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Original Article

ANN Optimized DA-STS Under Partial Shading Conditions

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Abstract *- Solar energy constitutes the primary source of energy within the universe. A variety of methodologies may be employed to effectively harness this energy. The deployment of solar panels is distinguished as a widely adopted and innovative method for the accumulation of this energy. When compared to stationary panels, rotating panels have demonstrated the capacity to produce greater energy outputs under certain circumstances, like partial shading conditions. Solar Tracking Systems (STS) are one of the main methods to track sun movement. The objective of STSs is to optimize energy production by orienting the load, typically solar panels, towards the sun. This is achieved by minimizing the angle of incidence between the incoming sunlight and the Photovoltaic (PV) panel, thereby enhancing the quantity of energy generated. The existing system, Grey Wolf Optimization (GWO) with Maximum Power Point Tracking (MPPT) method, yields a diminished amount of energy, resulting in a significant tracking error. To reduce the tracking error and enhance energy efficiency, the initially proposed method employing Particle Swarm Optimization (PSO) with Artificial Neural Networks (ANNs) has been implemented. This Neural Network (NN) mainly consists of an Adaptive Neuro-Fuzzy Inference System (ANFIS), which includes a workflow from data collection to deployment. This method generates better results than the existing one because of proper training, testing, and data implementation.*

Keywords *- ANN, PSO, Solar tracking systems, Solar energy, Partial shading conditions, Photovoltaic, Optimization.*

1. Introduction

Solar energy, as a renewable power source deriving from the sun as solar rays [1], is currently the subject of various research endeavors aimed at evaluating its significance for the future well-being of humanity, irradiance and exploring methods to enhance the amount of energy harnessed from the sun. A particular method employed for collecting solar energy and converting solar beams into electric energy is the utilization of a solar PV system[2]. The primary categories of solar PV panels, as per their ability to move, are fixed and tracking panels. Sun tracking technologies refer to mechanisms capable of following the sun's movement across the sky to optimize the photovoltaic panels' angles for peak electricity production, thus increasing energy yield. In comparison to fixed solar photovoltaics, sun trackers can increase exposure to direct sun rays. Depending on the axes' utilization while tracking the sun, solar tracking systems can be classified as single/dual-axis sun trackers. A single-axis solar tracker is a directional device capable of moving both vertically and horizontally [3], while dual-axis tracking systems can move both directions horizontally and vertically simultaneously [4]. The adjustment of the solar photovoltaic tilt angle ensures that the sun is intent on the tracking surface, thereby reducing the angle of intact between the beam reflector and the ground. The enhancement of solar tracking technology remains a prominent area of research interest, with efforts focused on improving the effectiveness of tracking devices through various control techniques [5]. The choice of appropriate controllers for operating solar tracking devices is crucial, with either manually operated or continuously operated regulators being two available options for effectively positioning the devices. Additionally, a range of programmable controllers, such as microcontrollers, motors, electrical circuitry, technical methods or Artificial Intelligence (AI) implementations, can be added to enhance tracking device performance [6].

The effectiveness of these controlling mechanisms varies according to the specific approach employed, with the primary objective being the optimization of solar tracking devices' efficiency. Consequently, there is a growing global interest in selecting good actuators and thereby enhancing available procedures to further advance solar tracking technology [7].

ANN methodologies have experienced substantial development over the past twenty years due to their extensive application in various domains, such as image interpretation, data manipulation, speech identification, sophisticated regulatory frameworks, meteorological forecasting, agricultural practices, comprehensive healthcare services, geotechnical projects, among others [8, 9].

Numerous scholarly publications extensively examine the utilization of ANNs technique for forecasting solar energy production based on a variety of atmospheric and geographical factors. Consequently, it is logical to fine-tune the variables of ANNs (such as synaptic connection weights) in order to enhance the accuracy of predictions. Within this context, a range of investigations have effectively employed genetic algorithms [10], Artificial Bee Colony (ABC) optimization [11], Artificial Ant Colony (AAC) method [12], Firefly algorithm [13], and various other optimization techniques to optimize the synaptic weights and biases of ANNs for enhancing overall predication performance [14].

The principal objective of this working endeavor is to formulate an innovative hybrid prediction mechanism by integrating the DA-STS methodology with ANN and two proposed hidden layers. The initial layer is designated to be responsible for selecting data inputs predicated upon diurnal and nocturnal distinctions, whereas the subsequent layer is charged with the automatic evaluation of the relevance of the inputs. The foremost intention of the suggested model is to employ real-time forecasting for the analysis of hourly energy output from four dual-axis solar monitors. The primary contribution of this manuscript can be succinctly encapsulated as follows:

- A novel hybrid ANN-based technique on the DA-STS is suggested to enhance prediction accuracy.
- To address the challenge of predicting volatility in solar energy production during nocturnal hours, it is advisable to implement an innovative Selective Layer (SL) that is contingent upon the differentiation between daytime and nighttime.
- In an endeavor to augment the efficacy of the labor-intensive and prolonged process of manually discerning the most needed sources for the predetermined framework, an innovative automatic signal relevancy determination selective layer has been instituted. This layer is predicated upon the softmax activation operations and the DA-STS methodology.
- A PSO framework is utilized to optimize the efficiency of solar panels' energy production.
- The proposed model integrates additional climatic factors and time-related variables to effectively assess the power output of four DA-ST configurations in practical scenarios.

The subsequent sections present a detailed outline of the research. In Section 2, the history of solar tracking systems and their implications are delineated. Section 3 delineates the DA-STS, which utilizes a hybrid framework that integrates ANN with PSO. Analysis of the software and outcomes are elaborated on in Section 4, while Section 5 gives a comprehensive discussion of the conclusions and discoveries of the suggested DA-STS.

2. Background to the Solar Tracking Systems and their Impact

Light Dependent Resistor (LDR) sensors serve as one of the neediest components of the monitoring system, which has been developed as a closed-loop management-focused active monitoring framework as delineated by Jamroen et al. [15]. The integration of these sensors within a pseudoazimuthal technological framework characterized by an architecture is employed in the tracking methodology to facilitate seamless rotation about the primary (north-south) and secondary (east-west) axes. The suggested tracking methodology and the static flat-plate approach were subjected to evaluation in the study for the purpose of conducting a direct comparison. Based on the results and the evaluation, the implementation of the system design, as opposed to the traditional flat-plate method, resulted in an enhancement of electrical power efficiency by an average of 44.89%.

Systems designed for the monitoring of solar positioning, which relies on sensor technology, demand meticulous installations and frequent calibrations, as demonstrated by Chowdhury et al. [16], are incapable of accurately determining the solar position during overcast or variable weather conditions. In contrast, methodologies for determining solar position establish the sun's location at a specified site and moment through the application of quantitative equations or astronomical data. The methodological approach delineated in the Astronomical Almanac (AA) was selected due to its effectiveness in determining solar positions, coupled with its accessibility and reliability. According to the results obtained, a sun monitoring apparatus that integrates the solar position methodology exhibits superior performance compared to a fixed technique and an optical monitoring approach, with enhancements of 13.9% and 2.1%, respectively.

This manuscript presents an innovative methodology for solar monitoring apparatus. Carballo et al. [17]. have formulated a novel strategy that harnesses economical, open-source computer vision apparatus and learning algorithms in response to the fiscal and operational constraints of the existing system. The encouraging preliminary trials conducted at a Platform called PSA demonstrate the considerable potential of the new methodology and establish it as a possible alternative solution to conventional systems. Through the adoption of the proposed approach, the control mechanisms and efficiency of the Sun monitoring device are enhanced by critical factors such as solar trajectory prediction, obstruction and shadow/shading area detection, environmental parameter attenuation, and measurement of concentrated solar power irradiance.

An exemplary technological innovation is represented by Solar Photovoltaic Blinds (SPB), which exhibit the dual function of inhibiting solar radiation from infiltrating an environment while simultaneously generating electrical energy. Kang et al. [18] undertook an extensive examination of the techno-economic viability of the intelligent SPB, considering the specific variety of Photovoltaic (PV) panels employed and the sun-tracking technologies applied to enhance the efficiency of SPB utilization. The intelligent SPB developed during this study was utilized in the experimental procedures, and the resultant data were employed to conduct a thorough assessment of the techno-economic parameters.

A meticulous analysis of the experimental findings revealed that (i) monocrystalline silicon PV panels delivered a power output that was 35.5% superior to that of amorphous silicon PV panels at a comparable cost, and (ii) direct sun tracking systems generated 12.9% more power than their intermediate sun tracking alternatives. The increased angle of incident sunlight results in diminished solar exposure, leading to an inability to effectively capture solar rays due to the fixed orientation of the solar array. This static positioning hinders optimal power generation as the sun traverses across the sky throughout the day. To address this constraint, Gurulakshmi et al. devised a Sun Tracking System (STS) that employs existing data to monitor the solar trajectory and adjust the solar panels accordingly to maximize electricity generation [19]. Furthermore, to guarantee the efficient utilization of energy produced by solar panels, a maximum power point tracking (MPPT) microcontroller has been adopted to sustain peak power output.

In the pursuit of advancing solar-driven water purification methodologies, Singh et al. have pioneered a Super-Wicking and Super-Light-Absorbing (SWSA) aluminum material [20]. This material exhibits a superior evaporation rate relative to an optimal device functioning at 90% efficiency, a phenomenon attributed to the reduced enthalpy of combustion within microcapillary structures. By minimizing the direct interface between the solar absorber and the aqueous phase, the thermal transfer to the bulk liquid is diminished, thereby facilitating localized heating at the SWSA interface. The strategic installation of the apparatus on a mobile platform, adjustable at various angles, enhances the exposure to solar irradiance, thereby facilitating seamless integration with industrial solar energy systems. The research underscores a remarkable 150% improvement in efficiency compared to single-sided SWSA configurations akin to bifacial photovoltaic solar arrays.

A detailed review of MPPT techniques for PV technologies, categorized into eight types, is presented by Podder et al. [21]. The categorization is predicated upon particular monitoring attributes inherent to these methodologies. A salient feature of this investigation is its concentration on fundamental characteristics and a comprehensive set of eleven criteria for the selection of methods, which have not been collectively examined in antecedent research. The thorough juxtaposition of merits, demerits, and classification delineated in this study may function as a significant reference point for prospective scholarly inquiries within this domain.

Kamadinata et al. propose two ANN approaches for predicting global longitudinal irradiance from sky to earth within 1 to 5 minutes [22]. The utilization of identification techniques is deemed unnecessary for these methods. In contrast to existing methods, which rely on cloud-based detection through visual information in sky images, the suggested approaches utilize color characteristics from a limited number of data points in the images. Despite minor differences, these approaches can effectively capture the variations in solar radiation patterns.

Gupta et al. investigate the MPPT methodology for PV systems using innovative circuits and analyze adjustable step size selection methods [23]. Within Matlab/Simulink, two separate variable step size techniques, the gamma scaling method and the delta P/delta V (Dp/Dv) method, have been developed. These scaling methods yield comprehensive results, which are subsequently assessed. When the PV array is subjected to sudden irradiation of 1000 W/m2, the suggested gamma-scaling method demonstrates superior efficiency with reduced peak-to-peak power fluctuations compared to DpDv.

Liu et al. propose an innovative MPPT control strategy for Solar PV Power Systems (SPPS) [24]. Traditional MPPT methods, like the perturbation and observation method, often struggle to attain the Maximum Power Point (MPP) under low light conditions and various shading scenarios, leading to decreased SPPS power output. The suggested system integrates multiple 430W PV solar modules linked to a boost inverter and an MPPT technology used control system. In order to tackle this particular challenge, a monitoring strategy for Maximum Power Point Tracking (MPPT) utilizing light waveguide differential techniques has been developed. This pioneering methodology is predicated on the assessment of variations in the optical system's angular position. The importance of this research is underscored by its ability to attain elevated Solar Photovoltaic Power System (SPPS) efficiency through the proposed MPPT control strategy, all while maintaining the existing physical circuit configuration and obviating the need for supplementary solar power measurement apparatus, thus facilitating reductions in both system costs and complexity.

The employment of intelligent systems with ANFIS algorithms for solar tracking and optimal angle forecasting has, to the best of the authors' knowledge, not been previously reported in the literature. Conversely, existing models primarily focus on forecasting either the peak power point or the levels of solar irradiance.

3. Proposed Dual-Axis Solar Tracking System

The focus of solar rays is optimized by directing sunlight onto PV panels to enhance solar energy absorption. Throughout the day, PV modules receive varying levels of sunlight, leading to fluctuations in irradiance on the panel surface. To maximize irradiation, sunlight should be orthogonal to the PV module area. The focus of this design is to develop a monitoring system using the pseudo-azimuthal method to track the sun's movement. The monitoring system consists of mechanical and electrical components, with rotational axes that aid in identifying mechanical vibrations. The electrical system includes electronic and microprocessor capabilities to monitor sunlight incidents on the Photovoltaic modules.

A novel methodology for DA-STS utilizing ANN is proposed to enhance both the convergence velocity and predictive precision of conventional ANN frameworks. The DA-STS technique, incorporating a proficient optimization strategy, is integrated with ANN deep learning methodologies within an innovative structural paradigm. In order to mitigate the variability associated with solar energy production during nocturnal hours, a Selecting Layer (SL) is introduced for data selection pertinent to daytime and nighttime conditions. The Automated Inputs Relevance Determinations (AIRD) systematically discern the most pertinent input variables to ensure precise forecasting.

The depiction of the proposed DA-STS system's workflow can be observed in Figure 1. Data input undergoes a process of collection, normalization, and selection of pertinent input. Subsequently, the ANN model is subjected to training and testing in order to analyse the Mean Square Error (MSE). A condition is then evaluated to determine if the specified threshold has been met; if not, the PSO method is employed to enhance the outcomes. Results surpassing the threshold are subsequently adjusted.

4. Particle Swarm Optimization

The PSO algorithmic method is a meta-heuristic optimization technique that is inspired by the increasing intelligence and cooperative behaviors observed in societies with structured populations. It is an evolutionary algorithm that aims to generate the optimal solution to a problem by leveraging a pool of potential solutions.

The fitness value is used to evaluate the optimization level of each candidate solution. The particles constituting the population are distributed across the search space of the problem, with the behavior of the swarm being influenced by the perspective of an individual particle.

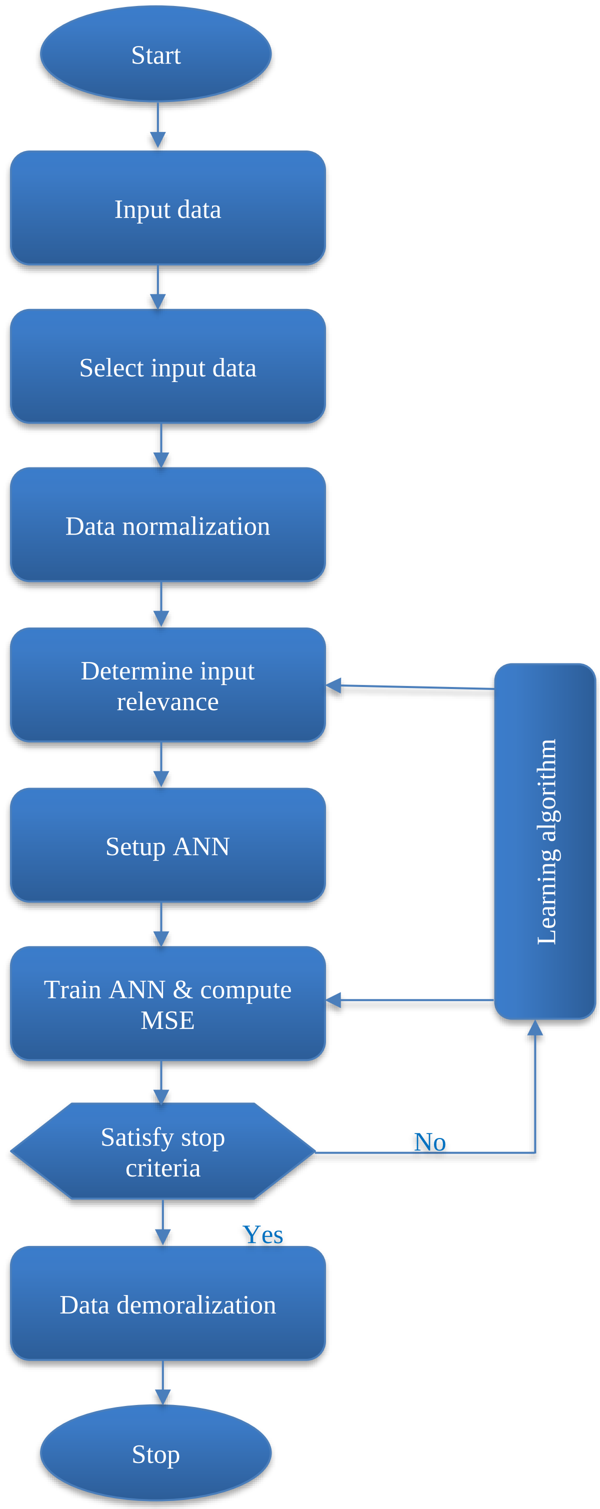

Fig. 1 Process flow of the proposed DA-STS System

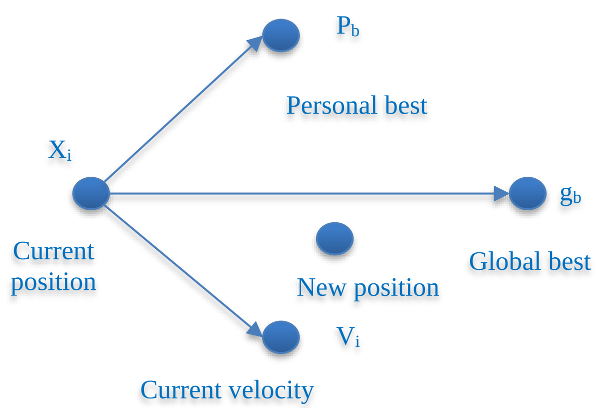

Fig. 2 The PSO-based position updating algorithm

At the commencement of the procedure, swarms are uniformly distributed across the search domain. The trajectory of a particle is affected by three principal elements: the inertia factor, the cognitive factor, and the social factor.

- The inertia component of the particle exhibits a proclivity to adhere to the path dictated by its existing momentum.
- The cognitive component cc_1: the particle endeavors to pursue the pinnacle of excellence.
- The social component cc_2: the particle demonstrates a preference for advancing towards the optimal standard achieved collectively by the entirety of the swarm.

The algorithm based on PSO for the purpose of updating positions is depicted in Figure 2. The movement of a particle from its existing position to a new location is governed by its velocity and orientation. Optimal results are sought by utilizing both individual and global best values. As per Equations (1) and (2), the particle transitions between iterations t and t + 1, with Equation (1) representing its velocity and Equation (2) indicating the distance travelled from the present position.

$$\mathrm{v_y(t+1) = wv_y(t) + cc_1rn_1\left(p_{by}(t)\text{-}d_y(t)\right) + cc_2rn_2\left(g_b(t)\text{-}d_y(t)\right)} \quad (1)$$

$$(t+1) = d_y(t) + v_y(t+1) \quad (2)$$

cc_1 and cc_2 are two parameters that signify the factors contributing to acceleration; depending on the optimization problem at hand, these parameters may not remain constant. rn_1 and rn_2 are two stochastic variables selected randomly from the interval [0, 1]. The velocity is represented by $v_y(t)$, and the particle weight updating factor is denoted by w. The global optimal value is represented by $g_b(t)$, while the local optimal value is denoted by $p_{by}(t)$.

The fundamental tenet of the PSO methodology initiates with the stochastic initialization of particles within the search domain, designating them with initial coordinates and velocities. The fitness metrics of the particles are assessed to ascertain the optimal positions of P and the cumulative swarm's 96 constituents in every iteration. The updating process persists until the termination criteria are satisfied. In the search process of the PSO system, two distinct phases are discerned: exploration and exploitation. The former serves to identify the most promising regions within the search space, while the latter is responsible for guiding particles towards the optimal solution discovered.

Equation (3) delineates the revised PSO velocity and position equations predicated upon the novel PSO attribute, while the amended distance value is explained in Equation (4).

$$v_y(t+1) = wvy(t) + cc_1rn_1\left(p_{b_y}(t) - d_y(t)\right) + cc_2rn_2\left(g_b(t) - d_y(t)\right) + m_k(q)cc_3rn_3\sum_{i=0}^{N}\propto_i\left(p_{b_y}(t-i) - dy(t)\right) + m_l(q)cc_4rn_4\sum_{i=0}^{N}\propto_i\left(g_b(t-i) - d_y(t)\right) \quad (3)$$

$$d_y(t+1) = d_y(t) + v_y(t+1) \quad (4)$$

Where cc_3 and cc_4 are the factors facilitating acceleration for disseminated temporal components, and t denotes the current iteration number. They are chosen uniformly to cc_1 and cc_2 respectively. N represents the maximum limit of the time-delay components $\propto(t)$, and the expressions (t) and rn_i (i = 1,2,3,4) formulate an N-dimensional vector consisting of stochastic components featuring values of either 0 or 1.

$$md_i = \frac{1}{P_s-1}\sum_{j=0}^{P_s}\sqrt{\sum_{t=0}^{D} d_{it}^{\ 2} - d_{jt}^{\ 2}} \quad (5)$$

The term P_s represents the magnitude of the swarm population, while D signifies the dimensions of the particles. The squared distance between the initial position and the revised position is represented $d_{it}^{\ 2} and\ d_{jt}^{\ 2}$. The study aims to ascertain the evolutionary component EV_f through md_i computational methods. The evolutionary vector is articulated in Equation (6).

$$EV_f = \frac{md_k - md_{min}}{md_{max} - md_{min}} \quad (6)$$

Whereas md_{max} and md_{min} signify the maximum and minimum extent of md_i within the swarms, respectively, md_k represents the globally optimal particle separation among mdi. The four developmental phases q(t) may be categorized into the following classifications based on the variables of EV_f as articulated in Equation (7).

$$q(t) = \begin{cases} 1 & 0 \le EV_f < 0.25 \\ 2 & 0.25 \le EV_f < 0.5 \\ 3 & 0.5 \le EV_f < 0.75 \\ 4 & 0.75 \le EV_f < 1 \end{cases} \quad (7)$$

5. Artificial Neural Network

A sophisticated deep-learning technique known as an ANN demonstrates various architectures, including feed-forward neural networks, Convolutional Neural Networks (CNN), and Recurrent Neural Networks (RNN). Each configuration proves advantageous within specific circumstances. The basic architecture of the ANN, comprising a single hidden layer, consists of interconnected neurons distributed across three consecutive layers. The architectural design of the ANN is illustrated in Figure 3. The initial layer, referred to as the input layer, merely disseminates its inputs to all the neurons in the subsequent layer, designated as the hidden units, without engaging in any computations. The formal depiction of the brain in Figure 4 delineates each synapse within the hidden layer, which receives inputs from the input tier, influenced by their respective parameters. The output efficiency of the trained ANFIS is recorded for analysis. Monitoring techniques were employed to assess the efficacy of the connection. A novel dataset was utilized during testing to assess the operational efficiency of the developed model. The efficiency attained by the ANFIS system was duly documented.

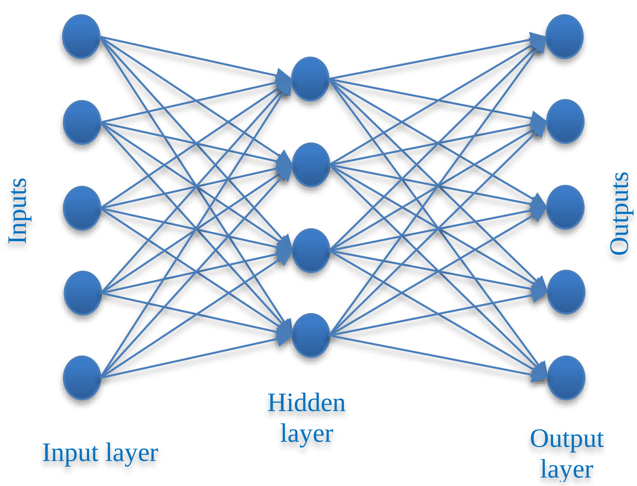

Fig. 3 The artificial neural network architecture

4 Simulation Results and Discussion

The results and justification underlying the proposed dual-axis sun tracking processors are elaborated upon distinctly in this section. An authentic mechanical solar tracking prototype, operated manually, was devised and employed to gather diverse parameters in order to fulfill the objectives of the developed solar tracking systems. The evaluation of solar power generation through the advised DA-STS is scrutinized, and the results are depicted in Figure 5.

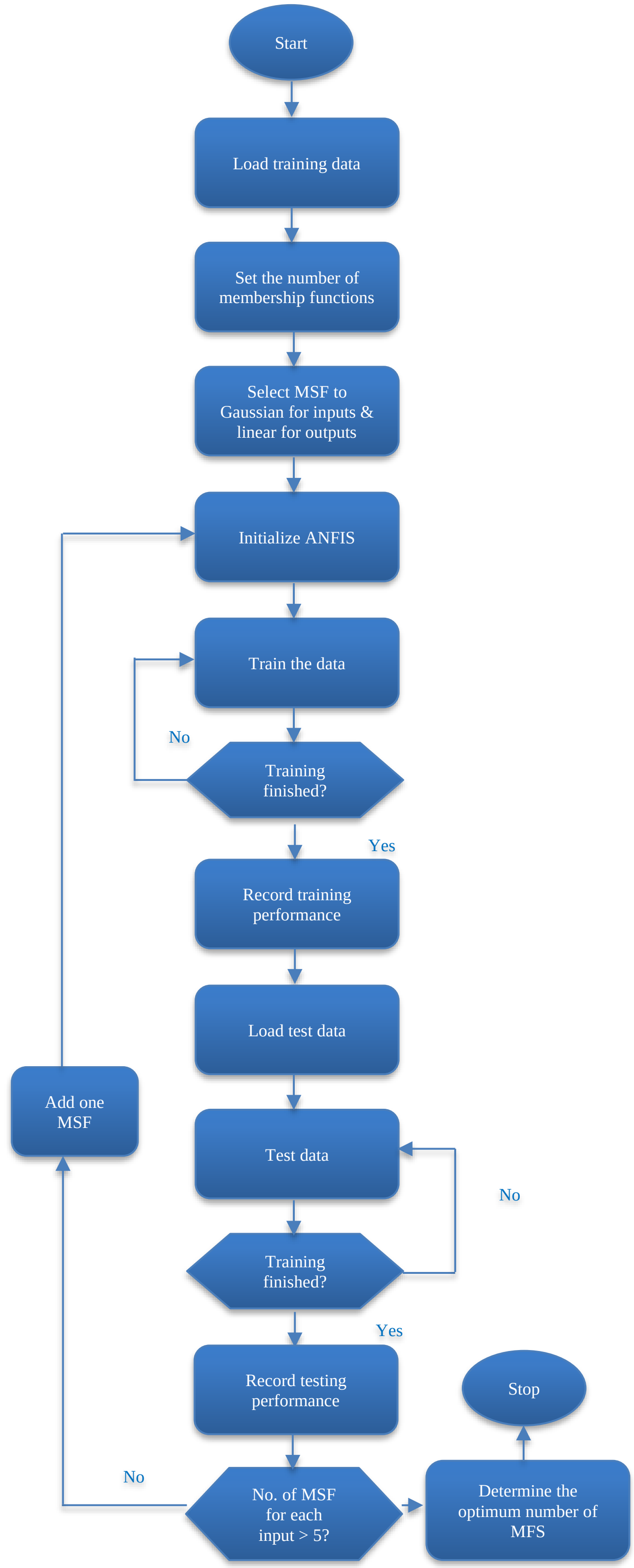

Fig. 4 ANFIS work process

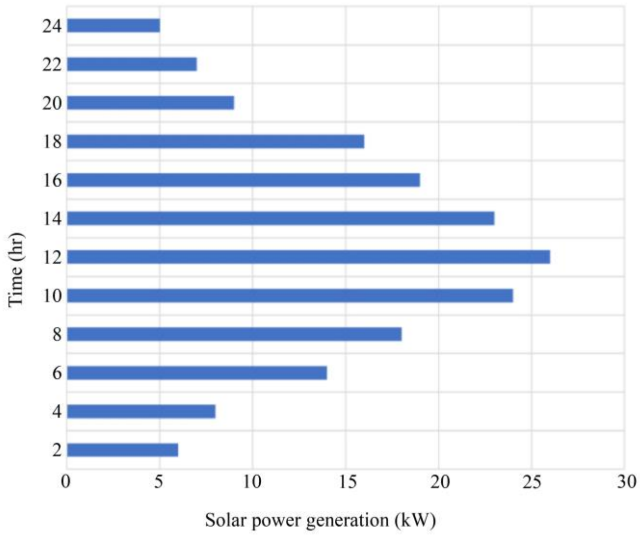

Fig. 5 Solar power generation analysis

The solar energy produced by the solar panel under the control of the dual-axis solar tracker is consistently monitored over 24 hours. The outcomes reveal peak power generation at midday, with a subsequent decline in power generation as night approaches. The proposed DA-STS mechanism boosts power generation through optimized outcomes and photovoltaic alignment utilizing the PSO algorithm.

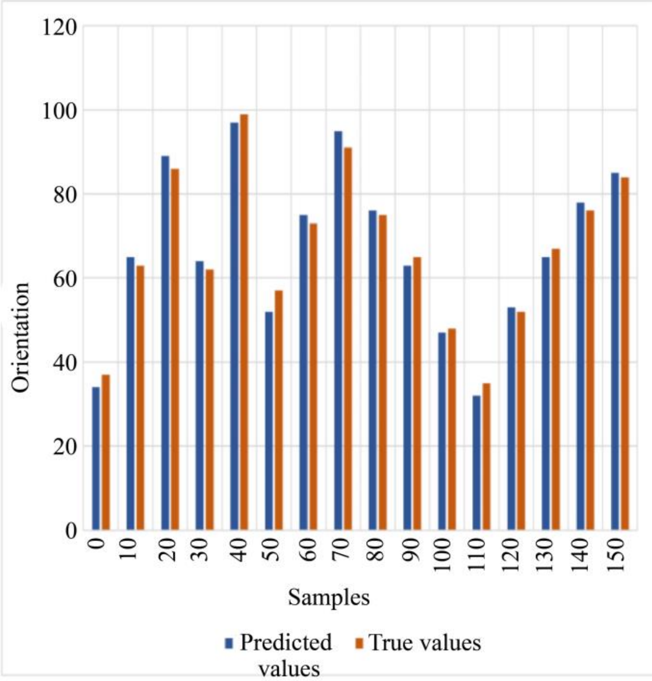

Fig. 6 Orientation analysis of the suggested DA-STS

The examination of the proposed DA-STS system's orientation analysis is conducted on the anticipated and authentic values of the Photovoltaic (PV) panels, as illustrated in Figure 6. Variation in sample count is implemented from 0 to 150, incrementing by 10 samples for the analysis. Utilizing the PSO model, the orientation of the solar panels is forecasted, and a comparison is made with the actual orientation. The findings demonstrate minimal discrepancy between the predicted and actual values.

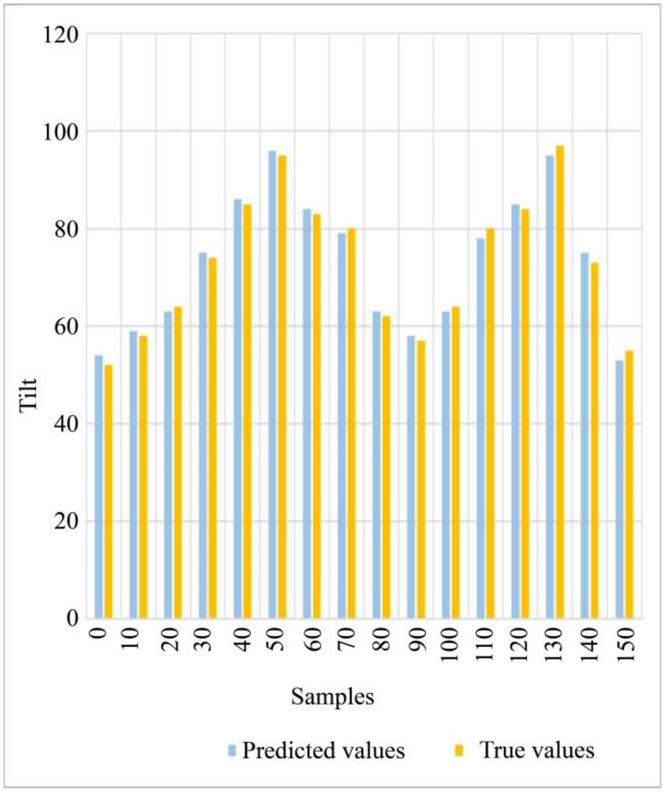

Fig. 7 Tilt analysis of the proposed DA-STS system

The most favorable results are attained through the utilization of an ANN for the training of models, PSO for the enhancement of outcomes, and ANFIS for the facilitation of the computational procedure. An examination of the tilt within the proposed DA-STS is performed, and a juxtaposition of the actual versus predicted tilt values of the solar panels is depicted in Figure 7.

The sample set spans from 0 to 150, comprising 10 samples for each iteration. The fluctuations in the tilt of the solar panels contribute to an augmentation in power generation.

The precise alignment of the solar panels at a designated angle is essential for optimizing energy production from Photovoltaic (PV) panels. The amalgamation of ANN, PSO, and ANFIS models within the proposed DA-STS system significantly bolsters prediction accuracy, leading to an enhancement in power output. The evaluation of the solar panels' tilt angle and orientation prediction accuracy is performed, and the outcomes are displayed in Figure 8. This provides a conclusive insight into the study based on the parameters of tilt angle and orientation.

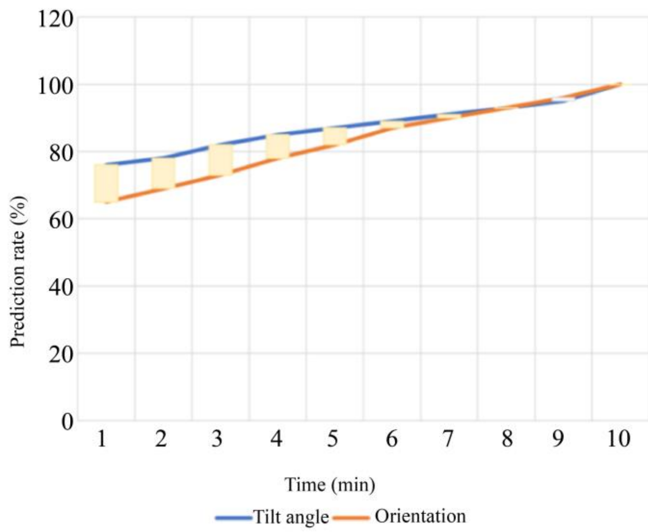

Fig. 8 Prediction rate analysis

The Greywolf optimization and PSO + ANFIS (Proposed method) simulation results will give the exact comparison, as in Figure 9.

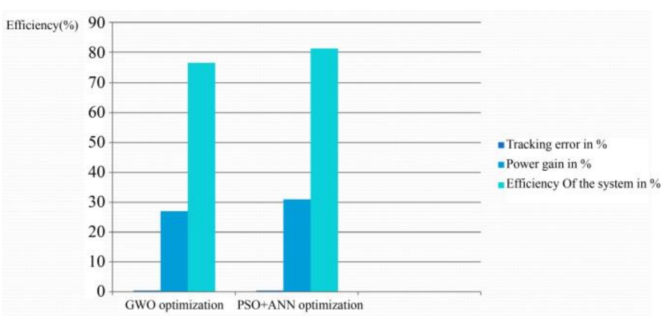

Fig. 9 Comparison of existing with proposed system results

5. Conclusion and Findings

In the present research, a unique combination of an ANN and ANFIS integrated with PSO has been established to create a pioneering Dual-Axis Solar Tracker System (DA-STS) technique aimed at forecasting the energy output of four distinct DA-STS. The effectiveness of the proposed model has been confirmed and assessed through the utilization of hourly data pertaining to seven meteorological parameters collected during the years 2022 and 2023 in Alice Springs, Australia.

To address the rapid fluctuations encountered in overnight energy forecasting, the DA-STS system is composed of two innovative hidden layers; the initial layer functions as a selection layer based on distinguishing features between daytime and nighttime. The subsequent layer, referred to as the Adaptive Importance Ranking Layer (AIRD), is utilized to accentuate the most pertinent signals for accurate forecasting by ascertaining the significance level of each input to the system.

The findings illustrate the proficiency of the DA-STS system in training the proposed model to reliably forecast the hourly energy output of the four DA-STS structures utilizing various statistical metrics (Mean Squared Error, prediction rate), in addition to a range of quantitative visualizations, thereby demonstrating the substantial effectiveness of these layers in conjunction with ANN architectures. The satellite solar panels have the potential to leverage this concept for the consistent harnessing of energy from the Sun at any given time. Future research pertaining to applications in renewable energy will focus on two principal domains: (1) the development of a multi-output fuzzified system-based meta-heuristic approach and (2) the proposal of alternative methodologies to accelerate the advancement of the DA-STS system.

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