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Energy Management Control of an Autonomous Hybrid System Based on ANN and Golden Jackel Algorithm

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Abstract: This study presents a self-sufficient hybrid solar and wind energy system to community area that the utility grid may have difficulty providing. This system, merging solar panels and a wind turbine with batteries for energy storage, employs an artificial neural network (ANN) and proportional-integral (PI) controller to track the maximum power point under varying weather conditions. The ANN makes the system more efficient with less energy losses, while the control system's accuracy is improved by the PI controller, enhanced by the golden jackal optimization algorithm (GJO) to get the best parameters for optimal performance. The results are compared with the particle swarm optimization (PSO) algorithm. The proposed system is designed using HOMER software, and the system simulations are implemented using the MATLAB/Simulink package.

Keywords: Hybrid PV/Wind, Artificial Neural Network, Maximum Power Point Tracking, Golden Jackel Optimization algorithm

1. INTRODUCTION

Escalating energy needs stem from population expansion, economic progress, and elevated living standards. Reliance on finite resources like oil, coal, and gas persists. Scientists strive to uncover sustainable alternatives and develop algorithms to

bolster renewable energy performance, mitigating weather-related power disruptions.

In [1], the authors presented the design framework for a standard hybrid renewable energy system (HRES) that integrates solar and wind energy, employing pumped hydro storage (PHS) as an energy storage system (ESS). The system analysis based on the levelized cost of energy (LCOE) and net present cost (NPC) to optimize different systems components using HOMER Pro. In [2], a method rooted in a multi-criteria assessment. The setup predominantly utilized wind and solar technologies, complemented by a pumped storage hydro system (PSHS), integrating these three technologies to achieve a harmonious and balanced operation. This hybrid system was

capable of both generating and storing electrical power. In [4], a hybrid energy system comprising solar PV, a fuel cell, a diesel generator, and a battery designed for a remote area in the UAE, simulated using HOMER Pro. In [5], a methodology was presented for optimal design of diesel/PV/wind/battery HRES for the electrification of residential buildings in remote areas. In [6], A study concentrated on assessing the technical feasibility and economic viability of an optimised HRES for providing electricity to Edem Urua, an off-grid rural community situated in the southern region of Nigeria. In [7], the study focused on developing a cost-effective, sustainable hybrid energy system for remote communities, combining wind and solar energy to balance economic, environmental, and security goals. This model supports Egypt's 2030 development plan and aims to make remote communities self-sufficient in energy and food production. In [8], The study designed an optimal HRES for a rural village in India, using solar PV, wind, diesel, batteries, and hydrogen storage. Optimized with HOMER Software, the system focuses on minimizing costs and maximizing renewable energy usage, with solar energy as the primary source. Sensitivity analysis highlights the system's efficiency under varying conditions. In [9], The research examined a wind/diesel/battery system for home use in South Sinai, Egypt, assessing economic viability and CO_2 reduction. Using HOMER software, the cost per kWh ranges from 0.221$ to 0.285$. Wind turbines have a significant impact on system performance, and CO_2 reduction models perform better in the Western Desert.

In [10], a techno-economic analysis of a hybrid wind-solar system was implemented for powering a water-pumping unit intended for small-scale irrigation. They utilized data from twelve locations in Sudan to estimate the water requirements for crops. For the techno-economic evaluation of various configurations, HOMER Pro software was employed. Given the greater expense and technical difficulties associated with wind turbines, alongside the simpler installation and maintenance of solar PV. Solar PV is deemed more favorable for such applications compared to the combination of wind and solar. In [11], an investigation was made into the techno-economic and environmental viability of deploying hybrid power installations, encompassing wind turbines, photovoltaic (PV) panels, diesel generators, and batteries, aimed at electrifying off-grid industrial and residential zones across various climatic areas in Spain. The optimal setup for such applications, incorporating PV, wind, diesel, and battery in a hybrid system, was identified for multiple locations within the country. One particular area displayed the least efficiency for these initiatives due to the highest cost of energy (COE) and NPC values. In the majority of locations, the recommendation was to opt for hybrid systems for most components.

In [12], HRES was examined, highlighting their potential and the need for further optimization to improve efficiency. It suggests that HRES can enhance the reliability of renewable energy and support its integration with the primary power grid, offering benefits for remote locations, including applications in water supply, desalination, and rainwater collection. In [13], the authors reviewed and analyzed data from 38 articles (2018-2023) on hybrid renewable energy systems, concluding they offer a viable power grid solution. The study highlights HRES trends and organizes information for specific reader interests.

In [14], the PV design perturb and observe (P&O) MPPT technique was presented to extract the maximum power from the PV. Using this technique with the boost converter, MPP (Maximum Power Point) was tracked at an efficiency reached to 99%. However, some fluctuations have been observed in the PV system's voltage, current, and output power. In [15], an MPPT technique was introduced that utilized the P&O algorithm with a multi-input DC/DC converter to optimize the power output from hybrid solar and wind turbine systems. The method showed promising performance, though some variations in the system's output voltage and power were observed. In [16], An ANN algorithm managed the system, with a PI controller smoothing its operation to ensure optimal MPPT working conditions. In [17], an efficient MPPT was presented for PV modules. The MPPT technique combines a backstepping controller and ANN. The Single Ended Primary Inductor Converter (SEPIC) has been employed to reduce the current ripple. In [18], the authors demonstrated an MPPT using an optimized multi-layer perceptron. Successful convergence to the desired output was achieved using the Levenberg-Marquardt algorithm. In [19], an improved MPPT method was introduced for wind turbines,

merging ANN and fuzzy logic to outperform the P&O approach in power extraction. In [20], a hybrid system was introduced merging photovoltaic and wind energy, proposing a new MPPT method for the PV/WT setup based on neural networks and fuzzy logic. In [21], a study was showed proposing an ANN-based MPPT (ANN-MPPT) for photovoltaic systems with a boost converter, comparing it to the Incremental Inductance with ANN (INC-ANN) method.

In [22], a control strategy was proposed for a Hybrid Micro Grid System (HMGS) integrating PV, wind turbines, diesel generators, and battery storage to

deliver consistent energy under various conditions. They used Multi-Objective Particle Swarm Optimization (MOPSO) to determine the optimal system composition and component sizing. In [23], a novel population-based optimization algorithm inspired by the hunting strategy of Golden Jackals was introduced. The results showed that, the GJO achieved very competitive outcomes compared to well-known meta-heuristics.

This paper explores powering remote community loads with a hybrid solar wind energy system and battery storage. Utilizing ANN, the system ensures optimal operation at the maximum power point. Control is maintained via a PI controller and optimized using the GJO algorithm to achieve ideal gains.

The primary objectives of this paper encompass:

- Design a HRES in isolated regions to generate electrical power for these regions.
- Propose an adaptive algorithm to optimize HRES.
- Use the GJO in the proposed system to obtain the optimal controller gains to reduce the oscillations and overshoot of the system output powers.
- Control the system to be more stable with any change in weather conditions surrounding the system.
- Extract the maximum possible electrical energy from renewable energy sources using artificial intelligence methods to raise the system’s efficiency.

The remainder of the paper is organized as follows:

The fundamental HRES explanation, information on the project location, load profile of the community load, and its energy sources are shown in section 2. The components of

the proposed model of a hybrid PV/Wind system with a battery as a potential storage system are shown in section 3. DC-link voltage control, the proposed MPPT which is used to track the maximum power point of hybrid PV/Wind system based on ANN algorithm with PI controller, and optimization techniques are shown in section 4. In section V,
simulation results with analysis are presented and explained. In section 5, the summary of concluded points is shown.

2. Hybrid Renewable Energy System Concepts

HRES denotes a system integrating various renewable energy sources and energy storage solutions to produce and deliver electricity collectively. A hybrid renewable energy system typically comprises at least two renewable energy sources. Integrating various renewable energy sources is an optimal solution for addressing energy deficits. This approach enhances the reliability and storage capabilities of power systems and contributes to mitigating the impacts of climate change. [2]. Weather changes such as temperature, clouds, and irradiance level can affect PV power output. Wind turbines' output is also affected by wind speed and direction. A PV system is combined with a wind turbine system to overcome these limitations. The proposed system utilizes a battery as an energy storage system and incorporates two sources of energy, wind and solar.

The project, situated in El-Nasr, Hurghada, Egypt, caters to a system with peak loads of 20.46 kW, particularly high from January, April to July, and November to December, with an average demand of 6.89 kW. Solar data spanning 30 years reveals
Hurghada's monthly average global horizontal irradiance (GHI) peaks at $8.07\ \mathrm{kW/m^2/day}$ in January and dips to $3.61\ \mathrm{kW/m^2/day}$ in December, with an annual average of $5.93\ \mathrm{kW/m^2/day}$. Similarly, wind speed data over the same period shows a maximum average of 8.63 m/s in January and a minimum of 6.04 m/s in November, with a yearly average wind speed of 7.13 m/s. All the data above about the load and energy sources are from the HOMER database.

3. Proposed System

This section presents the components of the PV/wind system with the ANN MPPT control technique, as shown in Figure 1. As shown in Figure 1, the two primary
sources, the PV array and wind turbine, are connected to a DC-DC converter to regulate the voltage to the desired value. ANN tracks the MPPs of both sources, and the difference between the actual and desired value is decreased to the minimum value by the PI-controller, which is enhanced by the GJO algorithm to obtain the best parameters. The DC-DC bidirectional control technique controls the battery bank charge and discharge [3].

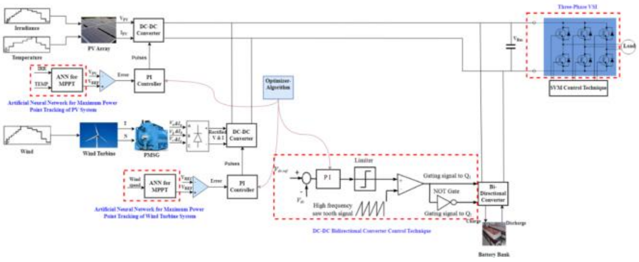


Fig 1. Overall system of PV/Wind system with ANN MPPT control technique.

3.1 Photovoltaic Array

PV technology directly transforms sunlight into electrical energy. The PV array consists of parallel connected strings, each consisting of a few series connected modules, all combined to generate DC power. The basic component of a PV module is the solar cell, or photovoltaic cell, often constructed from semiconductor materials such as silicon. Exposure to sunlight on these cells produces an electric current via the photovoltaic effect. Figure 2 shows the equivalent circuit of solar cells [8].

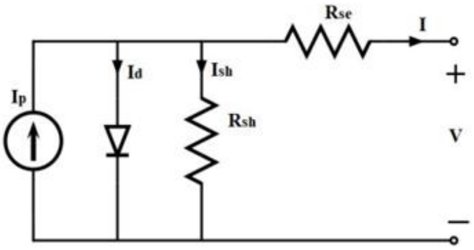


Fig 2. Equivalent circuit of the solar cell.

The mathematical equation of the PV current is [8]

$$I = I_p - I_{sr}.\left[\exp\left(q.\frac{(V + R_{se}.I)}{nKT}\right) - 1\right] - \frac{V + R_{se}.I}{R_{sh}} \qquad (1)$$

Where, I - output current, V- cell output voltage, I_{sr}- reverse saturation current, I_p- photon current, q- charge of electron (q=1.602e-19 C), R_{se}- series resistance, R_{sh}- shunt resistance, n-ideality factor of the diode (n=1.62), K-Boltzmann constant ($K = 1.381 * 10^{23}$ Joule/Kelvin), T-temperature of solar cell.

Based on Homer's optimization, the PV capacity is 68.3 Kw. The proposed PV array design comprises seventeen modules connected in parallel and ten in series, utilizing the PEMIAR-USA-SM400M module type. This module features seventy-two solar cells connected in series, with an efficiency of 20.17 % and is of the monocrystalline variety.

3.2 Wind Turbine

A wind turbine transforms wind's kinetic energy into mechanical energy, which is used to rotate the generator's prime move, which is coupled to the wind turbine shaft to generate electricity. It consists of several components: a tower, rotor blades, a nacelle, and a generator.

The mechanical power generated by the wind turbine, responsible for rotating the generator's shaft, can be expressed as follows:

$$P_m = \frac{1}{2} C_p(\lambda, \beta) \rho A v^3 \qquad (2)$$

Where, P_m-mechanical power, A – swept area, ν - wind speed, C_p - power coefficient, ρ - air density, λ - tip speed ratio, β -pitch angle.

$$A = \pi R^2 \qquad (3)$$

R - rotor blade radius.

$$\lambda = \frac{\omega R}{\nu} \qquad (4)$$

ω - rotor angular speed.

Based on Homer's optimization, the presented design includes only one wind turbine of type G-11, 11 kW HAWT which is designed for low to medium wind speed.

3.3 Battery

Battery energy storage systems are crucial for standalone systems, ensuring electricity supply matches demand. They store excess electricity from renewable sources when production exceeds demand and supply it when demand surpasses production. Given the variability of renewable energy due to weather changes, with solar panels generating power in daylight and wind turbines with sufficient wind, battery storage provides a stable energy source during periods of low or no renewable energy production.

Based on Homer's optimization, the presented battery bank design includes a string size of one hundred batteries and a nominal voltage of 6 V lithium-ion battery with 1 kW of energy storage for each battery.

The specification of the proposed system is shown in Table 1.

Table 1. The specification of the proposed system.

Equipment	**Parameters and Values**
PEMIAR-USA-SM400M solar module	Nominal output: 400 W Voltage at Pmax (Vmp): 41.3 V Current at Pmax (Imp): 9.69 A Open circuit voltage (Voc): 50.39 V Short circuit current (Isc): 10.26 A Maximum system voltage: 1500 V
G-11, 11 kW HAWT Wind turbine	Rated output: 11 kW Rate wind Speed: 11 m/s CUT in speed: 3 m/s Generator: PM 3 phase alternator (variable speed) Poles: 4 Frequency: 50 Hz/60 Hz, RPM: 375/450 Rated voltage: 400 V
Lithium-ion Battery	Nominal voltage: 6 V Nominal capacity: 1 kWh/167Ah Maximum charge/discharge current: 167/500 A

4. Control of the Proposed System

This section explains the method for controlling and stabilizing the DC-link voltage at a desired level, the MPPT control technique, and PI controller gains obtained using different optimization techniques.

4.1. DC-Bus Voltage Control

The battery bank is linked to the DC-link voltage via a DC-DC bidirectional buck-boost converter, ensuring the DC bus remains at the reference value. The battery bank's voltage can be maintained below the reference DC-link voltage (V_{dc-ref}) as the bidirectional converter can boost the voltage to the necessary level. Therefore, a reduced number of battery cells is required to be connected in series. In the model we propose, the battery bank voltage is maintained at 300 V, while V_{dc-ref} is kept at 600 V.

Figure 1 shows the control technique used in the DC-DC bidirectional converter to keep the DC-link voltage at the reference value. The DC voltage across the DC-link is measured and compared with the reference DC-link voltage (V_{dc-ref}), and then the error signal is processed through the PI controller. The output signal determines the duty cycle for switches Q_1 and Q_2 based on whether the system is in a charging or discharging state. The PI control parameters are obtained using two optimization algorithms: the GJO algorithm compared with the PSO algorithm.

During charging, current flows from the DC-link (high voltage) to the battery bank (low voltage); here, Q_1 is on, and Q_2 is off, making the DC-DC bidirectional converter function as a buck converter. In contrast, during discharging, current moves from the battery bank (low voltage) to the DC-link (high voltage); then, Q_1 is off, Q_2 is on, and the converter operates as a boost converter.

4.2. Three-Phase Voltage Source Inverter Control Technique

A three-phase voltage source inverter (VSI) converts DC energy from solar arrays and wind generators into three-phase AC power, facilitating the supply to AC loads. It employs the space vector modulation (SVM) technique for control, where the three-phase voltages are depicted as a rotating vector within a two-dimensional space vector hexagon. These sectors determine the active switches in the inverter, and based on the desired output voltage, the appropriate sector is identified.

4.3. Maximum Power Point Tracking Control Technique

Efficient renewable energy systems rely on MPPT control techniques to ensure maximum power point (MPP) operation. The proposed HRES model leverages an ANN algorithm inspired by the human brain for MPPT. The interconnected neurons process data and adjust operations based on changing weather conditions, resulting in precise MPP tracking by comparing reference and actual voltages under varying environmental factors. The PI controller then minimizes the discrepancy to achieve MPPT by adjusting the duty cycle of the boost converter. This approach optimizes power output and reduces losses for system stability, resulting in an energy-efficient and reliable HRES.

4.4. Optimization Techniques

The optimization of the PI controller involves tuning its parameters to find the best controller gains to reduce the error between the desired output voltage and the actual voltage to a minimal value, then producing the duty cycle, which controls the boost converter to track MPP.

The optimization technique in this article is based on GJO, and the results are compared with PSO. GJO is an alternative optimization method for solving real-world engineering problems. GJO is inspired by the collaborative hunting behavior of the golden jackals. The three elementary steps of the algorithm are prey searching, enclosing, and pouncing, which are mathematically modeled and applied in detail at [18].

5. Simulation Results and Discussion

This section presents and analyzes the simulation outcomes for each scenario carried out. The system is simulated at different irradiances, temperatures, and wind speeds. There are two cases that undergo simulation, which are:

1) The system was simulated under varying irradiance levels and temperatures with a constant wind speed of $11\ \mathrm{m/s}$. The wind turbine's power output was constant at $11\ \mathrm{kW}$. The PI controller is optimized with the PSO and GJO algorithms.
2) System simulation under varying wind speeds with constant irradiance level and temperature at $1000\ \mathrm{W/m^2}$ & $25\ ℃$. The output of the PV system was constant at $68.3\ \mathrm{kW}$. The PI controller is optimized with the PSO and GJO algorithms.

5.**1**. Comparative study of the system under varying irradiance levels, temperatures with constant wind speed

The performance of the PV/Wind system relies on an ANN design, with its response smoothed by a PI controller optimized using the GJO algorithm and benchmarked against the PSO algorithm. Simulations reveal the PV system's ANN configuration includes two inputs, a hidden layer with ten neurons, and a single output. The ANN's efficacy, measured by mean squared error (MSE). Figure 3 shows an acceptable MSE value of $2.29 * 10^{-6}$ at the 1000^{th} epoch.

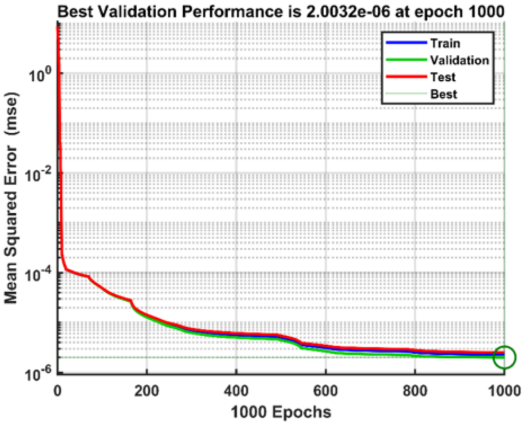
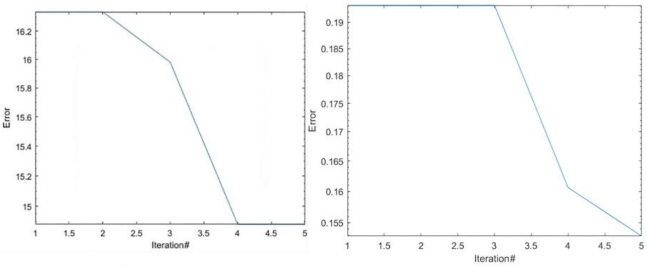


Fig 3. The ANN performance in terms of mean squared error (MSE).

Figure 4 shows that the resulting error of the GJO algorithm equals 0.1528946003, which is less than the error of the PSO algorithm, which equals 14.881.



(a) (b)

Fig 4. (a) The resulting error of the PSO algorithm; (b) The resulting error of the GJO algorithm.

Figure 5 shows the varying irradiance and temperature conditions to which the proposed system was exposed, with constant wind speed. Figure 6 illustrates the outcomes of the simulation executed on the PV/Wind system under these conditions. Sub-figures (a), (b), and (c) depict consistent PV voltage with negligible oscillations, smooth variation in PV current attributed to temperature and irradiance changes, and nearly reference-level PV power outputs. Additionally, transitions between states exhibit stability without oscillations. The PI controller is optimized using the GJO algorithm.

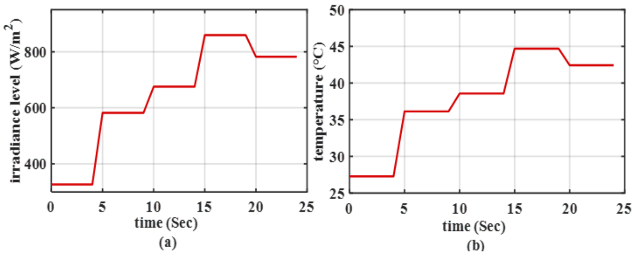


Fig 5. (a) Irradiance level change; (b) Temperature change.

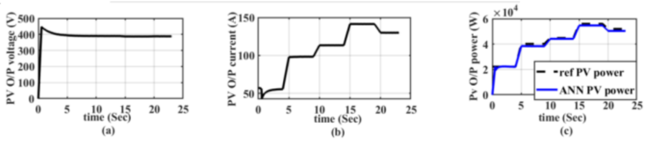


Fig 6. (a) PV O/P Voltage; (b) PV O/P Current; (c) Ref PV power vs ANN PV O/P power, optimized with GJO algorithm.

. Comparative study of the system under varying wind speeds with constant irradiance level and temperature

The PV/Wind system performance is founded on the designed ANN, and the system's response is softened using the PI controller. The PI controller gains are evaluated by the GJO algorithm and compared with the PSO algorithm. The specifics of the simulated neural network for the wind turbine system includes one input variable, two hidden layers, two of them of 20 neurons, and an output layer of one output variable. The ANN performance in terms of MSE is shown in Figure 7. It is evident that the acceptable value of MSE at epoch 1000^{th} equals $1.81 * 10^{-9}$. This indicates that the model's prediction error is exceptionally low at this stage of the training process. This value of MSE is evidence that the model has learnt to predict with high accuracy and minimal difference between the target and predicted outputs.

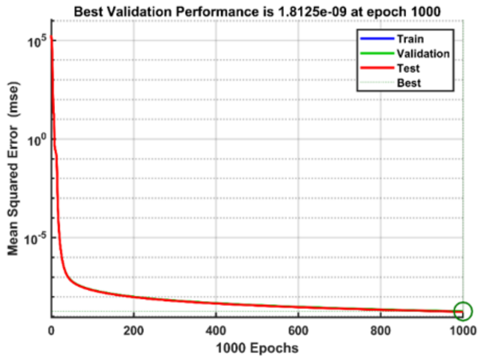


Fig 7. The ANN performance in terms of mean squared error (MSE).

Figure 8 shows that the resulting error of the GJO algorithm equals 0.001484646079, which is less than the error of the PSO algorithm, which is 8.3977. This is a vital difference that shows that the GJO algorithm is more effective in minimizing error than the PSO algorithm, suggesting that it has higher accuracy and better convergence compared to the PSO algorithm.

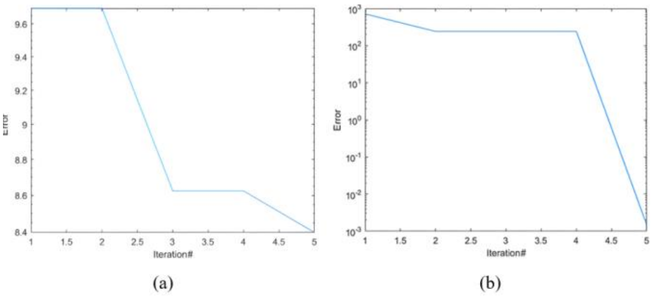


Fig 8. (a) The resulting error of the PSO algorithm; (b) The resulting error of the GJO algorithm.

Figure 9 shows the proposed system's exposure to varying wind speeds with constant irradiance and temperature conditions. Figure 10 displays the simulation outcomes of the PV/Wind system under these conditions. In this scenario, the wind turbine operates at fluctuating wind speeds, utilizing both ANN MPPT and PI controllers optimized with GJO algorithm. Sub-figures (a), (b), and (c) illustrate smooth variations in wind voltage, minor fluctuations in wind current, and near-reference-level PV power outputs with slight oscillations attributed to changes in wind speed.

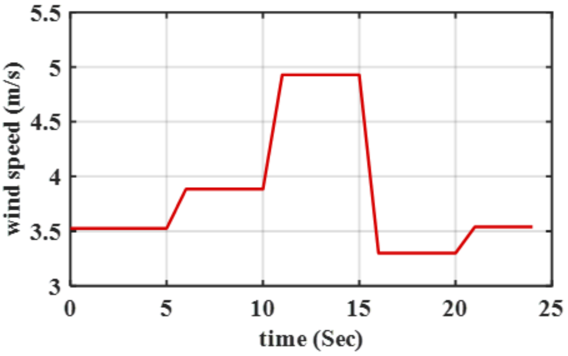


Fig 9. Wind speed change.

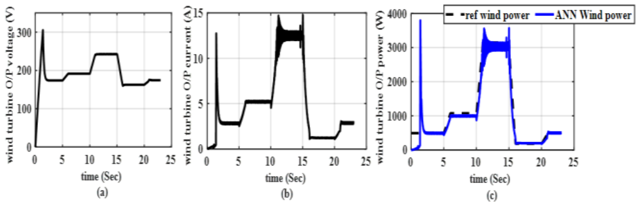


Fig10. (a) wind turbine O/P voltage; (b) wind turbine O/P current; (c) Ref PV power vs ANN wind turbine O/P power, optimized with the GJO algorithm.

Figure 11 shows that the three-phase voltages and currents of the load. Whether the irradiance, temperature, or wind speed vary, the output voltage and current are constant because the battery bank provides energy stability during varying weather conditions. Figure 12 shows the dc link voltage which is constant at 600 Volt.

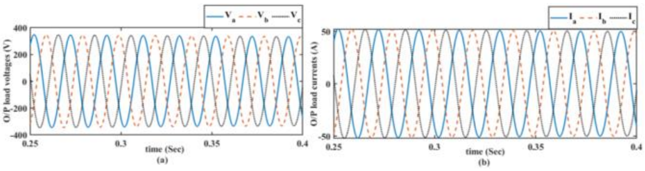


Fig 11. (a) The three-phase load voltages;
(b) The three-phase load currents.

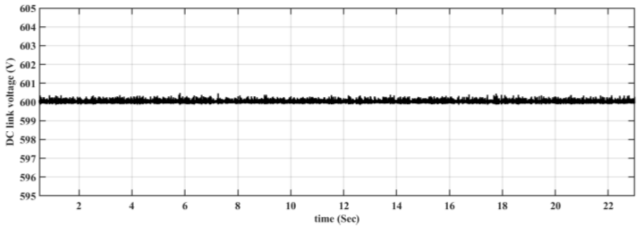


Fig 12. The DC link voltage.

6. Conclusion

This paper presents a scientific approach for supplying power to a 20.46 kW peak load in Hurghada City, Egypt, using an off-grid system combining solar PV arrays and a wind turbine integrated with a battery bank for continuous power during outages and storing excess energy. The proposed microgrid is designed, simulated, analyzed, and optimized by HOMER software. It is widely used in planning renewable energy projects to determine the most efficient and cost-effective ways to meet energy needs, especially for designing microgrid systems for rural areas that may have difficulty being supplied from the primary electric grid. The designed microgrid includes 68.3 kW solar and 11 kW wind turbine capacities, a battery bank with a string size of one hundred cells. The proposed system employs an ANN for efficient MPPT, and a PI controller optimized with the GJO algorithm to reduce the error between the desired output and actual output, improving system stability and exploiting all the produced energy with minimum losses. MATLAB simulations demonstrate the ANN's superior performance of the designed microgrid in achieving the desired outputs under varying weather conditions, reflecting the microgrid's robustness, and the data obtained from the simulations is compared with actual data from HOMER. Also, MATLAB simulations highlight that the error resulting from the GJO algorithm is much lower than that from the PSO algorithm, which achieves the required output of the designed microgrid with a minimum number of iterations.

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