



Two novel techniques for increasing energy efficiency of photovoltaic-battery systems



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ABSTRACT

A photovoltaic (PV)-battery power source consists of a PV panel, a primary DC/DC converter, and a battery or a batteries bank. It is generally used to provide electric energy for local consumers such as buildings. Maximum power point tracking (MPPT) schemes cannot be applied to it because the PV panel output current is only determined by the state of charge (SOC) of the battery. In this study, two novel techniques are proposed to increase the energy efficiency of PV-battery power sources. Replacing the primary DC/DC converter with a novel proposed DC/PWM inverter, and decomposing the PV panel into a set of parallel homogenous configured PV modules are the two proposed techniques. It is shown that the implementation of each technique effectively increases the energy efficiency of PV-battery power sources. The two techniques are combined to each other to implement a new PV-battery power source. It is proved that the energy efficiency of the new version is significantly more than conventional version. Simulated results performed in MATLAB/Proteus 6 verify an increase of 29% in the energy efficiency. Four PV-battery power sources have been built, and comparative experimental results are presented that verify an increase of 27% in the energy efficiency.

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1. Introduction

Several rechargeable batteries coupled to a PV panel through a primary DC/DC converter is known as a PV-battery power source. Thus, a PV-battery power source consists of a PV panel, a primary DC/DC converter, and a battery or a batteries bank. The PV-battery power sources are generally used to provide electric energy for local consumers such as buildings. For example, they are widely used in building integrated photovoltaic systems (BIPVS) [1]. The PV-battery power sources are strictly different from grid-connected PV systems, so that, maximum power point tracking (MPPT) schemes cannot be applied to them because the output current of the PV panel is only determined by the state of charge (SOC) of the batteries bank which is the sole load of the PV panel. Improving the performance of the PV-battery systems has been the subject of many research works [2,3]. Improving the charge process in a PV-battery system by directly charging the battery from the PV system without using any inverter/converter was reported in [4]. The main defect of directly charging the battery is that there is no any electronic device to regulate the charging voltage/current, so not only the battery life cycle is significantly shortened but also

the battery can be even damaged. As another research work, a charge control strategy for stationary PV-battery systems was presented in [5]. The proposed charge scheme uses dynamic programming to predict household loads and PV generation profiles. The energy conversion efficiency of the PV energy is significantly low because there is not any consideration about the energy efficiency in the charge process.

On the other hand, literature survey shows that the topics related to PV systems basically began by modeling and characterizing PV modules and solar cells [6–8]. The single diode model of a PV module/solar cell is a basic model that characterizes a PV module/solar cell by presenting an equivalent circuit including only one diode [9]. The single diode model consists of the four elements which are a shunt resistance, a series resistance, a current source modeling the photocurrent, and a diode the current of which depends on the reverse saturation current and the ideality factor. The estimation of these five parameters has also been the subject of many researches [10]. Extracting the mentioned five parameters using the analytic solutions of the I–V characteristic was reported in [11]. The estimation of the five parameters using nonlinear minimization algorithm [12], particle swarm optimization [13], genetic algorithm [14], differential evolution [15], semi-pattern search [16], pattern search [17], analytic-neural method [18], analytic method [19] and analytic-Lambert W function methods [20] have been also reported over the years.

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Nomenclature

E	electric energy consumed by the +57.6 V Li-ion battery during charge process (J)	$P_{Loss}(t)$	instant power loss in the primary DC/DC converter (W)
G	actual irradiation (W m^{-2})	$P_{Out}(t)$	instant output power of the primary DC/DC converter (W)
G_n	nominal irradiation (W m^{-2})	$P_{Out-PV}(t)$	instant output power of the PV module (W)
I	output current of the PV module (A)	$P_{max,e}$	experimental value of the maximum output power (W)
$I_{Bat-Char.}(t)$	charging current of the rechargeable battery (A)	$P\%$	shading percent
$I_{Out-PV}(t)$	output current of the PV module (A)	q	electron charge (1.6×10^{-19} C)
I_{PH}	photo current (A)	r	ripple factor
I_{PH_n}	nominal photo current (A)	R_s	equivalent series resistance of the PV module (Ω)
$I_R(t)$	electric current consumed by the internal circuit of the voltage regulator (A)	R_p	equivalent shunt resistance of the PV module (Ω)
I_{SC}	short circuit current of the PV module (A)	$R\%$	improving factor of the PV energy conversion efficiency
I_{SC_n}	nominal short circuit current of the PV module (A)	STC	standard test condition: $G = 1000 \text{ W m}^{-2}$, AM 1.5 solar radiation spectrum, $T = 25^\circ\text{C}$, $\theta_z = 48.19^\circ$
I_o	reverse saturation current of the diode in model (A)	t_{on}	“ON” state duration of PWM waveform (sec.)
$I_{o,n}$	nominal reverse saturation current of the diode in model (A)	t_{off}	“OFF” state duration of PWM waveform (sec.)
I_{th}	threshold current of the battery charger (A)	T	cell temperature on the PV module (K)
I_{mp}	current of the PV module at the maximum power point (A)	T_n	nominal cell temperature on the PV module (K)
K	Boltzmann constant ($1.38 \times 10^{-23} \text{ J K}^{-1}$)	$V_T = \frac{N_s K T}{q}$	thermal voltage of the PV module (V)
K_I	current/temperature coefficient (A K^{-1})	V_{T_n}	nominal thermal voltage of the PV module (V)
K_V	voltage/temperature coefficient (V K^{-1})	V	output voltage of the PV module (V)
n	ideality factor of the PV module	$V_{Bat.}(t)$	output voltage of the rechargeable battery (V)
N_s	number of the solar cells of a PV module connected in series	$V_{OC-Bat.}$	open circuit voltage of the rechargeable battery (V)
$P_{E-Conv.}$	electric power absorbed by the +57.6 V Li-ion battery in the conventional PV-battery power source (W)	V_{OC}	open circuit voltage of the PV module (V)
$P_{E-Second}$	electric power absorbed by the +57.6 V Li-ion battery in the second PV-battery power source (W)	V_{OC_n}	nominal open voltage of the PV module (V)
$P_{E-Third}$	electric power absorbed by the +57.6 V Li-ion battery in the third PV-battery power source (W)	V_{mp}	voltage of the PV module at the maximum power point (V)
$P_{E-Fourth}$	electric power absorbed by the +57.6 V Li-ion battery in the fourth PV-battery power source (W)	$V_{Out}(t)$	output voltage of the primary DC/DC converter (V)
		$V_{Out-new}(t)$	output voltage of the proposed DC/PWM inverter (V)
		$V_{Out-PV}(t)$	output voltage of the PV module (V)
		θ_z	solar angle (deg)

Finding the maximum power point (MPP) of a PV module and also performing a suitable maximum power point tracking (MPPT) scheme are the two other important problems associated with PV systems [21,22]. The two similar neural based MPPT techniques were presented in [23,24]. The performance of a PV module/panel is significantly affected by the environmental conditions such as dust. Several MPPT methods for PV systems under different environmental conditions were reported in [25–28].

PV modules are connected to each other to provide appropriate output voltage, current and power indicating the practical features of the formed PV panel/array. Determining the MPP of some PV modules connected in different possible configurations is the another very important problem because it results the determination of the MPP of a PV panel [29,30]. On the other hand, shading significantly impacts on the maximum output power of a single PV module and a set of the PV modules connected to each other to form a PV panel [31,32]. Finding the MPP of different configured PV modules becomes more difficult for shaded situations because some local maximum power points appear on the P - V curves of the some configurations such as series-parallel combination [33,34]. All the available PV panel configurations used in PV systems until 2014 were reported in [35]. The MPP of different configured PV modules was numerically determined using the Lambert W function as a mathematical tool in [36].

It is worthwhile to note that during last years, a hard attempt has continually been available to improve the energy conversion efficiency of solar cells by modifying the chemical processes

utilized to produced them [37,38], so finding and presenting some schemes to obtain a higher energy efficiency from the available solar cells and PV systems such as PV-battery power sources is considered as an excellent research work. According to this idea, some attempts have been performed for modifying and improving some elements of PV based energy systems [39–41]. As another example, a battery charger with MPPT function for low-power PV system applications was presented in [42].

As another attempt, in this study, the main part of a conventional PV-battery power source including a primary DC/DC converter and a PV panel is considered. At the first step of this research work, a DC/PWM (pulse width modulation) inverter with variable duty cycle is proposed for using instead of the primary DC/DC converter used in the conventional PV-battery power source, and for the first time, it is shown that the energy efficiency of the PV-battery power source is improved by replacing the primary DC/DC converter with the proposed DC/PWM inverter. At the second step, it is theoretically shown that the energy efficiency of the conventional PV-battery power source is effectively increased by decomposing the PV panel of the system into a set of parallel homogenous configured PV modules. In the third step of this study, the results obtained from the first and second steps are combined to each other, so that, both decomposing the PV panel and replacing the primary DC/DC converter with the proposed DC/PWM inverter are utilized to implement a new PV-battery power source. Then, it is shown that the energy efficiency of the new PV-battery power source is significantly more than the conventional version and also the two PV-battery power

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