A novel maximum power point tracking method for PV systems using artificial neural network

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This paper presents a novel maximum power point tracking method of a stand-alone photovoltaic system using artificial neural network. The proposed method estimates the maximum power of a solar module in different conditions. The main advantage of the proposed methodology, comparing to conventional methods is more accuracy. Also compared to other neural network based methods this model can be trained in less iteration and shows more stability based on different initial training points. Simulation and experimental results show that the model reaches a high fitness.

Keywords: neural networks, photovoltaic, modeling, maximum power point tracking.

1. INTRODUCTION

In the current century, the world is increasingly experiencing a great need for additional energy resources this has led to some undesirable effects:

Oil prices have doubled in the last eight years, increasing from 44 USD/barrel in 2003 to over 100 USD/barrel in the beginning of 2011. Besides according to a forecast that fossil fuel will still be available in 2030, but there won’t be a geographical balance between the energy supply and demand that will eventually lead to the exhaustion of fossil fuel.

Environmental threats are arising from the production of electricity from fossil fuels such as greenhouse effect. The climate changes can cause floods or dissertations which its light effects will lower water levels in hydro-electric facilities and may cause instability of the main electricity supply source in many regions [1].

As a result scientists are looking for alternative energy sources which would be able to solve the above mentioned problems. Photovoltaic (PV) energy could be an answer to that problem. This lead to rapid growth of using PV systems giving them increasing roles in electric power technologies, providing more secure power sources and pollution-free electric supplies [2].

Most basic advantages associated with photovoltaic systems are that they don’t produce any noise, require little maintenance and work quite satisfactorily with beam or diffuse radiation posing no health or environmental hazards [3]. Among various distributed power sources PV systems are, by nature, non-linear power sources that need accurate estimation of the
maximum power generation. For the operating a plant of power systems including PV systems, the accurate prediction of the maximum power from the PV systems is inevitable. The maximum power generation depends on the environmental factors, mainly the irradiation and the cell temperature [2]. The general block diagram of a stand-alone PV system is shown in Fig. 1. Corresponding to this figure, the DC-DC converters drain the energy from the photovoltaic module with maximum power point tracker (MPPT) control.

Over the years many methods have been proposed to extract the maximum power from PV cells. These methods vary in complexity, way they obtain maximum power point, sensors required, convergence speed, and cost, range of effectiveness and implementation hardware. In past few years the artificial neural networks (ANN) approach have received attention and increased their use very successfully in the implementation for MPP tracking [5–12] because of their advantages over conventional methods.

The main propose of this paper is to develop a novel maximum power point tracking method of a stand-alone photovoltaic system using artificial neural network. However, a neural network approach has been applied and is tested by data gathered from an actual solar module.

![Figure 1 General block diagram of a stand-alone PV system with MPPT.](image)

2. MODEL OF SOLAR PV ARRAY

The solar PV module consists of an appropriate series-parallel combination of solar cells that provides the required output voltage and current under normal conditions. Basically a solar cell is a p–n junction semiconductor that directly converts solar energy to electricity. The solar cell output current can be expressed as a function of photo-generated current, diode current and shunt current.

The photo-generated current ($I_{ph}$) depends on both irradiance and temperature. It can be expressed as a function of $G$, actual solar radiation (W/m²), $G_{ref}$, reference radiation (W/m²), $I_{ph\text{, ref}}$, reference photocurrent(A), $I_{acc}$, manufactured supplied temperature coefficient of the short circuit current (A/K), $T_c$, actual operating temperature of cell (C), $T_{c\text{, ref}}$, reference temperature(C) as shown below (K in $I_D$ is Boltzmann constant, $1.38 \times 10^{32}$ J/K):

$$I_{ph} = \frac{G}{G_{ref}} (I_{ph\text{, ref}} + I_{acc}(T_c - T_{c\text{, ref}})) .$$  

The diode current has been given on the Shockley equation:

$$I_D = I_0 (\exp\left(\frac{e(V_d)}{\eta KT_c}\right) - 1) \tag{2}$$

where, $V_d$ is diode’s voltage (V), $I_0$ the reverse saturation current (A), $\eta$ the diode ideality factor, $e$ the electron charge $1.602 \times 10^{-19}$ C, and K the Boltzmann constant. The reverse saturation current can be determined as follows:

$$I_0 = I_{0\text{, ref}} \left(\frac{T_c}{T_{c\text{, ref}}}\right)^3 \exp\left(\frac{eE_{sc}}{\eta K} \left(\frac{1}{T_{c\text{, ref}}} - \frac{1}{T_c}\right)\right) . \tag{3}$$

The cell temperature $T_c$, is dependable on ambient air temperature $T_A$, irradiance ($w/m^2$) and wind speed (m/s) as modeled in [4]:

$$T_c = 0.943T_A + 0.02 \text{ (Iradiance)} + 1.528 \text{ (wind speed)} + 4.3 \tag{4}$$

Equation (1) can be rewritten as follows

$$I = I_{ph} - I_0 \left(\exp\left(\frac{e(V + I R_s)}{\eta K}\right) - 1\right) - \frac{V + I R_s}{R_p} \tag{5}$$

where $R_s$ is the series resistance and $R_p$ is the parallel resistance [4].

It can be seen from above equations that a solar cell is in nature a non-linear element. Since the output of the cell depends on many parameters, controlling it so for giving maximum output power is very difficult.

2.1 Conventional MPPT methods [5]

2.2 Curve fitting Methods

There have been proposed some models like conventional single-diode, two-diode and modified two diode model, using mathematical equations or numerical approximations. Since their resolution is impossible by analogue control and very difficult by conventional digital control so their application is not suitable for obtaining the MPP. Thus a practical model is discussed in the following. It can be shown that P-V characteristic of a generator can be shown like Equation (6). Where $a$, $b$, $c$ and $d$ are coefficients determined by the sampling of n values of PV voltage ($V_{PV}$) PV current ($I_{PV}$) and PV power ($P_{PV}$) in the required interval. Thus the voltage at which the power becomes maximum and is obtained by means of Equation (7)

$$P_{PV} = a V_{PV}^3 + b V_{PV}^2 + c V_{PV} + d \tag{6}$$

$$V_{MPP} = \frac{-b \sqrt{b^2 + 3 ac}}{3a} \tag{7}$$

This process should be repeated in intervals in order to find a fine MPP. The number of samples will determine the accuracy. The disadvantage of this method is that both it requires accurate knowledge of the physical parameters relating to the cell material and manufacturing specifications or the expressions used are not valid for all climatological conditions. In addition, it requires a large memory capacity for calculation of the mathematical formulations.
Another problem is that implementation must be adjusted for the control system, which correspond to the maximum power point under pre-defined climatological conditions. This algorithm has two main disadvantages: one is that a large amount of memory is required for storage of the data. Besides, it is difficult to record and store all possible system conditions. Another problem is that implementation must be adjusted for a specific PV panel.

### 2.3 Look-up Table Method

In this method, the measured values of the PV generator’s voltage and current has been compared with those stored in the control system, which correspond to the maximum power point, under pre-defined climatological conditions. This algorithm has two main disadvantages: one is that a large amount of memory is required for storage of the data. Besides, it is difficult to record and store all possible system conditions. Another problem is that implementation must be adjusted for a specific PV panel.

### 2.4 Open-circuit voltage photovoltaic generator method

This algorithm is based on the voltage of PV generator at the MPP which is approximately linearly proportional, $K$, to its open-circuit voltage ($V_{OC}$). The proportional constant mainly depends on the fabrication technologies, fill factor and the meteorological conditions.

$$K = \frac{V_{MPP}}{V_{OC}} \approx Cons \tan \theta \leq 1. \quad (8)$$

The Flow chart of Open-circuit voltage photovoltaic generator method has been shown in Fig. 2. According to Fig. 2, the PV generator’s open-circuit voltage is measured by interrupting the normal operation of the system, with a certain frequency, storing the measured value. Therefore, the MPP is calculated, according to Equation (8), and the operation voltage is adjusted to the maximum voltage point. This process will be repeated periodically. Although being apparently simple, it is difficult to choose an optimal value of the constant.

This method has as an advantage that it is simple and low-priced. It uses only one feedback loop. Nevertheless, its drawback is assuming a fixed voltage for $V_{OC}$ is this because it won’t remain constant for a wide variation of temperature and insolation, and does not change appreciably, with the aging of cell. However, the interrupts system operation yields power losses when scanning the entire control range. Thus, the real power extracted is not considered to be of (from) the panels. That is, as it is assumed that for given open-circuit voltage the maximum point is determined if the operation point is incorrect, or slightly inexact, the extracted power will not be the maximum.

### 2.5 Open-circuit voltage photovoltaic test cell method

In order to avoid possible disadvantages related to the frequent interruption of the system, some paper suggested an alternative: use of a test cell. Thus, the PV generator’s open-circuit voltage is measured from that single cell, which is electrically independent from the rest of the PV array. Values of the $K$ resulted from test cell will be applied to the main PV generator. This method’s advantage is that it is simple and economical; it uses only one feedback loop control. As a result, it avoids the problems caused by the interruptions of the operation of the PV set out in the previous method.

$$K = \frac{V_{MPP}}{V_{OC_{test}}} \approx Constant \leq 1. \quad (9)$$

A disadvantage is that the test cell should have properties identical to each cell of the PV generator main. Therefore, $V_{OC}$ of the test cell is considered proportional to $V_{OC}$ of the PV unit used in the selection of the MPP. Finally, due to use of additional test cell it is an unsuitable method for applications with surface limitations.

### 2.6 Short-circuit photovoltaic generator method

This method is mainly like the above Open-circuit voltage method and is based on following equation:

$$K = \frac{I_{MPP}}{I_{SC}} \approx Constant \leq 1. \quad (10)$$

Also, like that the previous method, the proportional mostly constant depends on the fabrication technologies, solar cells technology, fill factor and the meteorological conditions.

However, in many cases, the way of determining $K$ is more complicated than only a fixed value. Sometimes a PV scanning is performed in intervals in order to calculate $K$. After obtaining $K$, the system remains with the approximation (4), until the next calculation of $K$. Because of similarities of this method with Open-circuit voltage method; it offers the same advantages and disadvantages as the above control.

### 2.7 Sampling methods

In algorithms based on sampling the voltage and current of PV generator has been measured. Using the measured values, $P(t)$ is determined. By using of later samples $P(t + \Delta t)$ is computed. After gathering the past and the present information on $P_{PV}$, the controller makes a decision depending on the location of the operating point. This tracking process repeats itself indefinitely until the peak power points reached. In conclusion, the following methods can be distinguished.

### 2.8 Voltage/ current feedback

In case of no battery present in the system, in order to tie the bus voltage at a nearly constant level, a simple control can be
applied. To do so the feedback of the PV voltage (current) and the comparison with a reference voltage (current) can be used to continuously adjust the duty cycle (D) of a DC/DC converter for operating the PV panel at a predefined operating point, close to the MPP. The block diagram of this method has been shown in Fig. 3.

The disadvantages of this configuration are the same as for the method of direct connection (PV generator plus load profile). In other words, the system is not able to adapt to changeable environmental conditions, such as irradiance and temperature. However, in presence of batteries in the system, a common technique is to compare with a reference constant voltage, where it is assumed that it corresponds to the MPP, under environmentally specific conditions. The resultant error is used to control the DC/DC converter.

Not only the implementation of this variant is not relatively simple, but also it fails as well to fulfill the proposed objective because it does not take into account the effects of irradiation and temperature variations. The advantages of this method are the same as the previous methods: it uses only one feedback-loop control. Nevertheless, it presents the following disadvantages: it cannot be applied in generalized systems because it doesn’t consider the effect of variations of the irradiation and temperature of the PV panels.

2.9 Perturbation and observe (P&O) method

This algorithm is may be the most popular among others. It is an iterative method based on the fact that near the maximum power point \( \frac{dP_{PV}}{dV_{PV}} = 0 \) There have been presented many variables to be measured and compute the above equation one of the basic ones is PV cell Voltage. The maximum point is reached when \( \frac{dP_{PV}}{dV_{PV}} = 0 \). The operating voltage of the PV generator is perturbed, by a small increment \( \Delta V \), and the resulting change, \( \Delta P_{PV} \) in power, is measured. If \( \Delta P_{PV} \) is positive, the perturbation of the operating voltage should be in the same direction of the increment. However, if it is negative, the system operating point obtained moves away from the MPPT and the operating voltage should be in the opposite direction of the increment. The disadvantage of this method appears in the case of a sudden increase of irradiance where the algorithm reacts as if the increase occurred as a result of the previous perturbation of the operating voltage.

2.10 Conductance incremental method

This method was proposed as an alternative to P&O and is based on Equation (11)

\[
\frac{dP_{PV}}{dV_{PV}} = 0 \text{ if } V_{PV} = V_{MPP} \\
\frac{dP_{PV}}{dV_{PV}} = \frac{d(V_{PV} I_{PV})}{dV_{PV}} = I_{PV} \frac{dV_{PV}}{dV_{PV}} + V_{PV} \frac{dI_{PV}}{dV_{PV}} = 0
\]

\[
\frac{dI_{PV}}{dV_{PV}} = -\frac{I_{PV}}{V_{PV}}
\]

The incremental variations, \( dV_{PV} \) and \( dI_{PV} \), can be approximated by the increments of both the parameters, \( \Delta V_{PV} \) and \( \Delta I_{PV} \). As a result we will have the following approximations:

\[
dV_{PV} \approx \Delta V_{PV} = V_{PV}(t_2) - V_{PV}(t_1) \\
DI_{PV} \approx \Delta I_{PV} = I_{PV}(t_2) - I_{PV}(t_1)
\]

By analyzing above equations and rewriting them as below, it is obvious that the current operating point can be found.

\[
\frac{dP_{PV}}{dV_{PV}} > 0 \text{ for } V_{PV} < V_{MPP} \\
\frac{dP_{PV}}{dV_{PV}} = 0 \text{ for } V_{PV} = V_{MPP} \\
\frac{dP_{PV}}{dV_{PV}} < 0 \text{ for } V_{PV} > V_{MPP}
\]

The main advantage of this algorithm is that it offers a good yield method under rapidly changing atmospheric conditions. Also, it achieves lower oscillation around the MPP than the P&O method. The disadvantage of this method is that it needs a complex control system.

2.11 Model Proposed in reference [4]

The model consists of a 3 layered perceptron which has an input layer of two neurons, a hidden layer of nine neurons and an output layer of two neurons. The first two layers use tansigmoid activation function and the last layer uses a linear one. The inputs are radiation and temperature and the outputs are maximum power point current and voltage obtained from a solar PV array The network uses the following configurations:

- training pattern = 124
- learning rate = 0.001
- set error goal = 0.00001
- number of training iterations = 1281
- momentum = 0.95

the proposed model reaches the goal in 1281 epochs

3. PROPOSED MPPT MODEL

The schematic diagram of ANN based MPPT for PV system has been shown in Fig. 4. In this system, a chopper controller has been designed based on ANN model. The input and output quantities such as voltage and current of buckboost converter under the assumption of a loss less circuit are related by the
Following equations:

\[
V_{\text{out}} = \frac{D}{D-1} V_{\text{in}} \tag{16}
\]
\[
I_{\text{out}} = \frac{1-D}{D} I_{\text{in}} \tag{17}
\]

where \(V_{\text{out}}\) and \(V_{\text{in}}\) are the converter output and input voltage, respectively. \(I_{\text{out}}\) and \(I_{\text{in}}\) are the converter output and input current, respectively. \(D\) is the duty cycle of the converter.

Based on equations 11 to 14, the duty cycle of the converter can be obtained by the following equation:

\[
D = \frac{1}{1 + \frac{V_{\text{in}}}{\sqrt{P_{\text{out}} V_{\text{out}}}}} \tag{20}
\]

The ANN model for MPPT is shown in Fig. 5. The ANN tracker architecture was reached by many trial and errors and showed the best approximation and stability among other tested models. The first model was a two layer perceptron, consisting of a tansig and a purelin function. Because of its global mapping ability. The accuracy was about 98%. For a better accuracy a more complex architecture was needed. So another layer was added. Among activation functions, logsig showed better accuracy and of course better generalization. As
shown in Fig. 5 the model consists of three layers: the input layer has three neurons with Log-sigmoid activation function. The hidden layer had four neurons with Tan-sigmoid activation function and the output layer has four neurons with linear activation function.

The inputs are solar insolation, cell temperature and load which were collected from a solar module. The output is the corresponding MPP. The ANN model was trained evaluated and tested in MATLAB and has the following properties:
Figure 10 Results of proposed network.

Figure 11 Measured maximum power point and NN output.

Total number of samples: 210
Learning ratio: 0.5
Maximum number of iterations: 1000
Typical number of iterations: 16
Error goal: 10–15
Performance function: mean squared normalized error (msne)
Train ration: 85%
Validation ratio: 5%
Test ratio: 10%

Training algorithm: Levenberge-Marquardt back-propagation (trainlm)
Data division: random

3.1 Data acquisition system:
In order to gather data, the data logger as shown in Fig. 6 has been used. This system consists of two main parts: Variable resistor and Data acquisition device. The data set was col-
lected in one day from 9 AM to 4 PM in the interval of every 2 minutes.

4. SIMULATION RESULTS

In this paper an ANN based maximum power point tracking controller for Solar PV system has been proposed and analyzed in MATLAB. Also, the proposed ANN based MPPT was tested developed by using actual data as shown in figures 7 until 9.

As seen in figures 10 until 12, the proposed network has approximated the maximum power point with high fitness in total. The model’s accuracy has been tested several times with the different combinations of the dataset. The achieved results have similar accuracy %99.20-%99.80 which shows the model’s reliability. Compared to architecture proposed by Anil K. Rai, the proposed model reaches its goal in about $\frac{2}{3}$th of iterations. Having learning ration of 0.5 compared to Anil K. Rai model which is 0.001, shows that the proposed model converges faster to the desired goal [4]. According to Figures 11 and 12, the ANN based controller in maximum power point tracking performance is more accuracy over the conventional methods and avoids the tuning of controller parameters.

5. CONCLUSION

A novel maximum power point tracking method was proposed. The proposed method uses an artificial neural network model to predict the maximum power that can be extracted from a solar module in different situations. The main advantage of the proposed methodology, comparing to conventional methods is more accurate and can handle non-linearity of PV arrays better due to its non-linear nature. Compared to other neural network based methods this model can be trained in less iterations and is faster as well. Simulation results show that the model reaches a high fitness. Also, the proposed model can be used as a reliable MPPT. Since cell temperature, solar insolence and output load are easily measured, this system can be used in any place such as stand-alone operation.

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