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Artificial intelligence-based maximum power point tracking controllers for Photovoltaic systems: Comparative study

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ABSTRACT

In Photovoltaic (PV) systems, maximum power point tracking (MPPT) is an indispensable task. To date, various MPPT techniques have been proposed in the literature using classical and artificial intelligence methods. However, those techniques are tested on different PV systems and under different environmental conditions. In this work, we attempt to summarize and to give a comprehensive comparative study of the most adopted Artificial Intelligence (AI)-based MPPT techniques. The MPPT techniques which will be described are based on: Proportional-Integral-Derivative (PID), Fuzzy Logic (FL), Artificial Neural Network (ANN), Genetic Algorithms (GA) and Particle Swarm Optimization (PSO). The developed MPPT controllers are tested under the same weather profile in the same photovoltaic system which is composed of a PV module, a DC-DC Buck-Boost converter and a DC load. Initially, Modelling and simulation of the system is performed using the MATLAB/ Simulink environment. Thereafter, the sliding mode control is applied to the converter in order to improve its performance. In a further stage, the different steps of development for each MPPT technique are presented. Simulation is performed to confirm the validity of the proposed controllers under the same variable temperature and solar irradiance conditions. Finally, a comparative study is carried out in order to evaluate the developed techniques regarding two principal criteria: the performance and the implementation cost. The performance is evaluated using comparative analysis of the tracking speed, the average tracking error, the variance and the efficiency. To estimate the implementation cost, a classification is carried out according to the type of the used sensors, the type of circuitry and the software level complexity. Recommendations that expected to be useful for researchers in the MPPT area about the validity of each MPPT technique are given in the last section.

1. Introduction

Electrical energy is the backbone of modern industry and an essential tool for modern life. Because of the growing demand for energy and the stress on conventional energy resources with undesirable impact on environment, the industry has been urged to accelerate the researches on alternative energy resources. Among the available alternative energies, Photovoltaic (PV) energy is one of the most promising renewable energies. PV energy is freely available and environment friendly. PV equipment generates electricity without any gas emissions and its operation is virtually silent. Moreover, its is simple in design and requires few maintenance [1,2]. Its construction as a stand-alone system can provide a large power supply for remote areas, whereas grid-connected PV systems are still quite expensive. PV power systems are now widely being installed around the world and the demand of such power is increasing every year.

As of the end of 2014, the worldwide installed photovoltaic capacity reached 178 gigawatts (GW) and in 2014 it is expected to reach 327 GW at the end of 2015 and at least 400 GW within the next four years. In this context, Algeria has launched an ambitious program to develop renewable energies (REn) in order to diversify energy sources and engage in sustainable energy use [3]. The Algerian energy strategy is mainly based on solar energy development, this choice is motivated by the huge solar potential in the country. PV power should achieve by 2030 more than 37% of national electricity production. However, the realization of PV systems remains a great challenge due to the high installation cost for PV arrays and the related equipment. Furthermore, Photovoltaic energy lacks reliability due to the direct dependence on weather conditions.

Photovoltaic energy comes from conversion of a part of the solar irradiance into electrical energy. This conversion is based on the photovoltaic effect. The PV modules are composed of the series and parallel association of many PV cells. The maximum power point of the PV module changes with the variations of solar irradiance and temperature levels. Because of the high cost of PV modules and their low efficiency (between 10 and 23%) [4,5], the integration of a robust

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Nomenclature

PV	Photovoltaic
AI	Artificial Intelligence
PID	Proportional-Integral-Derivative
FL	Fuzzy Logic
ANN	Artificial Neural Network
GA	Genetic Algorithms
PSO	Particle Swarm Optimization
I_{pv}	Current supplied by the cell (A)
T	Cell temperature
G	Solar irradiance
I_{light}	Photo-cell current (A)
I_{diode}	Direct Diode Current (A)
I_{sc}	Short-circuit current (A)
I_0	Reverse bias saturation current (A)
V_{pv}	Voltage across the cell (V))
I_{scref}	Short-circuit current in standard temperature conditions (A)
I_{0ref}	Reverse bias saturation current in standard temperature conditions (A)
T_{ref}	Reference temperature (25 °C)
G_{ref}	Solar irradiance reference(1000 W/m^2)
R_s	Series resistance(Ω)
n	Diode ideality factor
V_T	Heat Potential (V)
K	Boltzmann constant $(1,\ 380.\ 10^{-23}$ J/K)
q	The electron charge $(1,\ 6.\ 10^{-19}$ C)
$\mu_{I_{sc}}$	Short-Circuit Current Temperature Coefficient (A/°K)
E_g	Band gap of the semiconductor (eV)
N_s	Series connected cells number
N_p	Parallel connected cells number
$I_{pv}{}^G$	Global Current supplied by PV module (A)
$V_{pv}{}^G$	Global voltage of PV module (V)
P_{mp}	Maximum power available (W)
V_{mp}	Operating voltage value at maximum power (V)
V_{oc}	The open circuit voltage (V)
I_{sc}	Short-circuit current (A)
α	Duty cycle
T_d	The switching period
$i_i(t)$	Input current of the converter
$v_i(t)$	Input voltage of the converter
$i_o(t)$	Output current of the converter
$v_o(t)$	Output voltage of the converter
S	State of the converter switch
R_L	Resistive load
L	Inductance of the converter (35 mH)
C_1	Input capacitor of the converter (2.5 mF)
C_2	Output capacitor of the converter (5.6 mF)
G_v	Voltage conversion ratio
S_1	The sliding surface
K	Switching gain of the sliding mode controller
v_{iref}	Reference voltage
K_P	Proportional gain of MPPT controller
K_I	Integral gain of MPPT controller
K_D	Derivative gain of MPPT controller
μ_i	Firing strength
W_h	Weight of hidden layer
W_o	Weight of output layer
b_h	Biases of hidden layer
b_o	Biases of output layer
$\hat{V}_{mp}$	Estimated maximum power voltage
MSE	Mean Square Error
FSTS	Fixed Sampling Time Strategy
ASTS	Adaptive Sampling Time Strategy
v_i	Agent i velocity
p_{ibest}	Agent's i best position
g_{best}	Best position attained in the swarm
P_{max}	Theoretical maximum power
e_m	Tracking error
E_m	Average value of the tracking error
V_m	Variance of the tracking error
t_{rep}	Convergence time towards MPP
η	Photovoltaic module efficiency (%)

MPPT controller is necessary; maximum power point tracking (MPPT) consists of extracting the maximum power from the PV generator.

Conventional techniques are known and very well established in the literature such as Perturb and Observe [6,7], Increment of Conductance [8–12] and Hill Climbing [13,14]. These techniques are simple and easy to implement, but they suffer from oscillations at MPP and their efficiency is low. Several pieces of research are carried out to improve the performance of these techniques [15–19,9,11]. The use of Artificial Intelligence (AI) methods to improve the performance P & O-based MPPT technique is well reviewed in [20]. ANN was used to improve the performandce of P&O technique in [21]. Besides conventional MPPT techniques, Artificial Intelligence-based MPPT methods are efficient and can get better performances [22–25]. Fuzzy logic is used to improve the performance of perturb and observe in [26] and increment of conductance in [27]. Proportional-Integral-Derivate (PID) controller is widely used in control systems due to its simplicity, performance and stability in the steady state regime. An MPPT control using a fuzzy PID controller is proposed in [28,29]. The hybrid controller combines the advantages of fuzzy logic and conventional PID control.

Since the relation between the extracted power and the output voltage (P-V) is a highly non linear, FL and ANN are a suitable solutions for the MPPT problem. The digital implementation of the fuzzy controller has been carried out in [30–33]. The fuzzy controller was improved by selecting the best membership functions using genetic algorithms in [34] and particle swarm optimization in [35]. ANN approach is proposed and investigated in several works in the literature [36,37]. The requirement of a large database for training the ANN model is the main constraint of such controller. In work [38], the database was established from measurements of irradiance, temperature and the corresponding optimal duty cycle. In [39], the fuzzy controller is used to generate the database for training the neural network. Authors in [40,41] proposed an optimization of the ANN structure using genetic algorithms. A complex approach is proposed in [42] where a fuzzy controller is used to perform the choice between many ANN models, the choice of the local model is based on the optimal performance in the operating range of temperature and irradiance.

During uniform solar insolation, PV curve is characterized by a unique MPP. The case will be more complicated when the PV array is subjected to partial shading, i.e., the PV array receives non-uniform insolation. In such case, PV curve will be characterized by several peaks which one of them is the global MPP. The tracking of the global MPP seems to be an optimization problem. To date, several pieces of research have made attempts to realize global MPPTs by evolving different methods based mainly on meta-heuristic optimization algorithms. In evolutionary computing family, MPPT algorithms was proposed based on Genetic algorithms (GA) in [43–45] and Differential Evolution (DE) in [46–48].

In swarm intelligence family, Particle Swarm Optimization (PSO) for MPPT is preferred due to its simplicity and fast computation capability [49–53]. Furthermore, recent works have implemented