Modelling and design of a Grid-Connected PV–Wind Hybrid Power System Using Ant Lion Optimization Algorithm

KOPPULA SAI SUSHMA [1] | D.MOUNIKA[2]

[1]Pg Scholar, Dept of EPS, Kodada Institute of Technology & Science for Women-Kodad, Telangana.

[2] Assistant Professor, Dept of EEE, Kodada Institute of Technology & Science for Women-Kodad,Telangana.

ABSTRACT: This work focuses on the modelling and implementation of a grid-connected hybrid PV–wind energy system integrated with ALO-based MPPT and inverter control strategies. The proposed approach aims to enhance energy extraction efficiency, stabilize DC-link voltage, improve power quality, and ensure reliable grid integration. Due to dynamic environmental conditions, integrating and controlling these renewable energy sources is critical. To address this problem and enhance overall system performance, a PV module was operated with an ALO-based maximum power point tracking (MPPT) approach. The ALO-based MPPT algorithm effectively utilizes real-time PV voltage and current measurements to regulate the global maximum power point, ensuring optimal energy extraction under varying solar irradiance conditions. The outputs of both PV and wind systems are interfaced on a common DC bus, with a DC-link capacitor used to maintain a stable DC voltage and ensure proper decoupling between generation and grid-side operations. On the grid side, an ALO-based control scheme was implemented for VSI. The integration of the ALO control approach for VSI operation enhances the controller's ability to adaptively tune the control parameters, resulting in faster convergence, reduced steady state oscillations, and improved harmonic performance. Consequently, the ALO-PWM-based inverter ensures stable DC-link regulation, high-quality power injection into the utility grid, making it highly suitable for advanced hybrid renewable energy systems. The effectiveness of the proposed system is validated through simulation studies under varying irradiance and wind conditions.

KEYWORDS: ALO, DC-LINK, PV, WIND, GRID.

I.INTRODUCTION: As we search for more reliable, sustainable, and effective energy solutions, the role of hybrid and grid-integrated energy systems is expanding. The term "system of hybrid energy" is typically used when two or more green power sources, such as wind and solar, hydro, or biomass, are combined with energy storage devices or conventional energy sources. By leveraging the benefits of each energy source, these systems aim to maximize energy output and grid stability. Compared to discrete renewable energy sources, hybrid systems may produce energy that is more consistent and dependable [1]. Supply and demand balance is improved by integrating hybrid energy technologies into the grid. By combining different energy sources with different output characteristics, the overall unpredictability and intermittency of renewable energy can be decreased.

For the grid to remain reliable and stable, this integration is essential. By reducing the need for costly fossil fuels and increasing energy production, hybrid systems have the potential to reduce total energy costs. By providing energy independence to remote or off-grid locations, they can also reduce transmission losses and expenses. The main contribution of this work is its novel approach to enhancing grid-tied hybrid photovoltaic and wind generation systems' efficiency. The efficiency of energy systems that integrate hybrids is greatly increased by advanced control tactics. The study that compares the ANFIS with alternative control units like fuzzy-FOPID and fuzzy-PI controllers illustrates the significance of accuracy and flexibility in system control [2]. In [3], a comprehensive examination of existing renewable hybrid wind-solar energy sources is conducted, with an emphasis on optimal design methods, power converter topologies, and system modeling. Management and assessment of a wind and photovoltaic (PV) hybrid power plant connected to the grid. Additionally, a comparison of several power converter topologies utilized in the solar and wind HRES is given. This article discusses the technological challenges associated with HRES as well as the scope of upcoming discoveries and research on HRES.

This subject is the subject of another study [4]. It is conceivable to save fixed fossil fuel sources and save our world from damaging climate change with this one objective in mind. The goal of this research is to identify the best hybrid power mechanism combination that will enable Saudi Arabia to expand its present energy portfolio. It examines the state-of-the-art hybrid power systems and theoretical research done worldwide in a range of climatic conditions.

Wind and PV, DSL, and PV-DSL have average sizes of 790.0 kW and 295.0 kW, respectively, with average COEs of 0.349 and 0.355 US dollars per kWh. The total Wind and PV capacities range from 1.6 to 120.0 kW, with a normal size of 21.0 kW and a COE of 0.458 US dollars per KWh. The paper recommends the implementation of these HPSs in Saudi Arabia and the surrounding area due to their broad commercial, technological, and global acceptability. Control systems employ a variety of strategies to maximize performance, resolve challenging issues, and ensure system efficiency and stability.

These methods include Particle Swarm Optimization (PSO), Proportional Integral (PI), Artificial Intelligence Techniques (AIT), Simulated Annealing Algorithms (ASA), and Linear Programming (LP). The feasibility of utilizing a renewable hybrid energy system (HRES) that comprised power and a wind turbine in addition to a support system that included a diesel generator, a battery unit, and a converter to power a remote village in Iran's Hormozgan province was investigated in [5]. The results show that employing a diesel engine and a backup system made up of a battery and a converter is the most economical way to deliver energy when combining solar and wind power systems. Consequently, the price of electricity will be 1.058 USD/kWh, of which 64% will come from renewable sources. There are many optimization-related problems in our day-to-day lives. This study examines and contrasts several ideas and conventional approaches to control HRES's performance and energy consumption. Demand the Side Management (DSM) is used to create and assess a hybrid system that includes a diesel generator, a PV panel, a wind turbine, and battery storage in order to determine the most reliable and cost-effective Net Present Cost (NPC) solution, Cost of Energy (COE), and environmental impact. One of the most reliable and suitable paradigms for controlling Hybrid Renewable Energy Systems (HRES) is hybrid control [6].

A related work [7] presents a methodology for estimating the size of a self-sufficient PV, wind, battery, and DG system of hybrid electricity using IOT. An independent PV, wind, storage, and distributed generation hybrid power system's optimal size can be found via IOT. The data acquired using IOT was compared with the outcomes produced by GWO and HOMER software. The comparison demonstrates the effectiveness of IOT in identifying the optimal size for HRES components. The system described in [8] uses solar and wind energy sources in addition to battery storage. A few more effective storage systems are also examined. Based on a detailed examination of the various LFC possibilities, a FOPID controller optimized by FPA is suggested to address the LFC problem in the system. The review work will provide a thorough overview of the state-of-the-art LFC techniques to the scholars working on this topic.

The primary focus of [9] is a comprehensive review of the literature on the practical application in industry and FOPID control implementation. Significant issues with the production of FOPID controllers were identified and thoroughly examined. By reviewing a large number of pertinent articles on the rapidly evolving field of fractional-order control, highlighting notable achievements and limitations, and illuminating potential paths for the industry's future industrialization, we want to address some of these issues. [10] focuses on using fractional-order PID (FOPID) and conventional PID controllers in nuclear renewable hybrid energy systems (N-R HESs) to guarantee system stability. Both FOPID and PID controllers effectively regulate the system's frequency and maintain the N-R HES under the study's stability, according to the evaluation of these controllers' compatibility. PID and FOPID controllers are compatible with N-R integrated systems. However, FOPID is a more responsive controller than PID. A detailed research is offered where three smart controllers are employed to construct an efficient EMS for optimal microgrid stability, coupled with a microgrid system and a description of local control within a microgrid. The three suggested methods for microgrid stability—fuzzy logic, artificial neural network, and PID—perform exceptionally well, according to MATLAB Simulink simulation results.

In changes in load demand will create power and frequency oscillations despite generating at a consistent rate. To overcome the power and frequency deviation under generating and load demand situations, a competent control proposed action is required. In the context of fractional order (FO) calculus, integration from fuzzy controllers and proportional-integral-derivative (PID) controllers to control frequency and power deviation is referred to as a "FO-Fuzzy PID controller," which is modified utilizing quasi-opposition based. In terms of competitiveness, robustness, and stability against random load perturbation, changed system parameters, and system nonlinearities, the FO-Fuzzy-PID control approach performs exceptionally well. Give an example of a modified fractional-order proportional-integral-differential (FOPID) controller, or MFOPID controller. When compared to other JSO-tuned controllers (PID, FOPID, and PI), the MFOPID controller—a modified version of the FOPID controller—proves to be extremely dependable in stabilizing load frequency and interconnection lines in a multi-area power network. It is optimized for superior performance using the bio-inspired Jellyfish Search Optimizer (JSO).

II.PROPOSED SYSTEM: Fig. 1 illustrates the configuration of the circuit layout for a grid-integrated hybrid power generation integrated with ALO-based control strategies. The proposed circuit mainly comprises an ALO-based MPPT-controlled PV module, a PMSG-based wind energy conversion system, a VSC, and the utility grid. The ALO-based MPPT algorithm utilizes real-time measurements of PV voltage (V_{pv}) and current (I_{pv}) to ensure optimal power extraction under rapidly varying atmospheric scenarios. The outputs of both PV and wind energy sources are integrated through a common DC bus. A DC-link capacitor is employed to maintain a stabilized DC voltage, ensuring smooth power flow and effective decoupling between the generation side and grid-side dynamics. The combined DC power is then converted into three-phase AC using a VSI, where an ALO-based control scheme regulates the inverter switching by optimizing reference current and voltage signals in the synchronous d–q reference frame. This enables unity power factor operation, accurate control of active and reactive power, and reduced harmonic distortion. To further attenuate switching harmonics at the inverter output, LCL filters are incorporated into the system. Therefore, the proposed hybrid power generation system achieves improved dynamic response, reduced oscillations, enhanced efficiency, and stable grid integration.

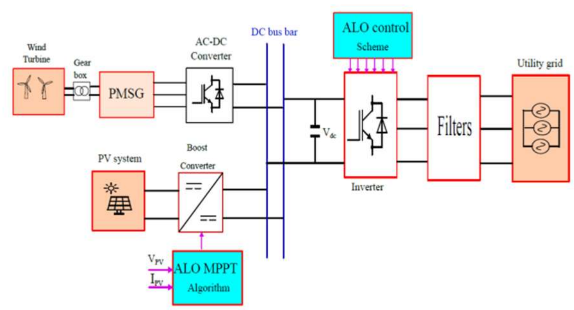


Fig.1 Circuit layout of proposed hybrid power generation.

The ALO based MPPT technique is an advanced bio-inspired optimization approach employed to ensure peak energy extraction from PV systems under dynamically varying atmospheric scenarios. In this method, the nonlinear power–voltage characteristics of the PV module are considered as an optimization problem, where the objective is to determine the optimal operating point corresponding to the global maximum power.

The fundamental objective of the MPPT algorithm is maximize PV output power (P_{pv}) therefore formulated as:

$$\max \ P_{PV}(V_{PV})$$

In the ALO framework, each candidate solution (ant) represents a possible duty cycle (D) of the DC–DC converter, while the antlion represents the best solution that guides the search process. To ensure feasibility within the permissible duty cycle limits, this random movement is normalized as:

$$X_i^t = \frac{(X_i^t - a_i)(d_i - c_i)}{b_i - a_i} + c_i$$

where $a_i$and $b_i$denote the boundary range of the random walk, and $c_i$and $d_i$indicicate the lower and upper bounds of the duty cycle. The interaction between ants and antlions is modeled such that the ants update their positions around selected antlions, enabling both exploration and exploitation:

$$X_i^{t+1} = \frac{X_{\text{antlion}}^t + X_{\text{random}}^t}{2}$$

Further refinement is achieved by guiding the search using the elite (best) antlion:

$$X_i^{t+1} = \frac{X_{\text{elite}}^t + X_j^t}{2}$$

The fitness of each solution is evaluated based on the extracted PV power:

$$\text{Fitness} = P_{PV} = V_{PV}(D_i) \cdot I_{PV}(D_i)$$

and the optimal duty cycle is selected as:

$$D^* = \arg\max(V_{PV}(D_i) \cdot I_{PV}(D_i))$$

This optimal duty cycle is applied to the DC–DC boost converter, whose voltage conversion relationship is given by:

$$V_{out} = \frac{V_{in}}{1 - D}$$

thereby adjusting the PV operating point to its maximum power condition. The iterative optimization continues until convergence is achieved according to:

$$| P_k - P_{k-1} | < \varepsilon$$

where ε is a predefined tolerance.

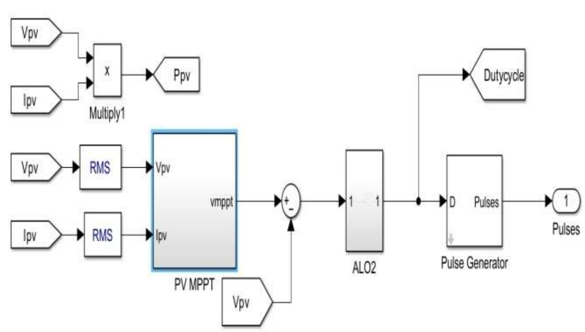


Fig.2 ALO MPPT algorithm.

For the smooth operation of the grid-connected DC–AC inverter and regulate the power flow to the grid an ALO-based control strategy is modelled in this work. The inverter converts the regulated DC-link voltage (V_{dc}) into a three-phase AC output while maintaining synchronization with the grid. The control is typically implemented in the d–q frame (I_d and I_q). The dynamic model of the inverter in the dq frame can be expressed as:

$$V_d = Ri_d + L\frac{di_d}{dt} - \omega Li_q + V_{gd}$$

$$V_q = Ri_q + L\frac{di_q}{dt} + \omega Li_d + V_{gq}$$

where V_d, V_q are inverter output voltages, i_d, i_q are currents, and ω is grid angular frequency. The DC-link voltage error is expressed as:

$$e_{Vdc} = V_{dc,ref} - V_{dc}$$

This error is processed by the ALO-based controller to produce the reference current I_d^*, thereby controlling active power flow. Similarly, the current control errors are defined as:

$$e_d = I_d^* - I_d,\ e_q = I_q^* - I_q$$

The ALO algorithm optimizes control actions by minimizing a fitness function, typically defined as:

$$J = e_d^2 + e_q^2$$

where the algorithm iteratively updates control variables using stochastic search behaviour modeled by random walks:

$$X(t) = \text{cumsum}(2r(t) - 1)$$

and position updates relative to elite solutions:

$$X_i^{t+1} = \frac{X_{\text{elite}}^t + X_j^t}{2}$$

Through this process, optimal values of control signals V_d^* and V_q^* are obtained, ensuring minimal tracking error and enhanced dynamic response. The SPWM technique employed to evolve pulses by comparing the reference signal with a high-frequency carrier wave, given as:

$$m_a = \frac{V_{ref}}{V_{carrier}}$$

where m_a is the modulation index. The switching function determines the inverter output voltage:

$$V_{inv} = m_a \cdot \frac{V_{dc}}{2}$$

Thus, the inverter produces a controlled AC waveform synchronized with the grid.

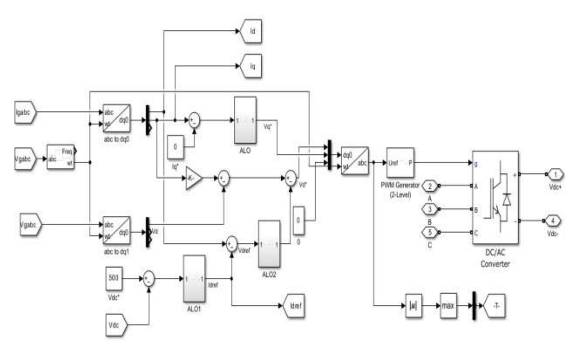


Fig.3 Proposed ALO control framework for operating the inverter

III.SIMULATION RESULTS:

Fig.4 depicts the MATLAB layout of the proposed hybrid power generation. To evaluate the effectiveness of the proposed system, simulations were carried out under dynamic environmental conditions.

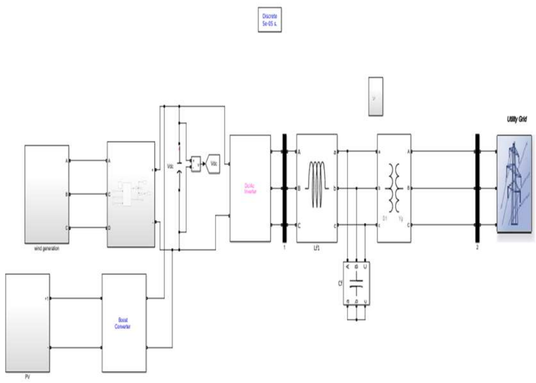
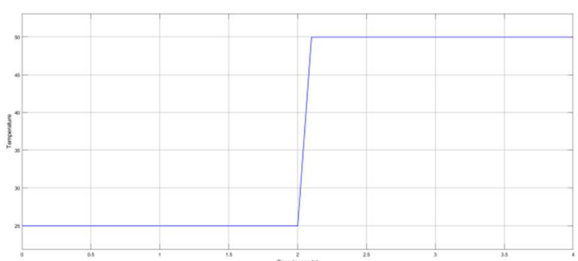
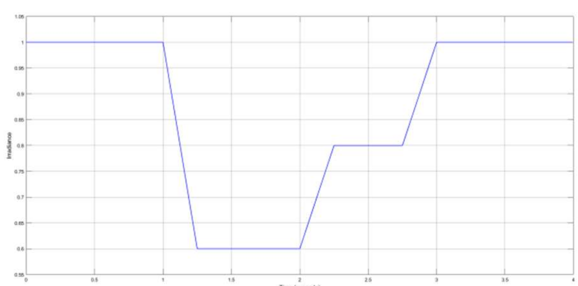
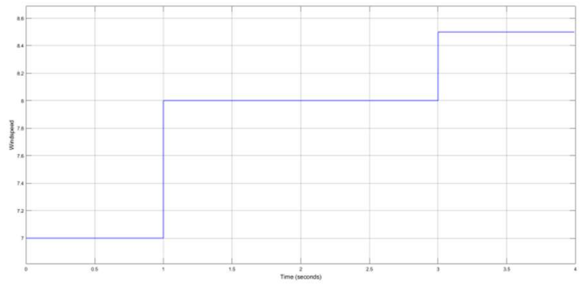
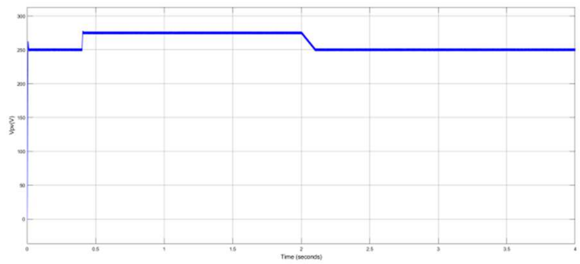


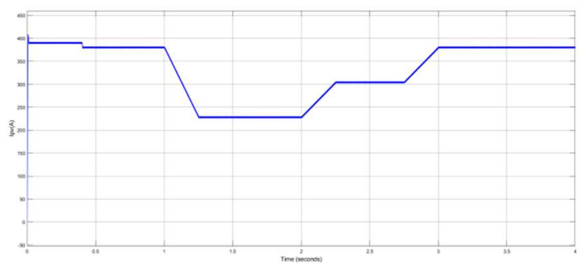
Fig.4 MATLAB layout of the proposed hybrid power generation.

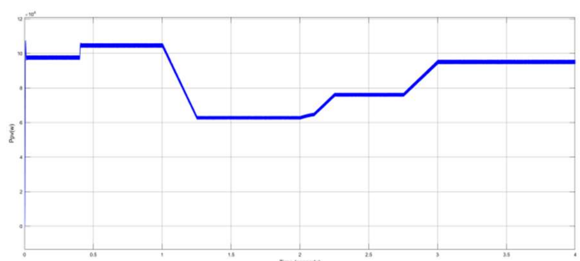


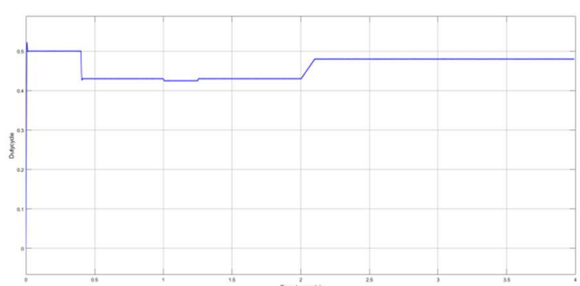


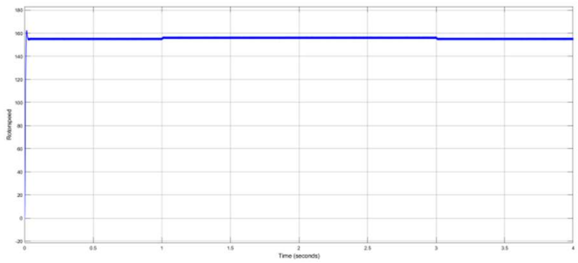












IV.CONCLUSION: This paper presents the modeling of a grid-connected PV–wind energy system with an ALO-based control strategy. The ALO-based MPPT algorithm demonstrates precise tracking of the global MPP point under both steady-state and dynamic irradiance conditions. The ALO-based MPPT approach provides a robust, adaptive solution for tracking the global MPP under rapidly changing solar-irradiation conditions. Unlike conventional techniques, it effectively minimizes steady-state oscillations, enhances convergence speed, and avoids local maxima traps, thereby significantly improving the efficiency and reliability of PV energy harvesting in hybrid renewable energy systems. On the grid side, the inverter operated with the ALO algorithm to achieve smooth integration of PV and wind energy sources with the grid. The obtained simulation results confirm that the ALO-based control approach significantly improves convergence speed, reduces steady-state oscillations, maintains DC-link voltage stability, and minimizes total harmonic distortion. These improvements make the proposed method a promising solution for modern hybrid renewable energy systems operating under different environmental conditions.

REFERENCES: [1] P. Bajpai and V. Dash, ‘‘Hybrid renewable energy systems for power generation in stand-alone applications: A review,’’ Renew. Sustain. Energy Rev., vol. 16, no. 5, pp. 2926–2939, Jun. 2012, doi: 10.1016/j.rser.2012.02.009.

[2] M. A. Hannan, Z. A. Ghani, M. M. Hoque, P. J. Ker, A. Hus- sain, and A. Mohamed, ‘‘Fuzzy logic inverter controller in photo- voltaic applications: Issues and recommendations,’’ IEEE Access, vol. 7, pp. 24934–24955, 2019, doi: 10.1109/ACCESS.2019.2899610.

[3] P. Roy, J. He, T. Zhao, and Y. V. Singh, ‘‘Recent advances of wind- solar hybrid renewable energy systems for power generation: A review,’’ IEEE Open J. Ind. Electron. Soc., vol. 3, pp. 81–104, 2022, doi: 10.1109/OJIES.2022.3144093.

[4] S. Rehman, ‘‘Hybrid power systems—Sizes, efficiencies, and economics,’’ Energy Exploration Exploitation, vol. 39, no. 1, pp. 3–43, Jan. 2021, doi: 10.1177/0144598720965022.

[5] K.Almutairi, S. S. H. Dehshiri, S. J. H. Dehshiri, A. Mostafaeipour, A. Issakhov, and K. Techato, ‘‘Use of a hybrid wind—Solar—Diesel— Battery energy system to power buildings in remote areas: A case study,’’ Sustainability, vol. 13, no. 16, p. 8764, Aug. 2021, doi: 10.3390/su13168764.

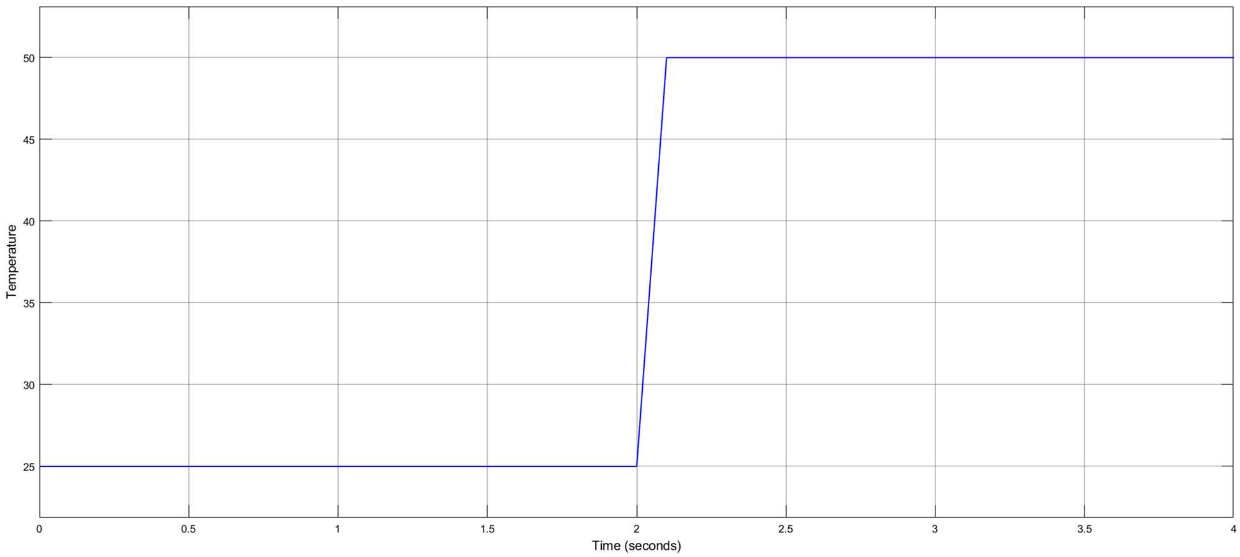
[6] M. M. Ibrahim, ‘‘Energy management strategies of hybrid renewable energy systems: A review,’’ Wind Eng., vol. 48, no. 1, pp. 133–161, Feb. 2024, doi: 10.1177/0309524x231200010.

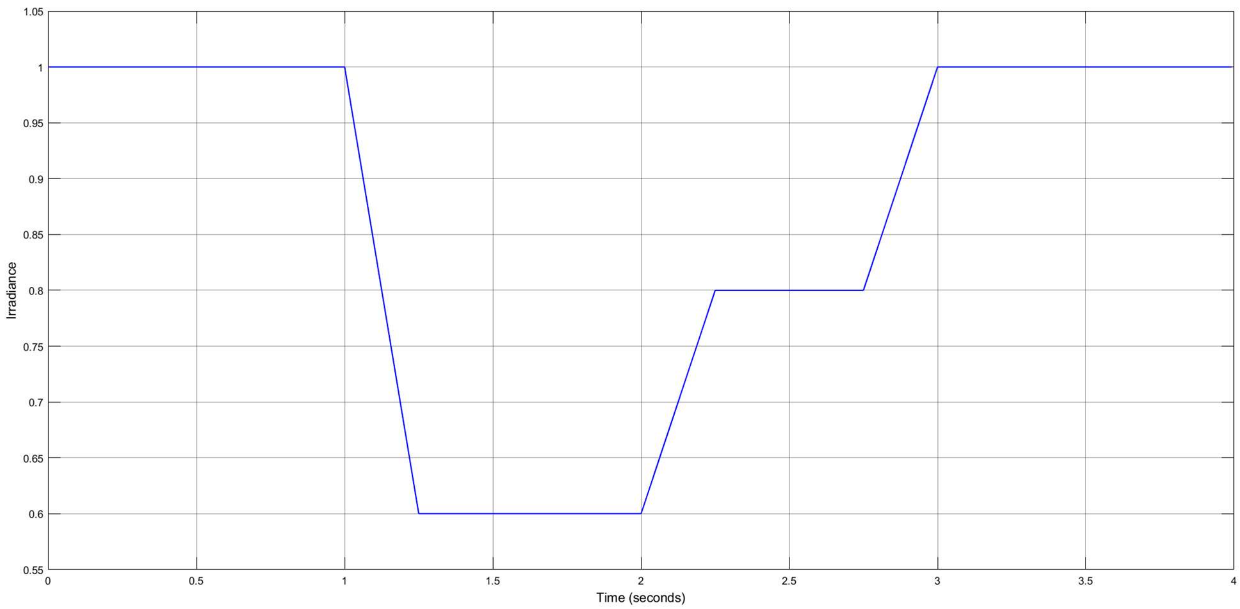
[7] A. Yamany, M. Mohamed, and Y. Mohammed, ‘‘Optimal sizing and economic evaluation of hybrid photovoltaic/wind/battery/diesel generation systems for autonomous utilization,’’ J. Adv. Eng. Trends, vol. 43, no. 1, pp. 47–65, Jan. 2024, doi: 10.21608/jaet.2022.131727.1147.

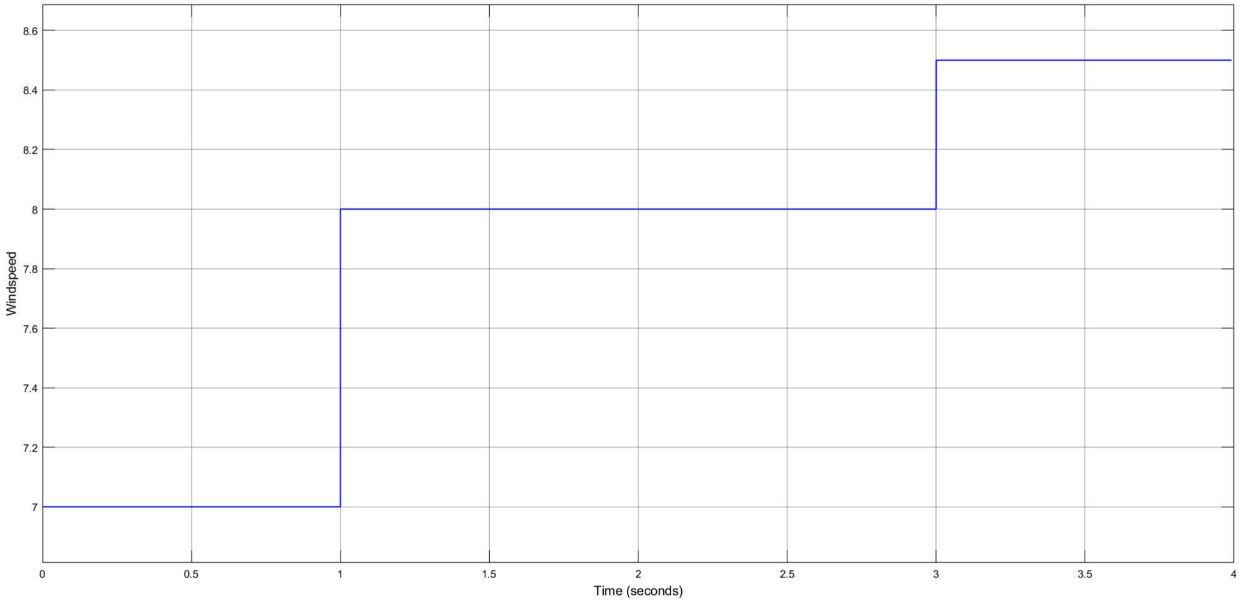
[8] M. Ramesh, A. K. Yadav, and P. K. Pathak, ‘‘An extensive review on load frequency control of solar-wind based hybrid renewable energy systems,’’ Energy Sources, A, Recovery, Utilization, Environ. Effects, pp. 1–25, Jun. 2021, doi: 10.1080/15567036.2021.1931564.

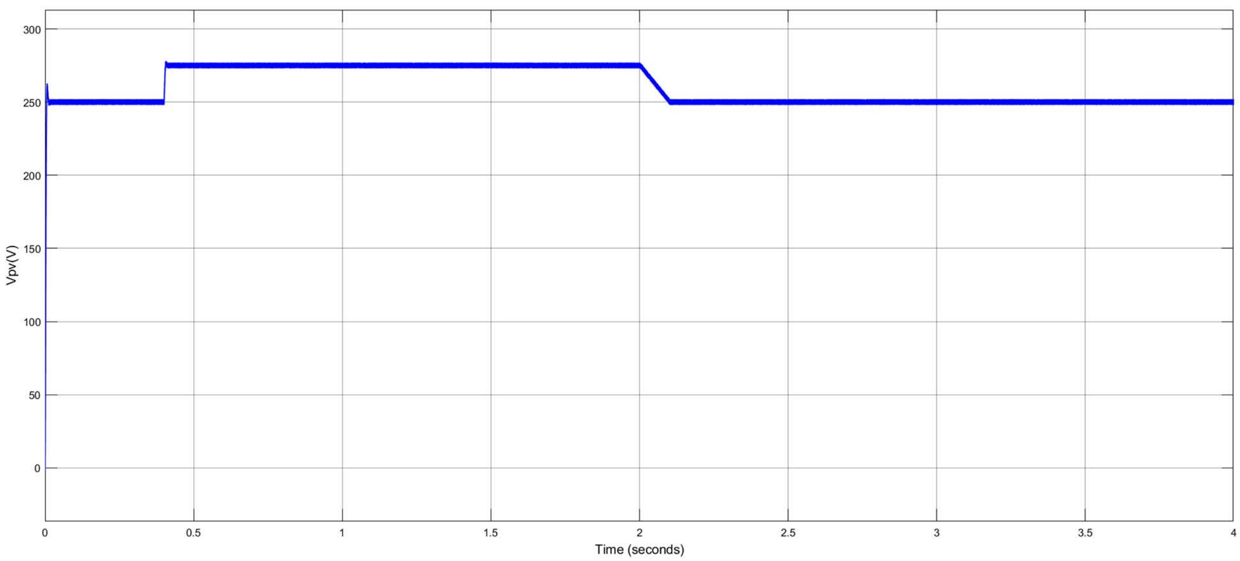
[9] A. Tepljakov, B. B. Alagoz, C. Yeroglu, E. A. Gonzalez, S. H. Hosseinnia, E. Petlenkov, A. Ates, and M. Cech, ‘‘Towards industrialization of FOPID controllers: A survey on milestones of fractional-order con- trol and pathways for future developments,’’ IEEE Access, vol. 9, pp. 21016–21042, 2021, doi: 10.1109/ACCESS.2021.3055117.

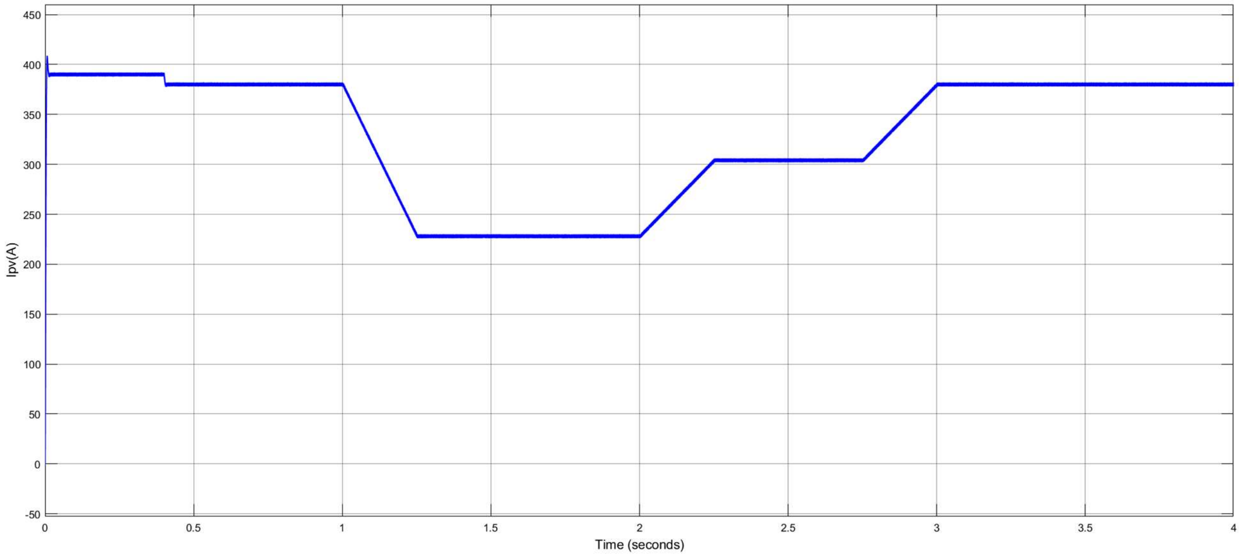
[10] R. Hasan, M. S. Masud, N. Haque, and M. R. Abdussami, ‘‘Frequency control of nuclear-renewable hybrid energy systems using optimal PID and FOPID controllers,’’ Heliyon, vol. 8, no. 11, Nov. 2022, Art. no. e11770, doi: 10.1016/j.heliyon.2022.e11770.

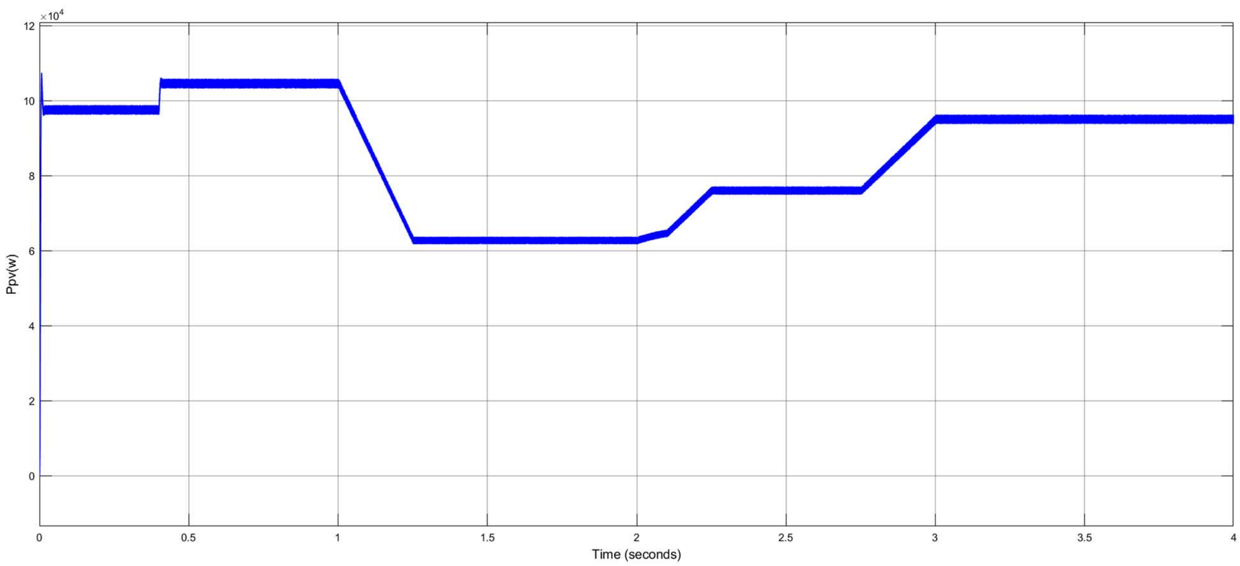

Temperature
Time (seconds)
50
45
40
35
30
25
0
0.5
1
1.5
2
2.5
3
3.5
4

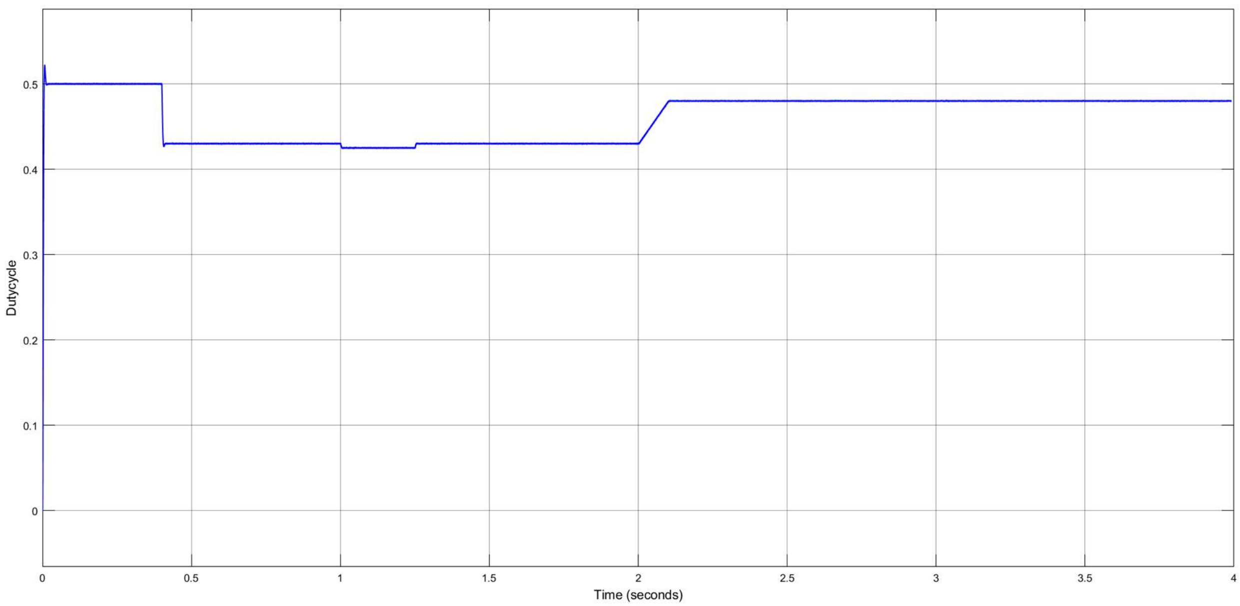

Irradiance
Time (seconds)
1.05
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0
0.5
1
1.5
2
2.5
3
3.5
4

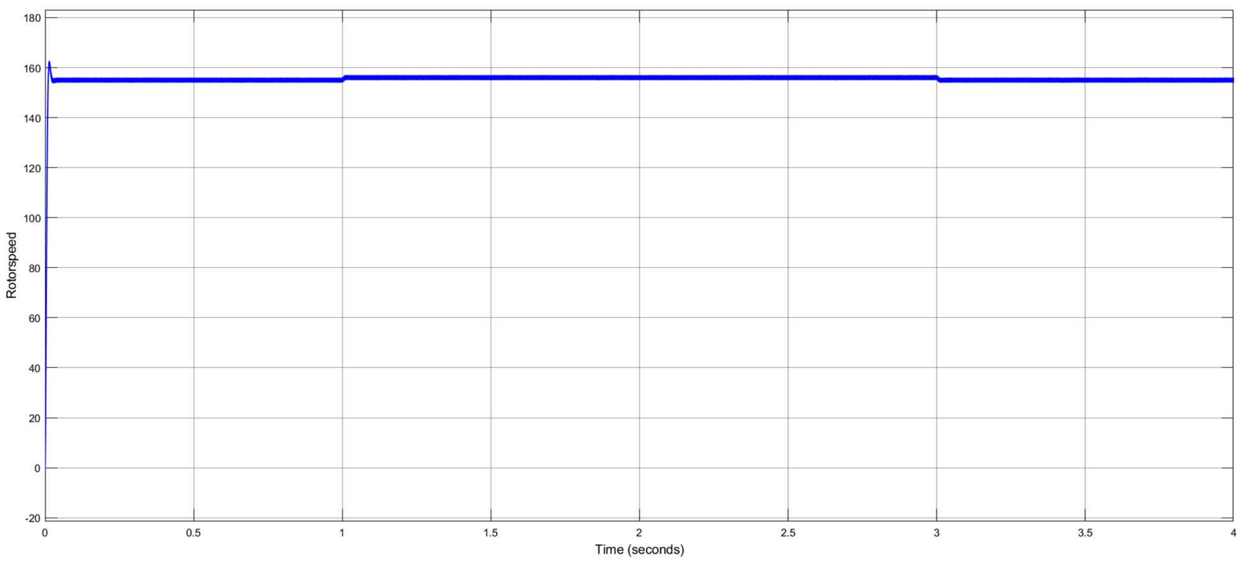

Windspeed
8.6
8.4
8.2
8
7.8
7.6
7.4
7.2
7
0
0.5
1
1.5
2
2.5
3
3.5
4
Time (seconds)

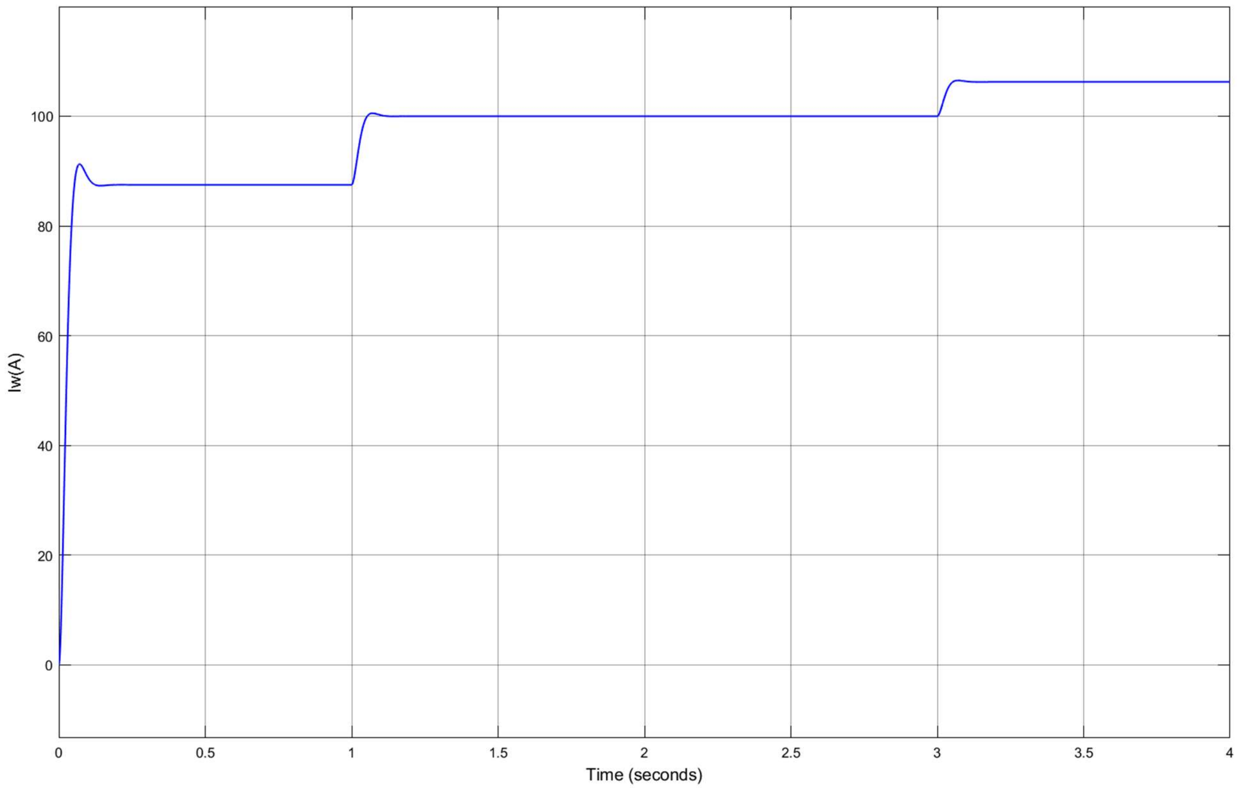

Vpv(V)
300
250
200
150
100
50
0
0
0.5
1
1.5
2
2.5
3
3.5
4
Time (seconds)

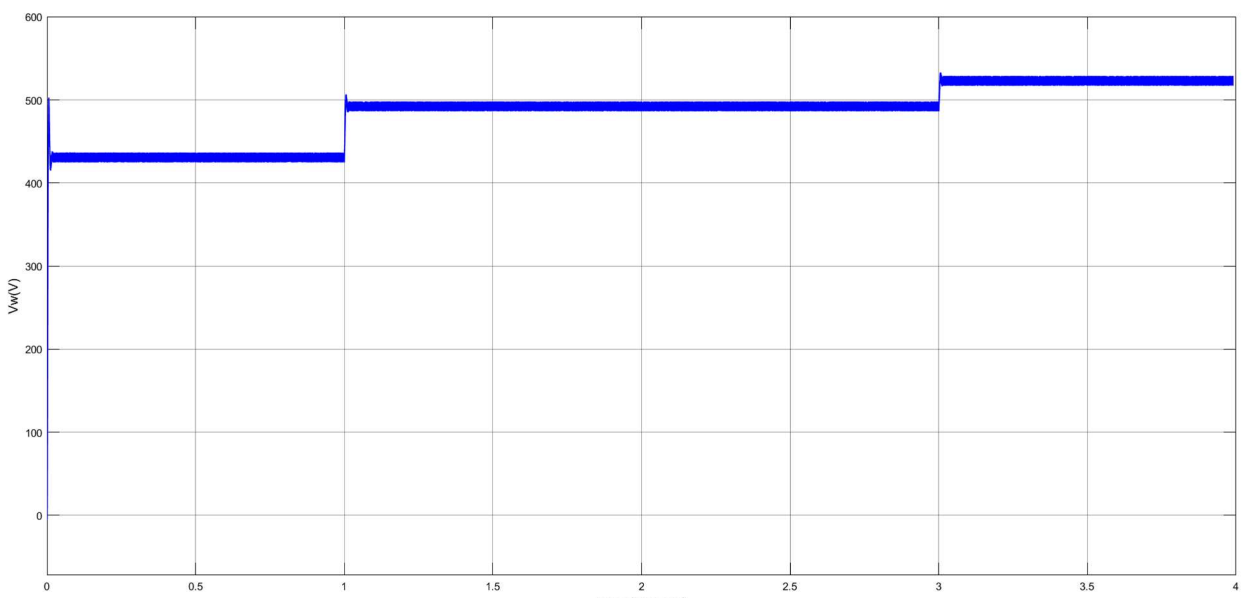

Ipv(A)
Time (seconds)

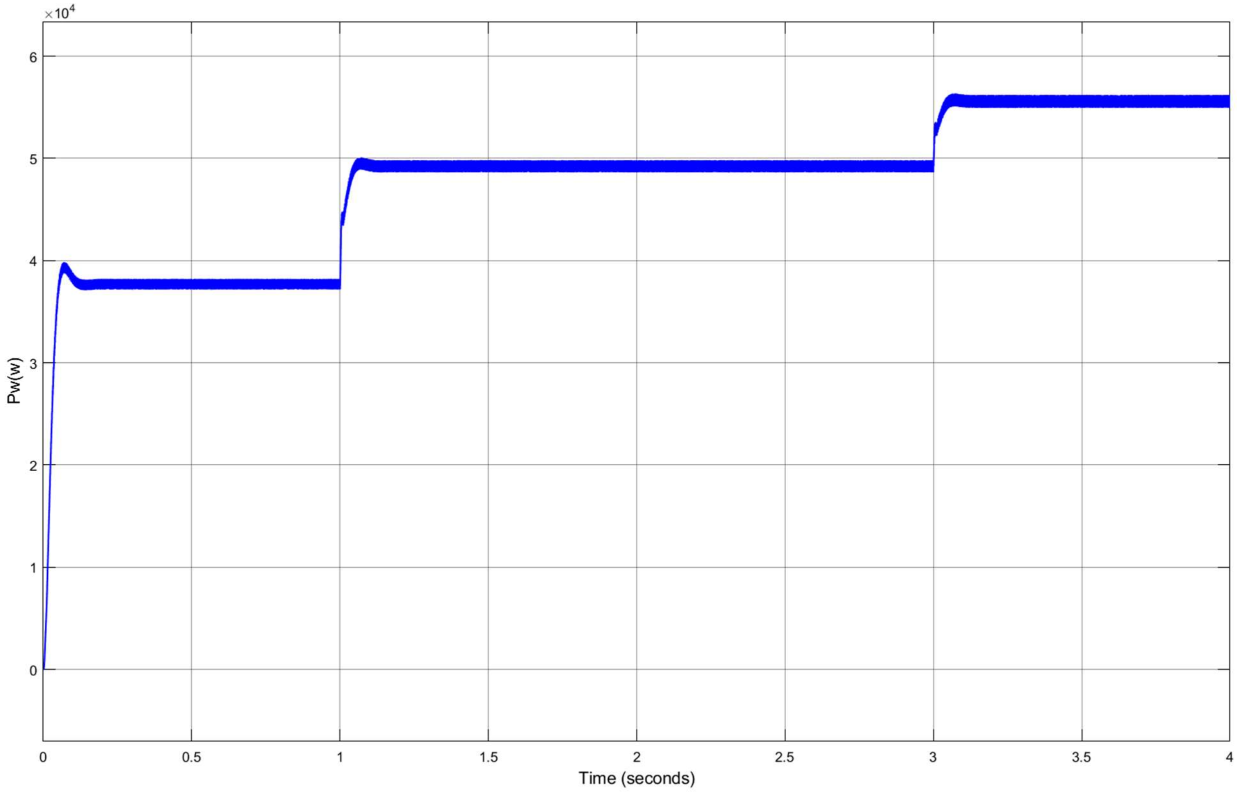

×10^4
Ppv(w)
Time (seconds)

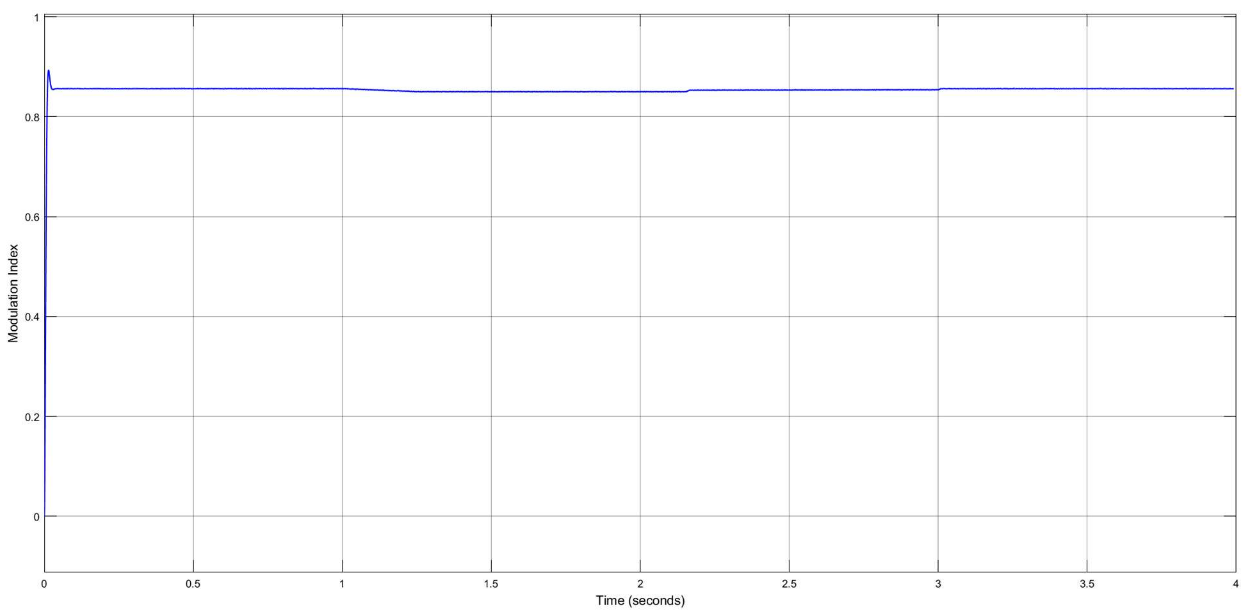

Dutycycle
0.5
0.4
0.3
0.2
0.1
0
0
0.5
1
1.5
2
2.5
3
3.5
4
Time (seconds)

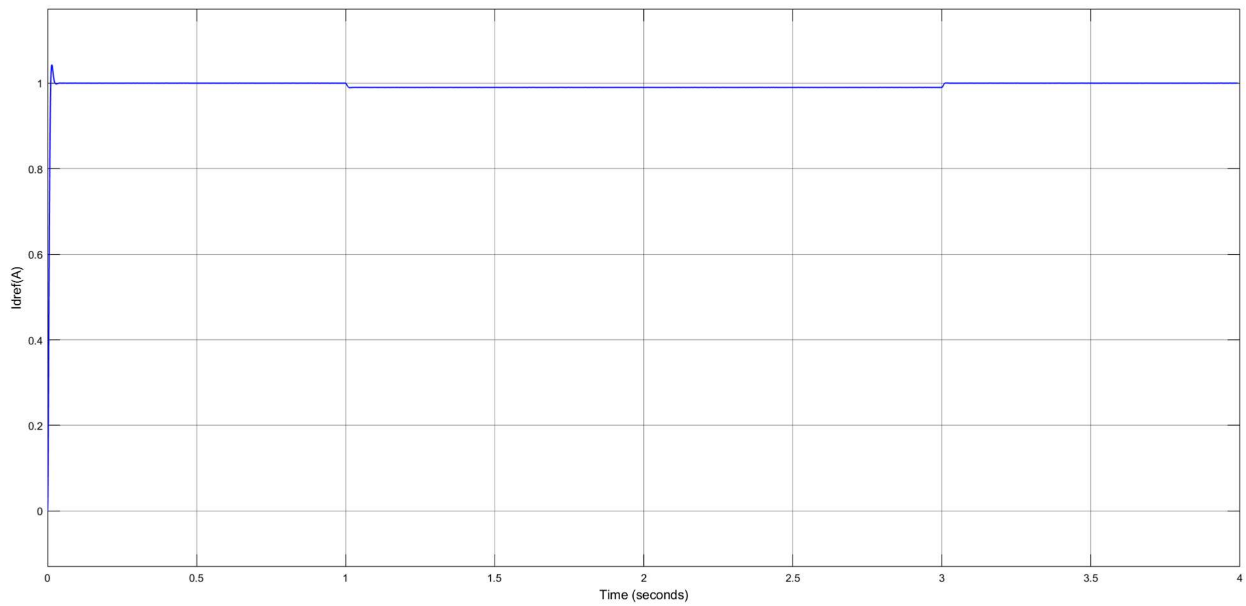

Rotorspeed
180
160
140
120
100
80
60
40
20
0
-20
0
0.5
1
1.5
2
2.5
3
3.5
4
Time (seconds)


Iw(A)
Time (seconds)

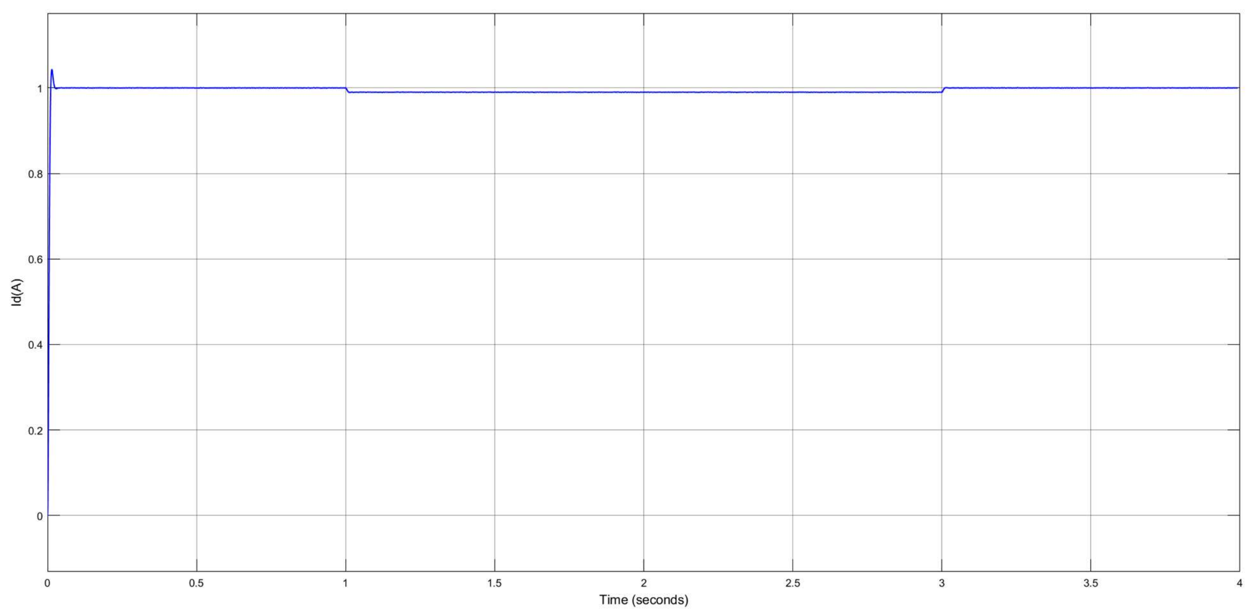

Vw(V)
Time (seconds)


×10^4
Pw(w)
Time (seconds)

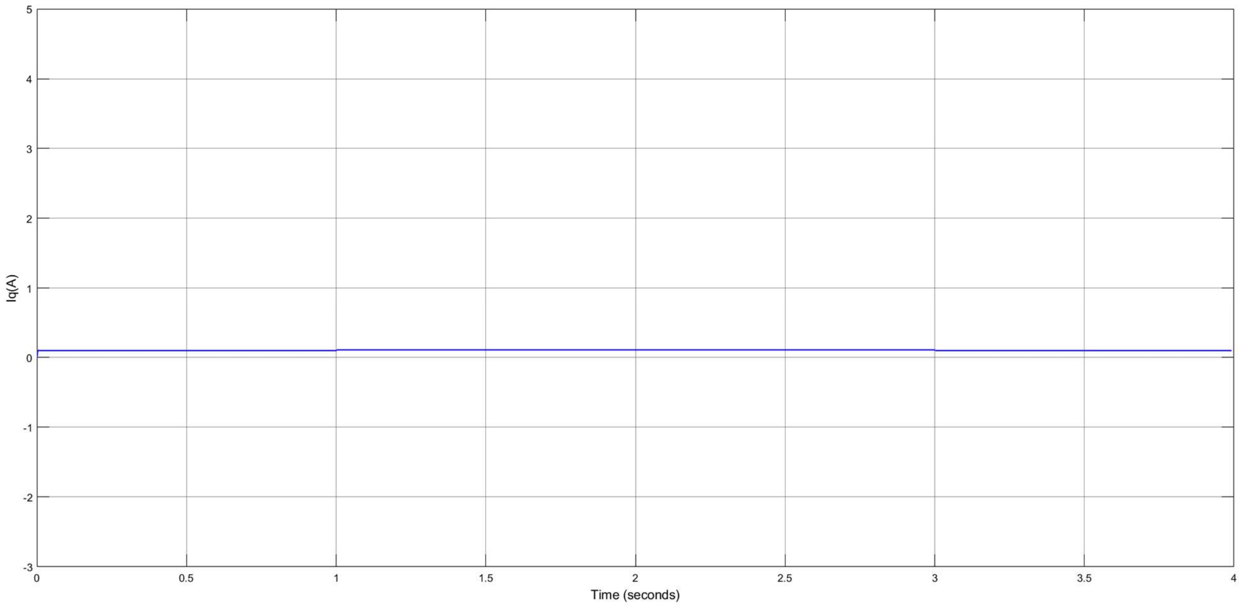

Modulation Index
Time (seconds)

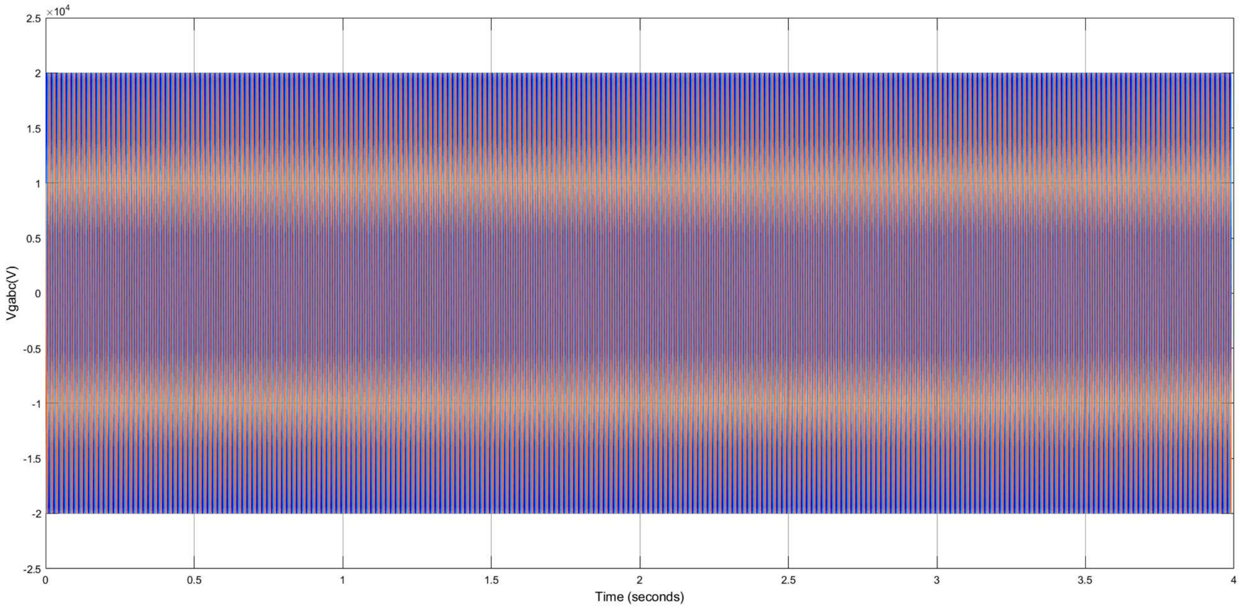


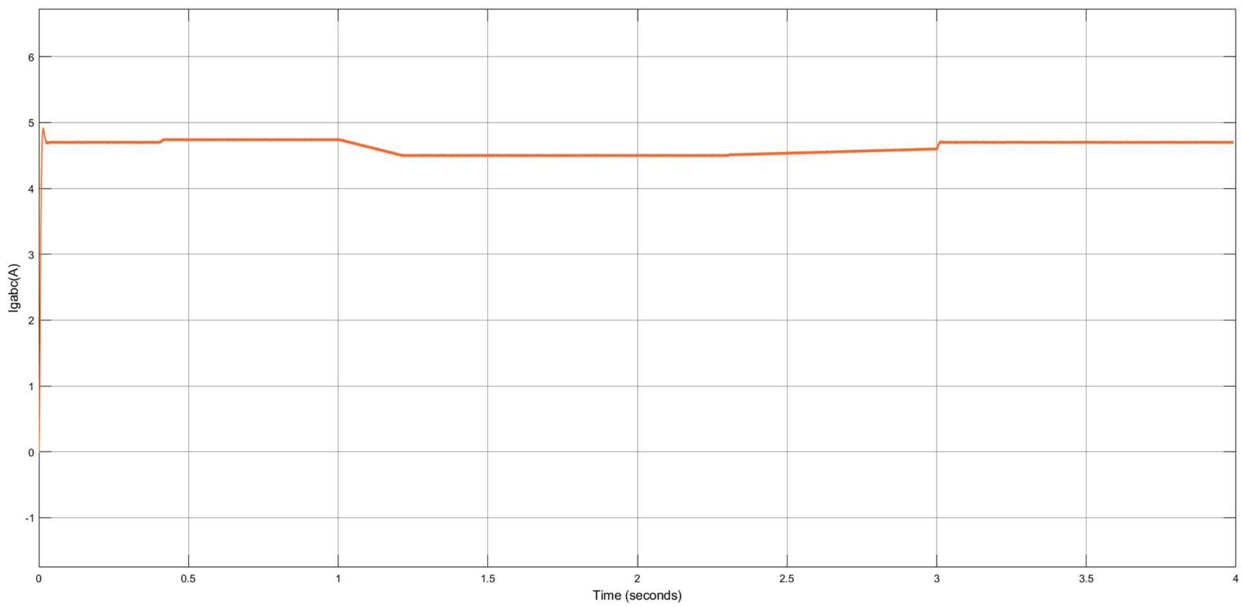
1
0.8
0.6
0.4
0.2
0
Idref(A)
0
0.5
1
1.5
2
2.5
3
3.5
4
Time (seconds)

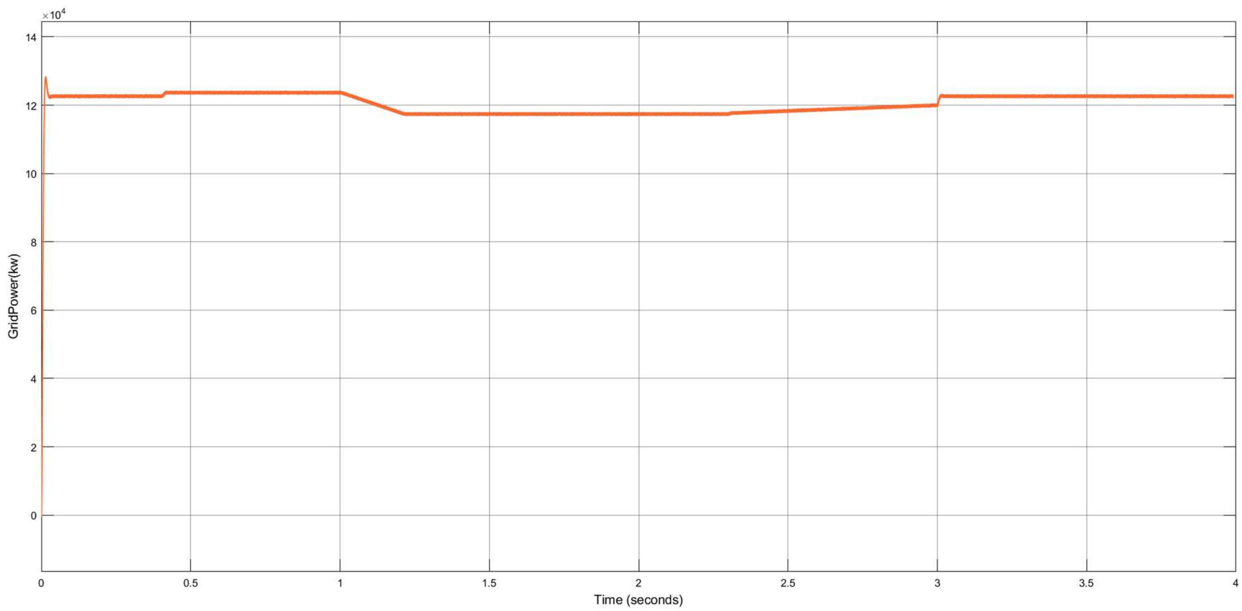


1
0.8
0.6
0.4
0.2
0
Id(A)
0
0.5
1
1.5
2
2.5
3
3.5
4
Time (seconds)


Iq(A)
Time (seconds)


×10^4
Vgabc(V)
Time (seconds)


Igabc(A)
Time (seconds)


GridPower(kw)
Time (seconds)