Self-Adaptive Solar EV Charging Interface for Standalone and Energy-Isolated Terrains

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Abstract

Any electric vehicles (EVs) are characterized by the limited energy storage capacity and, thus, need to be recharged after some distance has been covered. Although it is relatively easy to roll out charging stations in urban areas, charging infrastructure in rural and remote areas has been a major problem. As a solution to this concern, a number of large nations such as the United States, Canada, China, Russia, India, Australia and some of the Middle East are considering installing pillar-mounted solar-powered panels in remote areas to be used in emergencies to charge EV.To apply it in such cases, a special charging adapter is needed to control the charging current, guarantee safe and reliable termination of charging, and to extract as much power as possible using a Maximum Power Point Tracking (MPPT) method on the solar panel. A cost-effective EV charging adapter on the basis of one current sensor is suggested in this work. A Single Input Fuzzy Logic-tuned Deterministic Optimization (SIFL-DO) algorithm is presented to assist the work of MPPT and manage battery charging.The suggested adapter is very cost effective as it tends to have less sensor demand besides having rapid dynamic response. Besides, the SIFL-DO algorithm allows controlling the MPPT and charging with high accuracy and precision due to strong condition estimation and intelligent decisions. The performance of the developed adapter and its compatibility with the SIFL-DO algorithm are tested with the help of a hardware prototype. It also presents comparative studies with the state-of-the-art techniques. Lastly, the offered system is considered against the European standard EN 50530 in order to prove that the system can be used in the industry.

Keywords: *Solar PV, EV, battery charging, MPPT, sensor-less scheme.*

1.Introduction

EVs have come to be a rival to the traditional hydrocarbon-powered vehicles due to their lack of greenhouse gas emission as well as the source of fuel prices not being directly tied to the oil-producing nations. Moreover, the renewable energy, especially solar photovoltaic (SPV) generation, is more efficient when considered in terms of the complete energy cycle. Trends of the past demonstrate that in times of world war, the cost of fuel increases by a very large margin, but the cost of electricity does not change significantly. A combination of all the aspects mentioned above makes EVs a more sustainable and economically resilient means of transport than vehicles engine powered with internal combustion engines.

In spite of the fact that much effort is made to increase the efficiency of EV as well as to develop the supporting infrastructure, the EV charging is mainly introduced within two schemes: onboard and off-board charging. In onboard charging, the charging equipment is built-in to the vehicle and may either take AC or DC power. Conversely, off-board charging will be where the charging circuitry is located in the charging station. EVs may be charged by single-phase AC, three-phase AC or DC power, with the three each having their own strengths and weaknesses.

The problem of charging EVs with the solar energy is even more difficult than it would be in an ideal situation with stable weather and temperature. Solar irradiance and ambient temperature change with time and this leads to the changing power generation (1). As a result, the output power of solar panels is not linear which requires adoption of Maximum Power Point Tracking (MPPT) methods in order to maximize power out of the solar array (2). MPPT has been extensively researched both with the help of traditional mathematical approaches and such methods as neural and intelligent optimization, which have their advantages and disadvantages. These MPPT algorithms are normally used with DCDC buck or boost converters that control the output of solar panels by changing the pulse-width modulation (PWM) signal to the convertor. In order to optimize the transfer of energy in the process of charging EVs, solar panels will be charged to their highest point of power, which is determined by the voltage and current couple (Vmp, Imp) (3).

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Broadly, solar photovoltaic systems may be classified into standalone (remote) and grid-connected systems and power capacities may be small-power (low power) or high-power applications. In our situations, in most instances S.P.V systems installed may be in excess of several hundred kilowatts. The amperes of direct current that can be generated by large-scale SPV systems can be in the hundreds, so there is a great risk when direct connection is provided without proper regulation and control to the EV batteries (4).

FIGURE 1 EV charging infrastructure on remote location

A number of EV charging systems have been suggested in the literature using PV power, such as multifunctional off-board chargers (5), bidirectional EV chargers (6), Z-source-based chargers (7), wireless EV chargers (8), and intermittency-reducing charging systems (9). Although these solutions have been found to be technically effective, majority of them have a grid support during the charging process. They therefore cannot be used in remote or isolated locations where there is no access to a grid. In addition, an EV can generally charge at approximately 10-15 percent capacity of its battery. Normal chargers have the capability of providing currents of up to 32 A, which can provide a power level of up to 7.4 kW. In these charging processes, they do not always guarantee cooling of the battery thus correct current monitoring is crucial to avoid battery damage (10). This surveillance is frequently realized with the help of several sensors in order to study the output of the solar array .

Despite the increasing prevalence of solar PV setups, including in densely populated regions, owing to the high levels of governmental backing, EV charging infrastructure is sparse, even in areas of tier-2 and tier-3 cities, and near-nonexistent in countryside or remote areas. Not much research has focused on the accessibility of EV charging solutions in these remote locations, where complex and expensive charging stations may not be economical to install because of a low level of utilization. Furthermore, repair and replacement of infrastructure in remote areas is a burden, which adds to the risk of operation.

This is due to the fact that these limitations point to the inefficiency of the existing systems to accommodate emergency or remote charging of EVs. To curb this adversity, governments of major economies, including the United States, Canada, China, Russia, India, Australia, and some countries in the Middle East, are considering installing pillar-mounted solar panels in remote areas as emergency EV chargers as shown in Fig. 1. It will be necessary to operate it under such conditions with a special charging adapter to obtain the maximum power of the solar panel with the help of MPPT, monitor the current of the charge, and provide safe and trustworthy termination of charging. This leads to an obvious necessity of a small, inexpensive charging adapter which can be easily attached to any photovoltaic system, kept in the car, and utilized in the emergency cases as well as in the routine charging.

In spite of the fact that part of the work has been reported in the field, the current solutions usually use several sensor nodes, which prove to be cumbersome, costly, and more vulnerable to the electromagnetic interference. These sensors are mainly applied to control the power supplied to the EV as per the battery capacity limit. Moreover, no one system is able to presently operate with an efficient MPPT at the same time combined with a fine control of EV charging with only a small sensing architecture.

In order to solve these gaps, this study suggests a Single Input Fuzzy Logic-tuned Deterministic Optimization (SIFL-DO) model to monitor the maximum power point of the solar PV array and amount of current to charge the EV to maintain safe battery charge within recommended current limits. Only one sensor is used to monitor and control solar PV, as well as the charging current being fed to the EV, which makes the system much simpler and

less costly. Operational benefits of the proposed method are also revealed by experimental findings especially when the step-change is not constant. Compared to state-of-the-art algorithms, it is evident that the proposed SIFL-DO approach is better in performance. Last, the system is tested based on European Standard EN 50530 (15) to determine its adaptability to the industrial use.
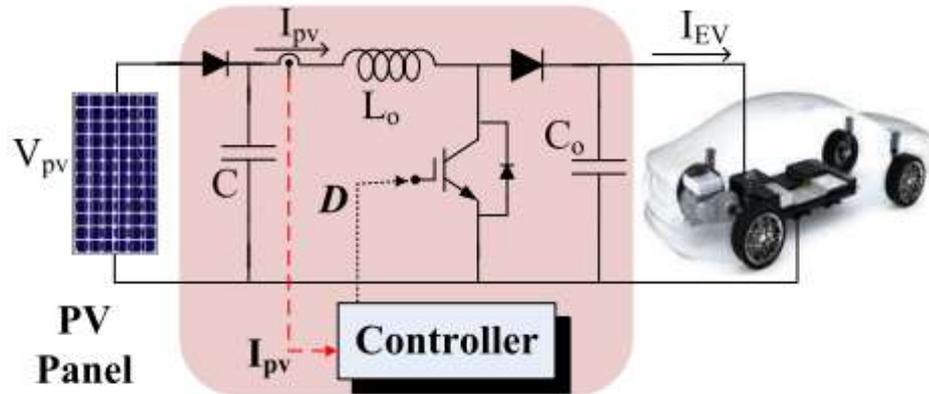

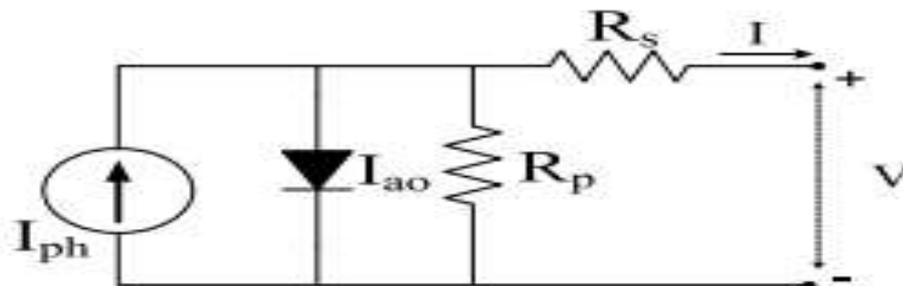**FIGURE 2** Single sensor based circuit of EV charging adapter

FIGURE 3 Solar PV cell electrical model

2. Proposed Control Scheme

2.1 System Layout

Figure 1 illustrates the proposed configuration of the complete EV charging system. In emergency or remote-area scenarios, an EV requiring charging can be directly connected to any nearby solar photovoltaic (PV) panel using the proposed solution, which is implemented as a compact charging adapter. Figure 2 presents the detailed circuitry of the proposed adapter. Although the solar PV module itself does not include additional control circuitry, the EV and the charging adapter can be interfaced with any available solar PV source. Both the maximum power point tracking (MPPT) control and the charging current regulation circuitry are fully integrated within the charging adapter.

2.2 Overall System Configuration

The proposed charging adapter architecture is shown in Fig. 2. It consists of a DC–DC boost converter, the proposed Single Input Fuzzy Logic–tuned Deterministic Optimization (SIFL-DO) controller, and a solar power monitoring unit implemented using a single current sensor. The complete circuitry can be enclosed within a compact housing, allowing the system to be used either as an off-board charger or installed within the vehicle for onboard charging applications.

2.3 Photovoltaic Cell Modeling

The electrical equivalent circuit of a solar photovoltaic cell is shown in Fig. 3. The single-diode PV model is used to represent the behavior of the solar cell and is mathematically described by Eq. (1). For a module consisting of n series-connected cells, the thermal voltage is given by

where k is the Boltzmann constant $(1.3806503 \times 10^{-23}\,\text{J/K})(1.3806503 \times 10^{-23}\,\text{J/K})(1.3806503 \times 10^{-23}\text{J/K})$, T is the absolute temperature, a is the diode ideality factor, and q is the

electronic charge. In this model, IPhI_{Ph}IPh represents the photocurrent generated by the PV cell, ISI_SIS denotes the reverse saturation current of the diode, *V* is the output voltage of the PV module, and VTV_TVT is the thermal voltage corresponding to the series-connected solar cells.

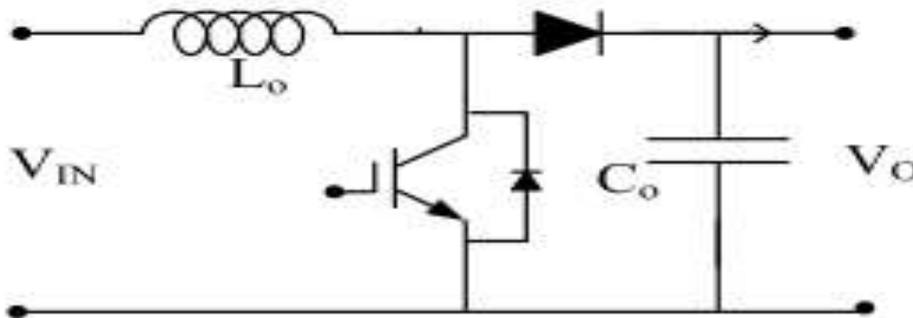$$I = I_{Ph} - I_S\left[exp\left(\frac{V + IR_S}{nV_T}\right) - 1\right]$$
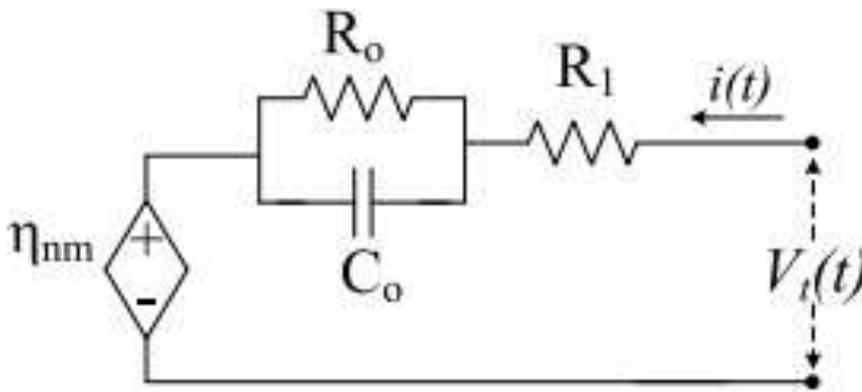

FIGURE 4 DC Boost Converter

FIGURE 5 Electrical Equivalent circuit of lithium-ion battery

2.2 DC–DC Boost Converter
The DC–DC boost converter, shown in Fig. 4, is designed to be interfaced between the solar PV array and the electric vehicle, as illustrated in Fig. 2. The primary function of the boost converter is to regulate and step up the PV output voltage to a level suitable for EV battery charging while enabling maximum power extraction from the solar array. For an ideal boost converter, the relationship between the input and output voltages is given by the standard voltage conversion expression.

$$V_O = \frac{V_{IN}}{(1 - D)} \tag{2}$$

$$V_O = \left(\frac{V_{IN} - V_{SW}D}{(1 - D)}\right) - V_D \tag{3}$$

$$V_{CHARGING} = \frac{V_{PV}}{(1 - D)} \tag{4}$$

$$V_{CHARGING} = \left(\frac{V_{PV} - V_{SW}D}{(1 - D)}\right) - V_D \tag{5}$$

2.3 Control Scheme

The primary objective of the single-sensor–based EV charging adapter (SS-EVCA) is to extract the maximum possible power from the solar PV array. The secondary objective is to monitor and maintain the charging current within safe operating limits to ensure reliable and secure battery charging. The proposed SS-EVCA achieves maximum power transfer by dynamically regulating the power delivered from the solar panel.

Figure 5 illustrates the battery equivalent circuit used for charging analysis, where R_1 represents the electrolyte resistance and η_{nm} denotes the open-circuit cell voltage. The charge transfer resistance, R_0, models the voltage drop caused by the load at the electrode–electrolyte interface. The effect of charge accumulation at the electrode surface within the electrolyte is represented by the double-layer capacitance, C_0. The battery terminal voltage and charging current are denoted by $V_t(t)$ and $i(t)$, respectively. During the charging process, the battery voltage relationship can be expressed accordingly.

$$\eta_{nm} < V_t(t) \tag{6}$$

$$\eta_{nm} = V_t(t) - i(t)R_1 - v_{Ro}(t) \tag{7}$$

$$\eta_{nm} = V_t(t) - i(t)R_1 - i_{Ro}(t)R_0 \tag{8}$$

$$\left. \begin{array}{l} i_{Co}(t) = C_0 \dot{v}_{Co}(t) = C_0[i_{Ro}(\dot{t})R_0] \\ i_{Ro}(t) + R_0 C_0 \frac{di_{Ro}(t)}{dt} = i(t) \end{array} \right\} \tag{9}$$

$$\frac{di_{Ro}(t)}{dt} = \frac{1}{R_0 C_0}(i(t) - i_{Ro}(t)) \tag{10}$$

$$\left. \begin{array}{l} -R_0 C_0 \frac{di_{Ro}(t)}{dt} = i_{Ro}(t) - i(t) \\ \ln|i_{Ro}(t) - i(t)| = \frac{-1(t+\lambda)}{R_0 C_0} \end{array} \right\} \tag{11}$$

$$i_{Ro}(t) = e^{\frac{-1(t+\lambda)}{R_0 C_0}} + i(t) \tag{12}$$

$$V_t(t) = \eta_{nm} + i(t)R_1 + \left(e^{\frac{-1(t+\lambda)}{R_0 C_0}} + i(t) \right)R_0 \tag{13}$$

$$P_{Charge}(t) = V_t(t) \times i(t) \tag{14}$$

$$P_{Charge}(t) = \left(\eta_{nm} + i(t)R_1 + \left(e^{\frac{-1(t+\lambda)}{R_0 C_0}} + i(t) \right)R_0 \right) \times i(t) \tag{15}$$

$$i(t) = (1 - D) \times I_{PV} \tag{16}$$

Since a lithium-ion battery serves as the load in an electric vehicle, the charging power of the battery can be defined based on the converter and system parameters, where D represents the duty cycle of the DC–DC boost converter. The initial time constant of the capacitor is denoted by λ. The solar PV current and voltage are represented by I_{PV} and V_{PV}, respectively. From Eq. (19), it is evident that the EV charging power is governed by the PV current and the converter duty cycle. Therefore, accurate measurement of

$IPVI\_\{PV\}IPV$ along with the computed duty cycle DDD is sufficient to achieve effective maximum power extraction.

$$P_{Charge}(t) = \left(\begin{array}{c} \eta_{nm} + ((1-D) \times I_{PV})R_1 + \\ \left(e^{\frac{-1(t+\lambda)}{R_0 C_O}} + ((1-D) \times I_{PV}) \right)R_0 \end{array} \right)$$
$$\times \left(\begin{array}{c} (1-D) \\ \times I_{PV} \end{array} \right)$$

(17)

$$P_{Charge}(t) = \max \dot{f}(I_{PV})$$

(18)

To accomplish this, a Deterministic Optimization (DO) algorithm is employed to determine the optimal duty cycle. An adaptive correction factor, $\omega\backslash omega\omega$, is introduced to enhance dynamic performance under varying operating conditions. The value of $\omega\backslash omega\omega$ is generated using a Single Input Fuzzy Logic (SIFL) controller. Finally, the EV charging power is calculated accordingly based on the regulated system variables.

3.Results and Discussion

In order to test the developed approach, a prototype of a hardware was created, as depicted in Fig. 8. The apparatus of the experiment uses two PLECS Real-Time (RT Box 1, Plexim, Processo) and an additional power supply (HTC Instruments DC 3005, DC 5 A linear power supply). Additional Hardware is also present in the form of an RT analog/digital breakout board, a Plexim digital expander, Hall-effect voltage and current sensors (LV25 and LA-55P), a Xilinx Zynq Z-7030 processor, a four-channel Tektronix oscilloscope (110 GHz), and the driver circuitry.
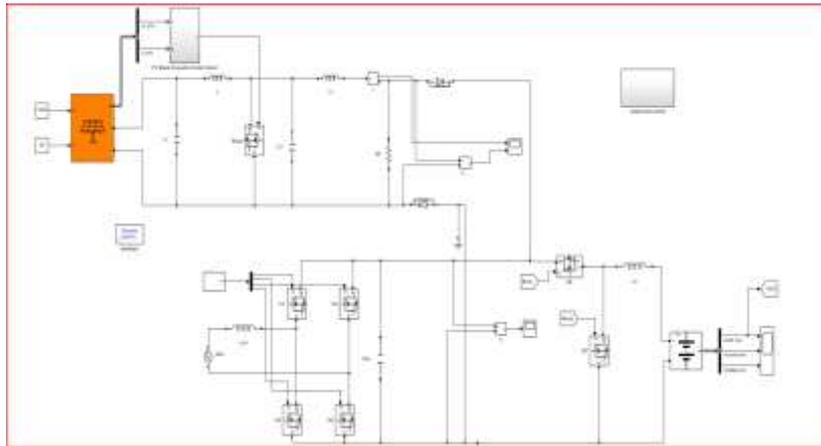

FIGURE 6 Simulation diagram of system

Three control algorithm types were tested by hardware experiments, namely the proposed SIFL-DO method, the already existing Perturb and Observe algorithm variously modified as Modified Perturb and Observe (MP&O) algorithm and the conventional Perturb and Observe (P&O) algorithm . In order to test the performance rigorously, the algorithms were put to test under extensive conditions of solar irradiance which were divided into two broad scenarios Case 1 and Case 2. Comparative analyses in the two instances were conducted according to the characteristic curves that were obtained on the solar PV array output parameters through experimentation. The comparisons are mostly geared towards the efficiency of the control algorithms and the power to the vehicle as a result of the battery charging of the EV.
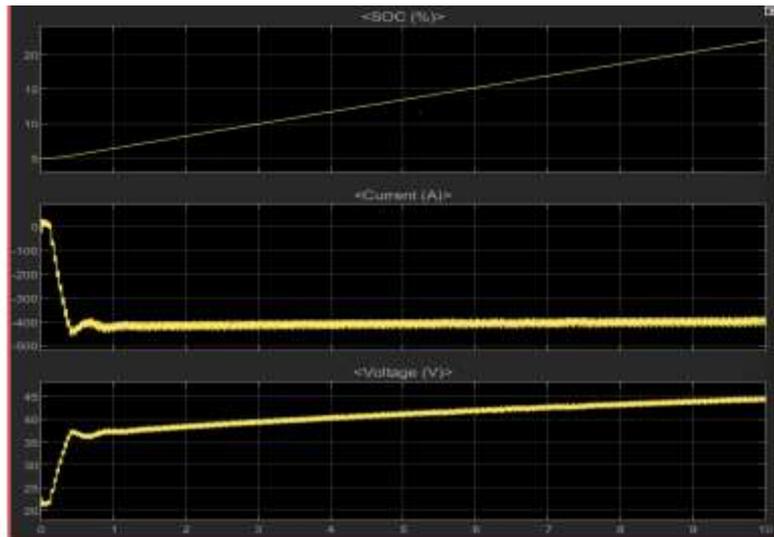
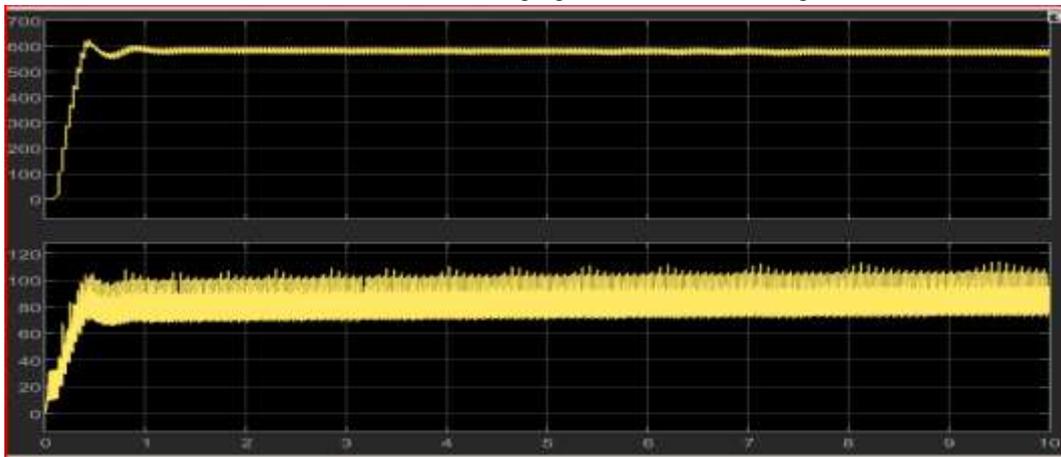**FIGURE 7** State of charging (soc), current &voltage

FIGURE 8 DC voltage

5. Conclusion

In this thesis, a new EV charging adapter topology aiming at using one current sensor is proposed. The single-sensor system is a cost-effective charging system that is sensitive to changes in operating conditions because of its low price, fast dynamic response and sensitivity, and the ability of the sensor to accurately detect changes in operating conditions. Also, a new control strategy is proposed to be used to control the battery charging and maximum power point tracking (MPPT) simultaneously, which is named Single Input Fuzzy Logic-tuned Deterministic Optimization (SIFL-DO). With the help of powerful condition estimation and smart decision-making technologies, the SIFL-DO algorithm is capable of overseeing the charging process, attains high-accurate MPPT and operates safely in the extreme conditions.

The effectiveness and functionality of the planned charging adapter and the SIFL-DO algorithm were checked through a hardware prototype. Extensive comparative research using state-of-the-art methodology shows better results of the proposed charging scheme. The main weakness of the approach is that a slightly more powerful processor is needed to execute the suggested control logic, but these processors are also widely used in the industrial context. To further confirm its suitability in industry, the proposed technology was tested according to the European Standard EN 50530 under which it performed all the requirements of performance satisfactorily. Altogether, the created solution is an efficient and less expensive method to use and use the pillar-mounted photovoltaic panels to charge EVs in rural and isolated areas.

Conflicts of interest

The authors have no conflicts of interest to declare

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