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Maximum power point tracking using Hill Climbing and ANFIS techniques for PV applications: A review and a novel hybrid approach

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ABSTRACT

The development of Maximum Power Point Tracking (MPPT) techniques is continuing in order to increase the generated energy from photovoltaic (PV) generators. A variety of MPPT techniques have been proposed and classified based on three main categories: offline, online and hybrid techniques. This paper presents a review of the most popular techniques for offline and online tracking of the Maximum Power Point (MPP), which are the Adaptive Neuro-Fuzzy Inference System (ANFIS) and Hill Climbing (HC) techniques, respectively. This is in addition to a review for all hybrid techniques reported in the literature demonstrating their main merits and shortcomings. Moreover, the present paper combines the ANFIS and HC as a hybrid technique for the first time. The proposed technique involves the features of the ANFIS and HC techniques and mitigates their shortcomings in order to increase the generated PV electrical energy. The proposed technique is a combination of two stages to assess the duty ratio (control signal) being applied to a boost converter for MPP tracking. The first stage includes a set point calculation loop to estimate the duty ratio. The second stage involves a fine tuning loop to determine the exact duty ratio corresponding to the MPP. This achieves maximum power transfer to the load even under nonuniform climatic conditions using a relatively simple control system. The proposed technique has been simulated in MATLAB/SIMULINK environment and compared with some other MPPT techniques (the Constant Voltage (CV), ANFIS, HC, Incremental Conductance (IncCond) techniques) for steady state and rapidly changing climatic conditions (Ropp and sine radiation tests) as well as load variations. The results reveal that the proposed hybrid MPPT technique outperforms other MPPT techniques in term of performances indicators, which include the tracking speed, tracking accuracy and energy gain factor.

1. Introduction

NOWADAYS, environmental issues generated by the use of traditional energy sources and energy crisis seem to acquire more attention around the world [1,2]. Moreover, inaccessibility of utility grids to remote areas and lack of rural electrification have prompted for alternative energy sources [3].

Recently, renewable energy resources, especially solar energy resource, considered as a mitigate-energy resource, are growing rapidly and are used in several applications, where photovoltaic (PV) generators can either be tie grid (operate in electric distribution systems) or can operate in autonomous systems, e.g., battery charging, domestic electric supply and pumping systems [4,5]. Solar energy as one of the most efficient renewable resource of energy is clean and reliable, making the harnessed PV energy a common interest of researchers [6–10].

On the other hand, PV generators suffer from a relatively low conversion efficiency, which lies in the range 15–20% [11–13]. This is in addition to other factors such as deposition of dust, wind movement, humidity level and atmospheric pressure, which are efficacious in the PV system performance. On one side, dust accumulation decreases the PV system efficiency due to deterioration of exposure to sunlight. On the other side, wind influences the PV system performance in two ways, which are its effect on dust and PV cell temperature. While wind movement promotes dust settlement by lifting it up, on the contrary, it dispels dust settlement causing PV surface cleaning. This is based on both the wind speed and direction [14]. As the wind speed increases the cell temperature drops with a subsequent improvement of the PV system efficiency [15]. To analyze the effect of humidity on PV system efficiency, the effect of water-vapor droplets on the irradiance level of sunlight has to be considered. When the light hits water droplets, it may be refracted, reflected or diffracted, which plunges the reception level

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Nomenclature

AI	artificial intelligence
ANFIS	adaptive neuro-fuzzy inference system
ANN	artificial neural networks
CSAM	current sensorless method with auto-modulation
CV	constant voltage
FIS	fuzzy inference system
FLC	fuzzy logic controller
FSCC	fractional short circuit current
HC	hill climbing
InCond	incremental conductance
LA	learning automata
MFs	membership functions
MPP	maximum power point
MPPT	maximum power point tracking
MSE	mean square error
OP	operating point
PI	proportional - integral
P&O	perturbation and observation
PSO	particle swarm optimization
PV	photovoltaic
SA	simulated annealing
SSE	steady state error
STC	standard test conditions
A	diode quality factor
d	duty ratio
d_m	duty ratio at P_m
G	radiation level (W/m^2)
I_m	module output current at P_m (W/m^2)
I_o	dark saturation current (A)
I_{ph}	photo-generated current (A)
I_{PV}	module output current (A)
I_{sc}	short circuit current (A)
k	Boltzmann's constant (J/K)
K_i	integral gain
k_i	temperature coefficient of I_{sc}
K_p	proportional gain
k_v	temperature coefficient of V_{oc}
n_s	series-connected cells
P_m	maximum output power (W)
P_{PV}	module output power (W)
q	electron charge (C)
R	resistive load (Ω)
R_s	series resistance (Ω)
R_{sh}	shunt resistance (Ω)
T	operating ambient temperature (°C)
T_j	junction temperature (°C)
V_m	module output voltage at P_m (V)
V_{oc}	open circuit voltage (V)
V_{PV}	module output voltage (V)
V_t	junction thermal voltage (V)
Δd	perturbation step
$\mathscr{K}EG$	energy gain factor
$\eta MPPT$	energy utilization efficiency

of the direct component of solar radiation, causing degradation of the PV system efficiency [15]. The atmospheric pressure is the weight of air in atmosphere of the earth, which is proportional to the gravitational force. The latter is inversely proportional to the altitude exerting more downward of the solar radiation. This increases the solar intensity to raise the PV system efficiency [16].

Therefore, this calls for PV system development through tracking the maximum of the available power under fluctuating climatic conditions [17,18]. Maximum energy tracking can be achieved by utilizing dynamic or static method. The tracking of sun movement is the basis for achieving the maximum solar energy in the dynamic method. However, this method may not be useful for energy conversion at small to medium power range due to its high cost and energy consumption. While in the static method, which is suitable for small power range, well known “maximum power point tracking (MPPT)” is achieved using a particular control technique. Such technique adjusts duty ratio d (control signal) for an electronic DC-DC converter with high switching frequency to achieve the maximum electrical power [19]. According to PV module characteristics, the maximum output power P_m depends on the climatic conditions, which are the operating ambient temperature T and radiation level G, and load characteristics. On the module I -V characteristics, there is a unique operating point (OP) enabling extraction of P_m. This is why tracking of this OP is essential in order to ensure efficient operation of PV generator, Fig. 1. Extraction of maximum power involves load characteristics adjustment under variations in radiation level and ambient temperature [20,21]. The fundamental objective addressed by the MPPT technique is to automatically determine the PV module output voltage V_m or output current I_m at which the PV module produces maximum output power Pm under a particular T and G. Many researches have been long working on extracting maximum output power from the PV generator by developing MPPT techniques [22]. The maximum power tracker not only increases the power delivered from the PV module to the load, but also enhances the operating lifetime of the PV system [23].

Several MPPT techniques have been proposed depending on their complexity, accuracy, tracking speed, hardware implementation, sensors used, effectiveness, parameterization, financial view, setup and popularity [22,24–32]. These techniques can be categorized in three main categories as offline techniques, which depend on PV module models, online techniques, which do not specifically rely on modeling of the PV module and hybrid techniques, which are a combination of the aforementioned techniques [20,22]. The offline and online techniques can also be referred to as the model-based and model-free techniques, respectively [20], or as “quasi seeks” and “true seeking” techniques, respectively [33].

Therefore, the purpose of this work is to present an intensive literature review on the most popular techniques for offline and online tracking of the MPP, which are the ANFIS and HC techniques, respectively. This is in addition to a review for all hybrid techniques reported in the literature demonstrating their main merits and shortcomings.

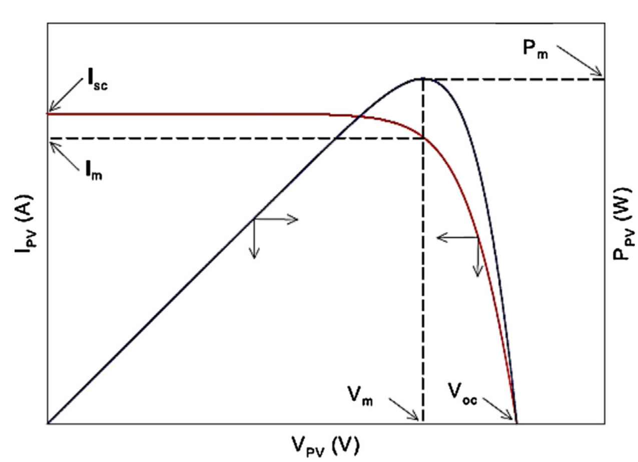

Fig. 1. Typical I-V and P-V characteristics. I_{sc}: short-circuit current, V_{oc}: open circuit voltage. I_m, V_m and P_m: current, voltage and power at maximum power point.

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