the PV module disconnected from the system, and then estimates the MPP voltage (Enslin et al., 1997). Temperature method estimates the open-circuit voltage using the PV module temperature (Park and Yu, 2004). Short-circuit current (SCC) technique uses the short-circuit current of the PV module to estimate its MPP (Masoum et al., 2002; Noguchi et al., 2002). Fuzzy methods convert the voltage and current of the PV module into fuzzy variables, and then fuzzy roles are used to track the MPP (Salah and Ouali, 2011; Algazar et al., 2012). A modified fuzzy algorithm is adaptive fuzzy MPPT method (Guenounou et al., 2014). Artificial neural network (ANN) based MPPT methods use the neural networks trained by the real data presenting the MPP voltage and current under different conditions. For instance, two feed-forward neural networks having two hidden layers were used for MPPT process in Rizzo and Scelba (2015). Perturb and observe (P&O) technique uses the voltage and current perturbations to find the MPP. Three versions of this technique are available: P&O fixed step-size (Ahmed and Salam, 2015), P&O variable step-size (Abdelsalam et al., 2011), and three-point weighted (Jiang et al., 2005). An improved P&O method with variable step-size is also available (Ahmed and Salam, 2015). Two modified methods called "particle swarm optimization adaptive neuro-fuzzy inference system (PSO-ANFIS)" and "P&O-ANFIS" were compared in Muthuramalingam and Manoharan (2014). The *P-V* curve slope is used to track the MPP in incremental conductance (IC) method (Fathabadi, 2016c; Fathabadi, 2016d). An improve version of the IC technique with better parameters is also available (Tey and Mekhilef, 2014). Extremum seeking control (ESC) method uses a nonlinear feedback system to estimate the MPP (Brunton et al., 2010; Lei et al., 2011; Bazzi and Krein, 2011). Ripple-based ESC method is a modified version of the ESC technique that is applicable only to grid-connected PV systems (Munteanu and Bratcu, 2015). Power management (PM) MPPT method that is more applicable to shaded situations (Orabi et al., 2015) and scanning method which finds MPP by scanning and comparing output powers (Kotti and Shireen, 2015) are the two other methods. A sensor based MPPT method first measures solar irradiance using sensors, and then estimates MPP (Bayod-Rújula and Cebollero-Abián, 2014). Hybrid prediction-P&O method combines the direct-prediction and P&O techniques to find MPP (Jiang et al., 2014). To increase the MPPT efficiency

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and tracking speed, the cuckoo search (CS) algorithm can be used to find MPP (Ahmed and Salam, 2014). Field program gate array (FPGA) based MPPT method finds MPP by comparing the instant output power with the calculated maximum power (Parlak, 2014). Auto-scaling variable step-size IC MPPT method uses a judgment criterion and auto-scaling variable step-size to enable the PV system to achieve a fast dynamic response and stable output power (Chen et al., 2014). Two researches showed that genetic algorithm (Daraban et al., 2014) and predictive model (Bouilouta et al., 2013) can be also used to find MPP.

In this study, a grid-connected solar powered EV charging station with V2G technology is designed and built. Other works are generally simulation based (Goli and Shireen, 2014; Brenna et al., 2014), and moreover, do not use an efficient MPPT technique (Nunes et al., 2015; Chandra Mouli et al., 2016). It is shown that the constructed station is a perfect EV charging station that optimally converts solar energy into electric energy because it uses a novel fast and highly accurate MPPT technique. The method only uses the output voltage and current of the PV array. It is also demonstrated that the EV charging station provides enough electric energy to charge EVs, and also can be even used to balance load demand in the grid connected to it (Fathabadi, 2015b). The rest of this paper is organized as follows. The design and implementation of the solar powered EV charging station is explained in detail in Section 2. Constructed system and experimental verifications are presented in Section 3, and Section 4 concludes the paper.

2. Design and implementation of the solar powered EV charging station

The solar powered EV charging station has been designed and constructed. The first step was to estimate the daily electric power that should be produced or provided by the EV charging station. A research was performed to estimate the average number of the EVs that should be charged hour by hour during a day. The number of the EVs that should be charged hour by hour during a day is shown in Fig. 1(a). Loading duration of each EV is one hour, so considering a Li-ion battery (60 V, 20 Ah) for each EV demonstrates that each EV needs 1.2 kW of electric power to be charged during one hour. Thus, the electric power needed to charge the EVs hour by hour during a day can be obtained by multiplying the EVs number shown in Fig. 1(a) by 1.2 kW that the result (charging profile) is shown in Fig. 1(b). In Fig. 2, the charging profile has been divided into two parts, the green and blue parts. The green portion of the charging profile is produced using solar energy in daylight, while the blue portion is provided by the grid. The configuration of the designed solar powered EV charging station is shown in Fig. 3. The solar powered station consists of a PV array, a unidirectional DC/DC converter dedicated to the PV array, a MPPT controller, 15 bidirectional DC/DC converters associated with the 15 charging stations provided for charging EVs, and a bidirectional DC/AC inverter connected to the grid. It can be seen that all the 15 EV charging stations have the capability of V2G connection that means each EV not only can be charged but also may be even discharged to help the grid to provide enough electric energy for consumers when load demand peaks in the grid. Considering the green portion of the charging profile shown in Fig. 2 and environmental conditions such as cloudy sky, a 24 kW PV array has been chosen for the PV system. The PV array has been connected to the DC bus through a unidirectional DC/DC converter, and the MPPT controller tracks the MPP of the PV array. To track the MPP, the DC link voltage is used as a reference voltage by the MPPT controller. The circuit of the unidirectional DC/DC converter dedicated to the PV array is shown in Fig. 4 (Fathabadi, 2016a). It is a high efficient DC/DC converter including only one N-MOSFET switch S_1. The

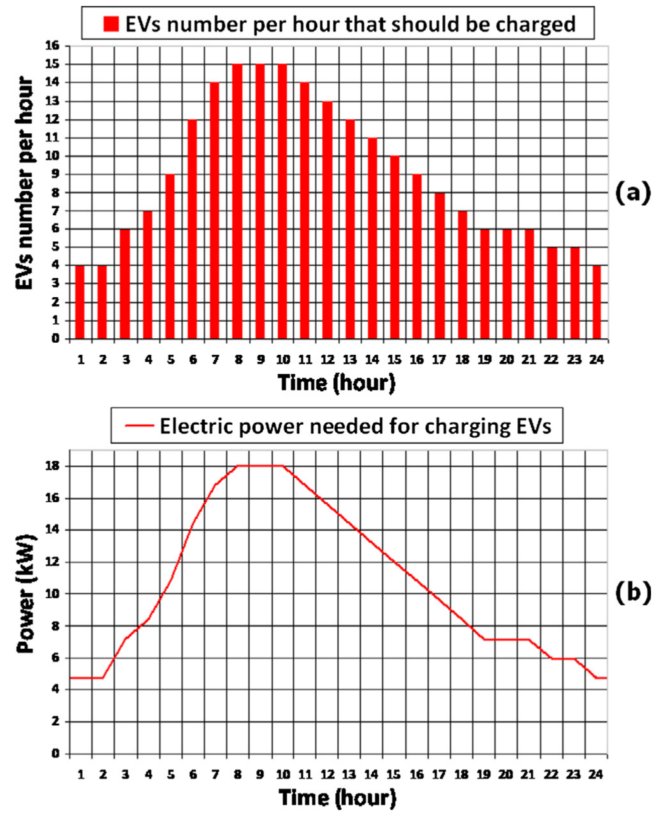

Fig. 1. (a) EVs number per hour that should be charged during a day. (b) Electric power needed to charge the EVs hour by hour during a day (charging profile).

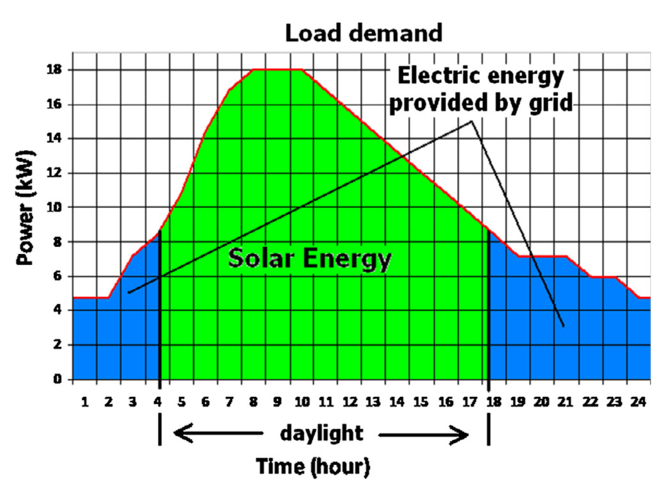

Fig. 2. Charging profile: Green portion is produced using solar energy, and the blue portion is provided by the grid. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

switch S_1 operates with a constant switching frequency of f_s and a variable duty cycle of $D_S = t_{on}/T_s$, where $T_s = 1/f_s$ is switching period, and t_{on} is the switch S_1 on-time. The gain of this DC/DC converter is obtained as (Fathabadi, 2016a):

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

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. 4. The implementation of the solar powered EV charging station is shown in detail in Fig. 5. The output of the unidirec-