Applied Energy 211 (2018) 50–63

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

# A robust design of maximum power point tracking using Taguchi method for stand-alone PV system

Ying-Yi Hong[a,*], Angelo A. Beltran Jr.[b,c], Arnold C. Paglinawan[c,d]

[a] Department of Electrical Engineering, Chung Yuan Christian University, Chung Li District, Taoyuan City 320, Taiwan
[b] Center for Research & Development and Department of Electronics Engineering, Adamson University, 1000 Manila, Philippines
[c] School of Graduate Studies, Mapua University, 1002 Manila, Philippines
[d] School of Electrical Electronics Computer Engineering, Mapua University, 1002 Manila, Philippines

## HIGHLIGHTS

- Insolation received on PV surface at various tilt angles was assessed.
- Taguchi method was applied to evaluate optimal factors.
- Enforced fuzzy logic MPPT, optimized by chaos PSO.
- Employed DSP-in-the-loop based on Opal-RT OP5600.

## ARTICLE INFO

*Keywords:*
DSP-in-the-loop simulation
Maximum power point tracking
Photovoltaic
Robust design
Taguchi method

## ABSTRACT

Solar photovoltaic (PV) cells have attracted substantial interest recently owing to environmental concerns and the energy crisis. However, the efficiency of power generation by solar PV cells depends on various factors, such as climatic conditions and tilt angle. Therefore, maximum power point tracking (MPPT) for PV modules is important. This work proposes a novel robust design, which relies on various combinations of insolations, temperatures, and tilt angles, in a stand-alone PV system with MPPT. Orthogonal experiments are carried out using the Taguchi method, avoiding a full factorial experimental design. In the proposed Taguchi-based MPPT robust design of the PV system, insolation and temperature are regarded as an input and 'noise', respectively; insolation passage, tilt angle, and load resistance are factors that affect the results of the Taguchi experiments in multiple scenarios. A fuzzy logic controller, tuned by chaos particle swarm optimization (PSO) was utilized to implement MPPT. A stand-alone PV system was used to demonstrate the results that were obtained by the robust design of MPPT and applicability of the proposed method. Finally, a Digital Signal Processor-in-the-Loop simulation was performed using an OP5600 real-time digital simulator by Opal-RT to demonstrate the viability of the proposed scheme.

## 1. Introduction

The Kyoto Protocol is an international treaty to reduce greenhouse gas emissions and thereby to reduce the effects of global warming [1]. Solar PV generation a promising renewable and clean source of energy because a PV systems converts energy directly into electricity. Such PV systems are environmentally friendly, quiet, easy to maintain, stable and secure, and do not emit greenhouse gases or carbon dioxide when they generate electrical energy [2,3]. Despite these advantages of the PV systems, the energy conversion by PV modules is inefficient apart from its non-linear behavior and dependence on the weather.

A maximum power point tracking (MPPT) system is a photovoltaic electronic system that varies the electrical operating point and allows PV modules to deliver maximum power. MPPT is imperative because the power, voltage, and current in a PV module are non-linearly related and sunshine conditions vary continuously. Therefore, the amount of extracted energy varies continuously. MPPT is an active field of research associated with solar PV systems [4–6].

In recent years, substantial progress has been made in MPPT with respect to solar PV.

Ishaque et al. [7] benchmarked the MPPT performance of a perturbation and observation algorithm and an incremental conductance algorithm. To do so, they used a direct control structure and a buck-boost converter. The duty cycle was the control variable. Sivakumar

* Corresponding author.
*E-mail address:* yyhong@ee.cycu.edu.tw (Y.-Y. Hong).

https://doi.org/10.1016/j.apenergy.2017.11.041
Received 16 July 2017; Received in revised form 22 September 2017; Accepted 5 November 2017

**Nomenclature**

| | |
|---|---|
| $\alpha$ | hour angle (°) |
| $t$ | time (h) |
| $\delta$ | solar declination angle (°) |
| $d$ | number of days |
| $\xi$ | solar azimuth angle (°) |
| $\lambda$ | latitude (°) |
| $\chi$ | solar zenith angle (°) |
| $\theta$ | angle between the board and solar rays (°) |
| $\zeta$ | plate azimuth angle (°) |
| $\phi$ | tilt angle of PV (°) |
| $\rho$ | reflection index |
| $C$ | diffused portion constant |
| $G_{b(s,t)}$ | solar direct radiation $\left(\frac{\mathrm{W}}{\mathrm{m}^2}\right)$ |
| $G_{d(s,t)}$ | sky-diffused radiation $\left(\frac{\mathrm{W}}{\mathrm{m}^2}\right)$ |
| $G_{r(s,t)}$ | ground-reflected radiation $\left(\frac{\mathrm{W}}{\mathrm{m}^2}\right)$ |
| $G_{(s,t)}$ | total radiation $\left(\frac{\mathrm{W}}{\mathrm{m}^2}\right)$ |
| $L$ | first word of a Latin square (Taguchi method) |
| $x$ | (subscript) number of experimental runs |
| $y$ | number of levels (Taguchi method) |
| $z$ | (superscript) number of control factors |
| $SNR$ | signal-to-noise ratio ($dB$) |
| $n$ | number of experiments (Taguchi method) |
| $y_i$ | value of global best in the $i$th experiment obtained by particle swarm optimization |
| $E(n)$ | operating power point |
| $\Delta E(n)$ | directional movement of operating power point |
| $\Delta D(n)$ | change in duty cycle |
| $D(n)$ | duty cycle |
| $x_p^{t+1}$ | updated position of particle |
| $v_p^{t+1}$ | updated velocity of particle |
| $\chi$ | type 1″ constriction |
| $\omega_{chaos}^t$ | chaos random inertia weight |
| $v_p^t$ | present velocity of particle |
| $x_p^t$ | present position of particle |
| $c_1^t$ | adaptive cognitive component |
| $c_2^t$ | adaptive social component |
| $p_{best}^t$ | best 'remembered' individual particle position |
| $g_{best}^t$ | best 'remembered' swarm position |

et al. [8] used the incremental conductance algorithm to MPPT owing to its simplicity, favorable performance under steady state conditions, and the fact that it can be executed using a low-memory processor. Ahmed and Salam [9] enhanced the performance of the perturbation and observation algorithm. They used a buck-boost converter with the duty cycle as the control variable. Kwan and Wu [10] developed a maximum power point tracker for a PV system using a variable antecedent fuzzy logic controller. They used an MSP430F5529 MCU and a SEPIC converter in their experiment. He et al. [11] executed a perturbation and observation algorithm and an incremental mass-resistance algorithm for maximum power point tracking. Rizzo and Scelba [12] used an artificial neural network to estimate the maximal power that is delivered by a PV system with non-uniform insolation. They conducted various case study and various test data sets. Arulmurugan and Suthanthiravanitha [13] presented a Hopfield neural network-based fuzzy logic, which included a PI controller to control the pulse width modulation for a buck boost zeta converter under various irradiation conditions. Ahmed and Salam [14] used the cuckoo search mechanism to search the maximum power point. Their method was verified using variable solar insolation and temperature in a Matlab/Simulink simulation environment. Fathabadi [15] developed a sensorless dual-axis solar tracker that was controlled using maximum power point tracking. Farhat et al. [16] implemented a sliding mode control algorithm in a boost converter under variable climatic conditions. They used Matlab/Simulink and the dSPACE real-time digital control platform. Prasanth Ram and Rajasekar [17] proposed leader particle swarm optimization, which uses mutation to find the maximum power point under uniform and non-uniform irradiances. In several studies, metaheuristic optimization algorithms have been hybridized with other stochastic or conventional MPPT algorithms [18–21] to exploit the strengths of both.

The aforementioned works have the following limitations. (a) The perturbation and observation algorithm and the incremental conductance algorithm perform well with steady-state insolation and temperature, simple MPPT, and are favored for implementation using a low-cost processor hardware; they suffer from the poor or slow convergence of MPPT under dynamic climatic conditions. (b) Fuzzy logic overcomes the limitations of a PID controller and supports excellent MPPT under varying weather conditions. However, MPPT cannot be effective if the membership functions are not finely tuned. (c) An artificial neural network exhibits adaptive learning, excellent tracking of the MPP, and the ability to solve non-linear problems. However, the numbers of layers and neurons in such a network are uncertain; it takes a long time to converge, and the accuracy of MPPT depends on the available data because the learning process for training the neurons takes a long time, so the required memory, computational load, and CPU time are high. (d) A brood parasitism technique such as the cuckoo search algorithm is fast and performs akin to swarm algorithm. Its MPP tracking depends on levy flight, and the algorithm used to compute MPP is complex. (e) MPPT-controlled sensorless solar tracking eliminates the need to purchase additional current and voltage sensors, saving costs. However, many computations must be conducted, increasing the CPU count in finding the MPP. Incorrect estimation of the direction of the sun by the PV module yields an incorrect MPP. (f) Although, sliding mode control mechanism has a simple structure and is effective, it is likely to suffer from the development of unwanted oscillation during maximum power point search. (g) Adding a mutation operator to the particle swarm optimization may improve the effectiveness of the algorithm. However, particles are likely to become trapped at local optima. (h) Hybridizing stochastic algorithms may provide effective tracking of the MPP under changing environmental conditions but doing so may increase the complexity of the algorithm by increasing the number of parameter calculations and the computational time to converge. (i) Solar energy is associated with various degrees of insolation and most of the MPPT studies that were cited above did not consider the assessment of insolation by the PV at particular site. (j) In the cited literature, structured analyses are conducted but multiple scenarios are not considered and factors, such as insolation passage, load, and tilt angle, that influence the maximal power generation, are ignored with respect to stand-alone PV system.

Robust design [22–24] refers to a method for optimizing a process or product that yields quality output designs at minimal development costs with low sensitivity to fluctuations of uncontrollable variables. Taguchi [24,25] proposed a special experimental design for studying the effects of numerous variables on an output, and this method bears his name. The Taguchi design of experiments may significantly improve process or product design that depends on numerous factors. Taguchi's design of experiment (DOE) method is an organized and efficient approach to improving products or processes [23,25]. The scientific community has recently become increasingly interested in applying the method of Taguchi to engineering problems, favoring the development of algorithms [22,26,27], robotics [28,29], motor design and battery charging [30,31], inventory routing [32], communications [33], economic dispatch [23,34], and traffic forecasting [35], to name just a few examples. The method of Taguchi is widely used to improve processes,