Fast-Accurate Dual-Axis Solar Tracker Controlled by P&O Technique with Neural Network Optimization

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***Abstract*— This paper proposes a fast-accurate method to locate the sun through dual-axis sun tracker rapidly and accurately. The tracking time is reduced to decrease the power consumption and improve the dynamic performance. The controlling procedure is closed-loop combination of Multi-Layer Perceptron (MLP) neural network and Perturbation & Observation (P&O). If the sun deviates from solar panels significantly, the sun tracker will operate quickly, but inaccurately by using the neural network. But if the sun gets away slightly, the sun tracker will operate accurately, but slowly by using P&O. So, by combining these two given cases will cause to track the sun fast and accurately. The error back propagation training algorithm is firstly used to train the neural network and in the next step the Modified Particular Swarm Optimization (MPSO) method used to optimize the neural network. The results indicate that the tracking time of proposed method is 42%-49% less than other which is used for comparison. So, the sun tracker has better dynamic performance, lower power consumption and increased efficiency.**

Keywords— Perturbation & Observation (P&O), dual-axis solar tracker, neural network optimization, Modified Particular Swarm Optimization (MPSO) method, MPPT, Solar PV.

I. INTRODUCTION

The solar energy is one of the renewable energies which is converted into electrical energy by solar cells. The serial and parallel combination of these cells contribute to various range of voltages and currents. On the other hand, the widespread availability of this energy makes to utilize it as energy source in various fields like moving vehicles such as identification aircraft, cars etc. In addition to the various advantages of solar cells, low efficiency and expensive equipment as well as nonlinear dependence of output power upon the working point and environmental conditions such as temperature and sunlight intensity are known as the major problems of solar cells. Therefore, two general methods are used to achieve the maximum power production of solar cell. The first method deals with Maximum Power Point Tracking (MPPT) which is based on electrical parameters and the second method which is based on both electrical and mechanical equipment (sun tracker). Numerous MPPT techniques have been developed in the literature for tracking the MPP. In [1], the classification and comparison between the methods which are more practical in MPPT field are introduced. Some of the most important methods are the Perturb and Observe (P&O), the Incremental Conductance (IC), Fractional open-circuit voltage (FVOC), fractional short-circuit current (FSC), Neural network, Fuzzy logic control, etc. The Perturb and Observe (P&O) algorithm is the most commonly used in many PV systems [2].

Some articles also are a combination of above methods. For instance, in [3] the combination of P&O, fuzzy and power prediction methods are used. In [4], the methods of modified IC and the neural network are employed. In the field of the sun tracker, various methods are employed to control the rotation of PV plates toward the sun to receive the maximum perpendicular sunlight on them. Sun trackers are categorized as passive and active trackers. In passive trackers, the heat of the sun is used to create imbalance and thermal expansion of a gas which has low boiling point. These trackers mostly have low accuracy and speed. They have weak efficiency at low temperatures but there is less complexity in their controller [5]. Some other passive trackers are based on the chemical properties of shape memory alloy. These trackers are inexpensive, but they change due to the chemical reaction with the environment during the time [6- 7].

Active trackers (Single-axis and Dual-axis) use motors, gearboxes, sensors and microcontrollers. The motors move rapidly, and are controlled by controlling signals of microcontroller accurately. Although, they consume energy but are more effective than passive trackers. Active trackers are also divided into single and dual-axis groups. Dual-axis trackers are more complicated but more efficient than single-axis ones [5]. In a study on single-axis trackers, theoretical aspects related to the design of a single-axis system are presented [8]. In some papers, the single-axis sun trackers are going to the continuous change of azimuth angle. They are more efficient than a fixed solar panel, but less efficient than the dual-axis trackers [9, 10]. In [11], the sun tracker uses four electro-optical resistors to move the panel according to differences between them. In [12], the author has developed a solar tracker system using a battery, a servomotor, a charger and two sensors with the aid of the MATLAB software. The system has been able to track the east-west route by one axis. The controller rotates the panel toward the sun based on the signal transmitted by the sensors.

In [13], a single dual-axis tracker is designed using a 76-bit controller and five optical sensors. One of the sensors

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detects atmospheric conditions such as being day or night, cloudy or sunny weather and the other four sensors provide the information to rotate in the east-west and the north-south direction. It can switch the work cycle and adjusts the rotation of panel according to the season or area. In other articles, smart algorithms, such as neural or fuzzy networks are utilized to determine the rotation of sun tracker. For example, in [14], the author obtains the amount of rotation at azimuth and altitude angles as the output of the fuzzy controller for dual-axis sun trackers.

In [15], the dual-axis tracker is designed using the neural network. In this method several factors such as temperature, azimuth and altitude angle of solar panel, time, intensity of light, humidity, wind speed etc. are considered as inputs of the neural network and the azimuth and altitude angles of the sun are the output of neural network. This article tends to consider all the effective factors to track the sun in an optimal and adaptive way. In [16], dual-axis controlling is designed using Support Vector Machines (SVM). The LabVIEW software is used to control the stepper motors. The values of optical sensors and production power of solar cell are the inputs of controller and according to them, the controller determines the rotation. In [17], TF-Fuzzy controller is adopted for modeling and controlling the dual-axis sun tracker. Since the parameter K_p of PID controller is likely to change, four state matrixes are considered as four conditions. Then the optimal values of parameters are specified by using the membership function in the fuzzy control. In [18], the author uses the fuzzy logic method. Four low power solar panels are installed on the four sides of the main solar panels, and solar modules track the sun as far as there is a voltage difference between low power solar panels. In [19], the tracking system is only based on astronomical calculations without making use of optical sensors. In [20], a robot is used to rotate the dual-axis solar panels toward the sun. The tracking sun is according to astronomical calculations using the MATLAB software. The results are compared with the PVsyst software which indicates the high accuracy of calculations for Algiers. PID controller is also used to control the motors and the homogeneous transformation matrix is utilized to illustrate the sun position in fixed-reference plate. In [21], dual-axis sun tracker system is designed based on a predictive algorithm. This algorithm is based on time. The azimuth and altitude angles of the sun position relative to the panel, are calculated and the servo motors rotate accordingly. The result indicates 27.4% increased efficiency compared to the fixed panel. In another article, the author employs a hybrid method of time and optical sensors. The tracker first detects the sun based on time and if the sensors recognizes a difference, the direction of tracking will be modified [22]. In a newer method, the tracking is based on the output power of PV and no optical sensor is used. The maximum produced power of solar panel is considered as a function of azimuth and altitude angles. The tracker tries to modify the tracking direction trough changing the angles [23]. Some articles also attempt to reduce the energy consumption. For instance, in [24], a dual-axis tracker is designed by auxiliary panel. Changes in the azimuth and altitude angles are tracked by a small panel and then, the main panel which is larger, detects optimally. In [25], the author designs and develops a dual-axis sun tracker which only one motor is used to reduce the energy consumption and increasing the efficiency in the tracking system.

In the fractional open-circuit voltage (FOCV) approach, an estimated relationship between open-circuit voltage and array voltage is used [26]. Like the P&O technique, this technique is low-cost and easy to implement. Because of using an estimated relation, the FOCV technique is not an exact MPPT. Neural network and fuzzy logic MPPTs have presented rapid satisfactory performance, but the difficulty of these techniques is the need for hardware and software [27-28].

Many papers have proposed optimization algorithms such as artificial bee colony [29], chicken swarm [30], PSO [31-32] and wind-driven optimization [33] as an MPPT controller. The accurate tracking of maximum power point (MPP) and slow convergence to the MPP can be mentioned as the main advantage and disadvantage of these methods, respectively. In several papers, neural network (NN) and fuzzy logic (FL) have been proposed as an MPPT [34-38].

In this paper, a fast-accurate technique is proposed for active dual-axis trackers. Compared with the previous works, the main contribution of this paper is using combination of P&O and neural network methods to track the sun quickly and accurately. The tracker detects the sun in shorter time and increases the efficiency. The light intensity at four optical sensors on the solar panels are measured as the input data. If the differences between input data are slight, the azimuth and altitude angles will be changed slowly and tracking is performed accurately by using P&O method. This case occurs when the sun position has an insignificant distance from the perpendicular axis of the panels. But, if the sun has a significant distance from the perpendicular axis of panels, the differences between sensors values will be greater than the adjustable boundary value. So the azimuth and altitude angles of sun, are estimated by the neural network and homogenous transformation matrix as the output data. In this case, the tracking is accomplished fast, but there is not enough accuracy. Obviously, tracking of the sun can be a combination of both cases. The Multi-Layer Perceptron (MLP) neural network is used and its training is performed in two steps. First, the error back propagation training method is adopted, and then the MPSO algorithm used to optimize network. The major contributions of this work are summarized as follows:

- A new fast method is proposed for active dual-axis trackers.
- Combination of P&O and neural network methods is used to track the sun quickly and accurately.
- The MLP neural network is proposed and its training is performed by MPSO algorithm to optimize network.

The rest of this paper is organized as follows. In Section II, the problem statement and preliminary knowledge are introduced. Section III discusses the solution algorithm. Numerical results are given in Section IV. And finally, the conclusions are given in Section V.

II. MODEL DESCRIPTION

The proposed method for MPPT consists of four main issues: PV panel, active dual-axis tracker, P&O algorithm, and the MPSO optimization technique. The following sections will describe each issue separately.

A. PV panel

Solar cell is a p-n junction semiconductor, with which characteristics similar to diodes. Fig.1 shows the equivalent circuit of solar cell where I_{PV} and V_{PV} are the output current and output voltage of the solar panel, respectively. I_{ph} is photo-current which is proportional to the solar irradiation. The electrical model is simplified by taking R_{sh} very large and R_s very small. The relation between the array terminal current and voltage is

$$V_{PV} = \frac{nKT}{q}\ln\left(\frac{I_{sc}}{I_{PV}}+1\right) \quad (1)$$

$$I_{PV} = I_{sc} - I_{PVO}\left[\exp\left(\frac{q\left(V_{PV}+I_{PV}R_S\right)}{nKT}\right)\right] - \frac{V_{PV}+R_S I_{PV}}{R_{sh}} \quad (2)$$

The photo-current can be expressed by

$$I_{ph} = \left(\frac{G}{G_n}\right)\left|I_{scr} + k_i(T-T_r)\right| \quad (3)$$

where: I_{sc} is light induced current (A), n is the diode ideality factor, K is Boltzmann constant, q is the electronic charge IPVO is saturation current (A), T is cell temperature (K), Tr is reference temperature (K), G is solar irradiance (W/m^2), G_n is reference irradiance (W/m^2), I_{scr} is short circuit current at reference condition, K_i is short circuit temperature coefficient and I_{sc} depends on the irradiance level *S* and on the array temperature *T*, while I_{PVO} and V_T depend on *T* only. The PV array current I_{PV} is a nonlinear function of the PV array voltage V_{PV}, of the irradiance level *S* and of the temperature *T*.

B. Single and Dual-axis Trackers

Solar trackers are grouped under two basic categories: the single-axis trackers and the dual-axis trackers. The single tracker rotates east to west following the sun's movement, and the dual trackers include vertical and horizontal movements i.e. they can incline or tilt to account for winter and summer sun angles. Single-Axis Trackers are trackers with only one degree through which they rotate or use as axis of rotation. This axis is usually aligned following the North meridian. They rotate azimuthally from east to west following the path of the sun. Double or Dual-Axis Trackers have two different degrees through which they use as axis of rotation. The dual-axis are usually at a normal of each rotate both east to west (zenithal), and north to south (azimuthally).

C. P&O Algorithm

The principle of P&O is perturbation by acting decrease or increase on the PWM duty cycle of boost converter and then observing the direction of change of PV output power. If at any instant j the output PV power P (j) & voltage V (j) be greater than the previous computed power P (j−1) & V (j-1), then the direction of perturbation is maintained otherwise it is reversed [3]. The flow chart of algorithm has 4 cases as shown:

When $P<0$ & $V(j)>V(j-1)$, this yields to $D(j+1)=D(j)-SD$
When $P<0$ & $V(j)<V(j-1)$, this yields to $D(j+1)=D(j)+SD$
When $P>0$ & $V(j)<V(j-1)$, this yields to $D(j+1)=D(j)-SD$
When $P>0$ & $V(j)<V(j-1)$, this yields to $D(j+1)=D(j)+SD$

where SD is chosen by trial and error simulation. A simulation of the P&O algorithm has been implemented in MATLAB.

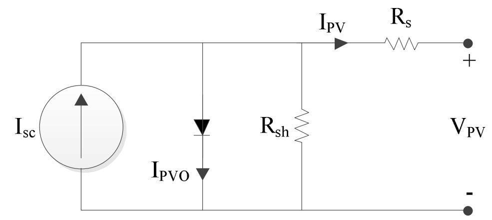

Fig. 1. Equivalent circuit of a solar cell.

D. Modified PSO

PSO algorithm originally suggested is based on the cooperative movement of birds and their effects on motion to reach the most optimum course. The PSO algorithm initializes with a set of the unanticipated solutions (particles) [39]. To find the optimum solution in the problem, span searches by updating generations. Each particle is defined multi-dimensionally by two values which are position and velocity of particles related to each dimension. In each step of population movement, each particle updates by two best values.

In this paper, a modified PSO algorithm based on the two new PSO like algorithms namely, the parameter-free PSO (pf-PSO) and the particle swarm optimization like algorithm via extrapolation (e-PSO) is proposed. In pf-PSO algorithm, the position of each particle is updated directly with the local best and global best particle positions and it does not have any velocity equation. In the e-PSO algorithm, the current particle position and the global best particle position are involved in the extrapolation operation.

To incorporate the merits of both the pf-PSO and e-PSO methods together into a single method, a modified PSO is proposed in this paper. The MPSO method first identifies a near optimal fitness solution and then produces a better solution with a faster convergence rate [2].

E. Analysis of the Proposed Solar Tracker

The maximum power point (MPP) of PV depends on several factors such as the sun radiation, temperature and load current. Therefore, several methods are used to optimize the performance of solar systems. One of these methods is using sun trackers to absorb the maximum light. The general schematic of the proposed system is shown in Fig.2.

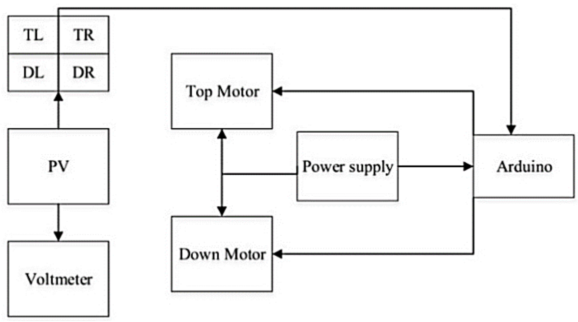

Fig. 2. Fig. 2: Schematic of proposed system

The Down Left (DL), Down Right (DR), Top Left (TL) and Top Right (TR) sensors measure the intensity of sunlight. The sun moving causes to change radiation angles. So, the sensors value change and the new azimuth and altitude angles are calculated by analyzing the new data according to the proposed algorithm. Finally, the panel is placed in front of the sun by sending the controlling signals to the up and down motors. Deh is the mean difference of sum of the left and right sensors. Dev is the mean difference of sum of the top and down. They are calculated as formulas (4) and (5). In the proposed algorithm, if Dev or Deh are greater than the boundary value, the coordination of the sun position relative to the moving plate will be considered as a function of intensities of radiated light on the four optical sensors as formulas (6-8).

$$Dev = \left(\frac{TL + TR}{2}\right) - \left(\frac{DR + DL}{2}\right) \quad (4)$$

$$Deh = \left(\frac{TL + DL}{2}\right) - \left(\frac{TR + DR}{2}\right) \quad (5)$$

$$x_0 = F(TL, TR, DL, DR) \quad (6)$$

$$y_0 = G(TL, TR, DL, DR) \quad (7)$$

$$z_0 = H(TL, TR, DL, DR) \quad (8)$$

The point $(x_0 \cdot y_0 \cdot z_0)$ is the coordination of the sun position relative to the moving plate. The functions F, G and H are unknown, and are estimated with neural network. Using these functions, the sun coordination is obtained relative to the moving plate. But to rotate motors, the sun position must be determined relative to the fixed plate. Hence, the homogenous transformation matrix is used to reflect the coordination on the fixed plate [20]. The position of the light source relative to the moving and fixed plates are shown in Fig 3.

III. The Proposed Algorithm

The Multi-Layer Perception (MLP) neural network is used, and the network consisting of three layers. The hidden layer's activation function is the tansig and the output layer's activation function is the purelin. In Fig. 4, the sun's images are shown relative to the axes of moving plate. As it can be seen, the image of sun's position in the positive half of x-axis corresponds to the TL and DL sensors and in the negative half of x-axis corresponds to the TR and DR sensors. For this reason, as shown in Fig. 5, the inputs of neural network are TR+DR and TL+DL values to obtain the x_0. Similarly, the neural network's inputs for computing y_0 are TL+TR and DL+DR values; sum of the four sensors TL+TR+DL+DR is used to estimate z_0. The neural network is trained by the error back propagation method and then optimized by the MPSO algorithm.

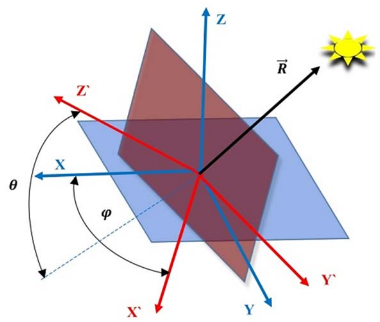

Fig. 3. The sun position relative to the rotating frame (red) and the fixed frame (blue)

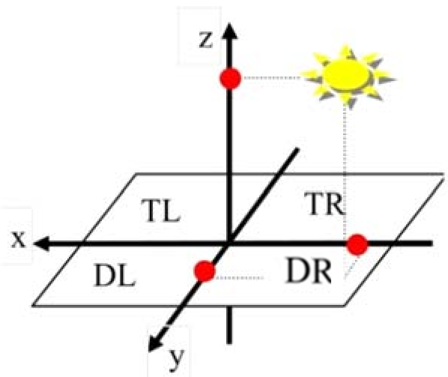

Fig. 4. The sun's images relative to the axes of moving plate

IV. Numerical Results and Discussions

Two scenarios were considered to test the proposed algorithm through MATLAB simulation. In each scenario, the light source and moving plate of the solar module were placed in a determined position and the tracking time and the sensors values were recorded and compared between the proposed algorithm and the presented method in [23] which was based on feedback from the produced power. The displacement of first scenario was along the azimuth angle (φ) and the second one was along the altitude (θ) angle. When the panel moved toward the light source, the values of all four optical sensors increased and when reached to equal value, the module was completely in front of the light source and the tracking was completed. In all scenarios the boundary value set to 135 unit and tolerance was 20 units.

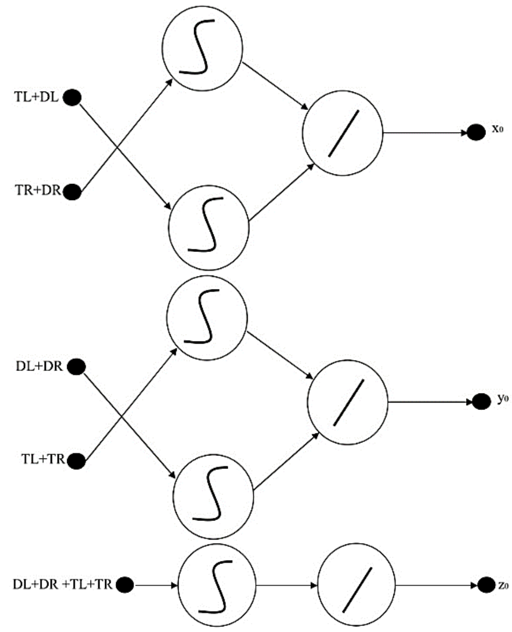

Fig. 5. Internal structure of neural network

A. Scenario 1

In this scenario, the light source was placed at the angles of $\varphi_{ref}(azimuth) = 150$ degree and $\theta_{ref}(altitude) = 20$ degree. The initial angles of solar panels were set at φ=20 degree and θ=20 degree. In the first test, the tracking was performed according to the proposed algorithm. The values of sensors were shown in Fig. 6 during the time.

The time of steady state of first test (944 ms) was less than the presented method in [23] (1664 ms). It was because of the using the neural network to determine the location of light source. It caused to jump at break point and reduce steps to move toward the target. Break point referred to the condition which the difference between the sum mean of the right sensors ($(TR+DR)/2$) and the left sensors ($(TL+DL)/2$) was more than boundary value. In the following, the tracker accurately moved toward the target by using the P&O algorithm. Finally, the solar panels were located in front of the light source. Since the tracking was accomplished step-to-step. So the tracker consumed more energy and had a weaker dynamic in tracking.

B. Scenario 2

In this part, the light source was placed at the angles of φ_{ref} =150 degree and θ_{ref}=90 degree. The initial position of panels was set at φ=150 degree and θ=20 degree. In the first case, the tracking was accomplished by the proposed algorithm and the values of sensor were recorded and shown in Fig. 7. The required time of proposed algorithm to reach the steady state (428 ms) was less than other method (850 ms) [23].

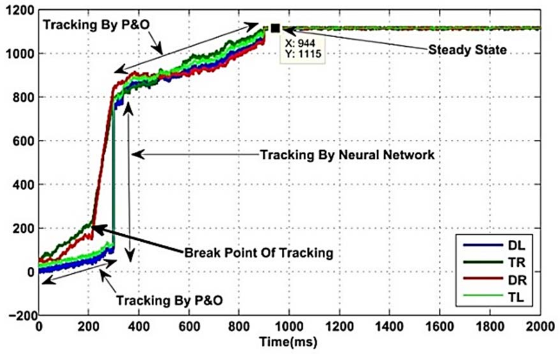

Fig. 6. Sensors' values in the first scenario, using the proposed algorithm

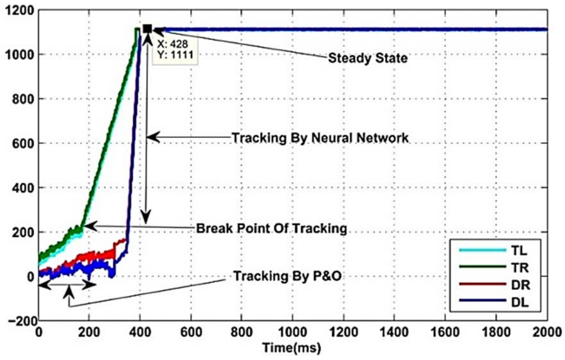

Fig. 7. Sensors' values in the second scenario, using the proposed algorithm

The tracking time of proposed method reduced 49% than other method. It was because of using the neural network to estimate the coordination of light source. Break point pointed to the condition which the difference between the sum average of the top sensors and the down sensors was more than boundary value which caused to jump in tracking. But second case took more time to reach the target point relative to the first test. In the TABLE I, the coordination of the initial point and the target point, tracking time and the values of sensors in the steady state were shown in the all two scenarios. The tracking time of proposed method compared with other technique in two scenarios, decreased 49% and 42% respectively. It was because of using the neural network to estimate the coordination of light source.

Therefore, the proposed technique had more saving of energy, better dynamic and increased efficiency. On the other hand, both methods had same accuracy because the total values of sensors approximately were equal in both methods at steady state.

TABLE I. RESULTS OF TWO SCENARIOS BASED ON PROPOSED METHOD

Case	Initial Coordinate (Degree) (φ,θ)	Target Coordinate (Degree) $(\varphi_{ref},\theta_{ref})$	Tracking Time (ms)	Total Values of sensors in steady state
Case 1	$(20,20)$	$(150,20)$	944	4460
Case 2	$(150,20)$	$(150,90)$	428	4444

V. CONCLUSION

In this paper, a fast- accurate method for controlling the dual-axis sun tracker which is a combination of MLP neural network and P&O algorithm, is presented. When the sun significantly deviates from the perpendicular axis of the solar panels, the difference in the values of optical sensors are greater than the boundary value. So, the coordination of the sun's position is estimated by MLP neural network and the tracker moves toward it fast. But there isn't enough accuracy. But if the sun's position slightly deviates from the axis perpendicular to the panels surface, the difference between the values of optical sensors will be less than the boundary value. So, in this case the panels move toward the sun accurately and gradually, by using the P&O algorithm. The tracking which can be the combination of both them is performed fast and accurately. So, the proposed method reduces the tracking time and reaches to more saved energy, increased efficiency and better dynamic.

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