

Adaptive Neuro-Fuzzy Based Intelligent Control For Enhanced Stability And Power Quality Of Grid-Connected Hybrid Pv–Wind Energy Systems

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Abstract

The increasing application of renewable energy sources in the contemporary power system needs intelligent control approaches to tackle the problems related to the intermittency of sources, nonlinearity, and power quality issues. In this paper, a novel intelligent control approach based on an Adaptive Neuro-Fuzzy Inference System (ANFIS) is introduced for a grid connected hybrid system of Photovoltaic (PV) – wind energy system. The presented intelligent controller uses the capability of learning neural networks and reasoning based on fuzzy logic to produce optimal switching signals for the DC-AC inverter. The DC-link voltage error and its change rate have been selected as the input variables of the ANFIS controller for implementing adaptive control under different operational situations. The proposed approach is implemented in MATLAB / Simulink by using the combination of PV and wind energy source through a DC-link, maximum power point tracking (MPPT), three-level inverter, filter and grid interface. The performance of the controller has been analyzed under the conditions of variation in the load requirement, EV charging requirement, generation of renewable energy, DC-link voltage response, grid current response and Total Harmonic Distortion (THD). The obtained results indicate good power flow control, DC-link voltage response, grid current balancing, and enhanced power quality. The suggested ANFIS controller gives a lower grid current THD of 1.91%, while FOPID and fuzzy-PI controllers give grid current THDs of 2.20% and 3.50%, respectively. Thus, the suggested ANFIS controller exhibits better adaptive control performance. The suggested intelligent control approach provides a solution for improving stability and grid integration performance of PV–wind energy systems.

Keywords-Adaptive Neuro-Fuzzy Inference System (ANFIS); Hybrid Photovoltaic-Wind Energy System; Grid-Connected Renewable Energy; Intelligent Inverter Control; DC-Link Voltage Regulation; Power Quality Improvement; Total Harmonic Distortion (THD); Artificial Intelligence-Based Control.

I. Introduction

The rising need for sustainable energy across the world has led to the incorporation of renewable energy into modern energy systems. PV and wind energy systems are some of the most promising options owing to their ability to generate clean energy and reduced environmental effects. However, the problem of intermittency associated with renewable energy poses various difficulties including that of power variations, voltage variations and ensuring reliable operation when connected to the grid under different environmental conditions. The use of hybrid PV-wind systems is one solution to ensure better access to



renewable energy owing to the complementary nature of the generation systems [1]. Hybrid renewable energy systems that operate when connected to the grid need sophisticated control methodologies to ensure that the system operates effectively. Changes in solar radiation, wind speed and load requirement can have significant effects on energy generation and lead to instabilities in the DC-link voltage [2]. Traditional controllers like PI, PID, and fuzzy control techniques have been commonly used for renewable energy conversion systems; nevertheless, due to their dependency on fixed parameter values, these controllers are not very effective during drastic changes in the conditions of operation. In order to eliminate these shortcomings of conventional controllers, intelligent control algorithms that use Artificial Intelligence (AI) have received much attention in recent times for renewable energy systems [3].

The use of intelligent control algorithms for renewable energy sources has greatly improved the performance of hybrid renewable energy systems by maximizing the extraction of power, controlling voltage, and improving the performance of converters. New intelligent control algorithms have shown great potential for maintaining system stability and avoiding performance degradations due to uncertainties in renewable sources [4]. Another important factor that must be addressed in grid-tied renewable energy systems is power quality owing to harmonic distortion, fluctuations in currents, and converter switching. The use of intelligent control schemes has been more common in the recent past, as they have helped enhance the efficiency of inverters, minimize harmonic content, and ensure stable interaction between the grid and inverter in dynamic operating conditions [5]. In addition to conversion level control, energy management becomes crucial in terms of integration of renewables, storage, electricity trading between grid and renewables, and load variations. AI-based energy management approaches become very useful in terms of making decisions for power distribution in such systems [6]. The recent advances in smart grid and micro-grid systems have once again proved the necessity of efficient energy management, prediction, and power flow control techniques for effective use of renewable energy sources [7].

Along with control at the level of converter, the proper energy management system and power flow regulation play a critical role in ensuring reliable and efficient performance of renewable energy systems that are connected to the grid. The intelligent energy management methods can help with providing adaptive decision making in cases when there are variations in generation of renewable energy, load requirements, and energy availability [13]. The incorporation of control and management methods allows ensuring stable power transactions between the renewable energy resources, storage units, and grids [14]. In addition, monitoring and adaptive energy management techniques should be used to increase the flexibility of renewable-based microgrids [15]. The integration of artificial intelligence into advanced energy systems allows optimizing, predicting, and improving the performance of renewable energy integration [16]. Intelligent scheduling techniques and those based on neural networks enable more efficient use of renewable energy by dealing with uncertainties involved with the variable generation and varying demand profile [17]. Energy management systems that utilize artificial intelligence also facilitate the coordination, reliability, and

sustainability of smart grids with renewable energy sources [18]. In addition to the above, adaptive online control is essential to enable efficient power flow and stable operation of hybrid energy systems connected to the grid under varying operating conditions [19].

Table 1. Comparative Review of Recent Intelligent Control Strategies for Grid-Connected Hybrid Renewable Energy Systems

Ref .	Objective	Technique / Method	Application	Major Findings	Limitation / Research Gap	Relevance to Present Work
[1]	Improve control and performance of PV–wind hybrid systems	ANFIS-based intelligent control strategy	Grid-connected PV–wind hybrid energy system	Improved adaptive control and renewable integration performance	Limited analysis of DC-link regulation and detailed power quality improvement	Directly supports ANFIS-based hybrid renewable control
[2]	Enhance power quality in hybrid renewable systems	ANFIS controller with hybrid series active power filter	Grid-connected PV/wind system	Reduced harmonics and improved power quality	Focus mainly on filtering; limited inverter control analysis	Supports ANFIS application for power quality enhancement
[3]	Improve stability of hybrid microgrid operation	GA-ANFIS controller	PV–wind hybrid microgrid	Improved adaptive response and system stability	Optimization increases computational complexity	Supports optimized ANFIS-based nonlinear control
[4]	Improve robustness of hybrid power system control	ANFIS-based double integral sliding mode control	Grid-integrated hybrid energy system	Enhanced disturbance rejection and voltage regulation	Complex controller design and tuning requirements	Supports intelligent adaptive controller development
[5]	Improve converter control in	GAO-ANFIS controller	Hybrid solar PV–wind	Improved converter performance	Requires optimization process and	Relevant for ANFIS-based

	PV–wind systems	with seven-level converter	power system	e and power quality	higher computation	inverter control
[6]	Improve renewable energy extraction and grid control	Modified DTC with ANFIS-based MPPT	Grid-connected hybrid renewable system	Enhanced MPPT and dynamic performance	PV and wind controls are not fully coordinated	Supports hybrid renewable integration strategy
[7]	Improve MPPT performance of hybrid microgrid	Optimized ANFIS with ZOA and AGTO algorithms	Hybrid renewable microgrid	Improved maximum power tracking capability	Optimization increases controller complexity	Supports advanced ANFIS-based MPPT approaches
[8]	Improve wind energy conversion control	Hybrid ANFIS–PI robust controller	Wind turbine generation system	Improved robustness and tracking performance	Limited application to complete hybrid systems	Supports ANFIS replacement of conventional controllers
[9]	Develop efficient MPPT technique	Intelligent maximum power tracking method	Grid-connected PV–wind system	Improved power extraction under variable conditions	Focus limited to MPPT performance	Supports renewable power optimization
[10]	Improve grid-tied solar conversion control	ANROA-based optimization control	Grid-connected solar energy conversion system	Improved efficiency and control performance	Optimization-based methods lack adaptive learning	Highlights need for AI-based adaptive control
[11]	Improve microgrid power quality and management	Adaptive control scheme	Renewable energy microgrid	Improved power management and quality	Limited focus on ANFIS-based inverter switching	Supports adaptive power quality enhancement

[12]	Optimize renewable energy flow management	Intelligent energy management system	Hybrid renewable EV charging station	Improved energy distribution and charging management	Mainly focused on EMS, not converter control	Supports coordinated renewable energy management
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Even though PI, FOPID, and fuzzy-PI controllers cannot overcome the problem of dealing with the nonlinear nature and fast change in hybrid PV-wind generation systems, there is the need for adaptive intelligent control to achieve more stability and better power quality. The main novelty of this study can be found in the design of the ANFIS adaptive controller for the grid-tied hybrid PV-wind energy system that optimizes the switching signal of the inverter by learning the nonlinear mapping between DC-link voltage error and its derivative. The objective of the study is to create an intelligent control algorithm using artificial intelligence (AI). The proposed AI method intends to provide control inputs for driving the DC/AC converters such that the energy conversion becomes efficient and the system performance is improved by managing the changes in the energy demand in varying loads.

II. Research Methodology

This study focusses on developing an intelligent controller based on ANFIS approach for the grid connected hybrid PV-Wind energy generation system. The proposed research methodology starts with designing an intelligent ANFIS controller, which employs artificial intelligence techniques such as neural network learning and fuzzy inference techniques to cope up with the non-linear behaviour of the renewable energy generation system. The inputs of ANFIS controller are selected as the DC-link voltage error (e) and change in voltage error (Δe), which generate the optimized switching signal of the DC-AC inverter. The ANFIS controller is developed through the training procedure which involves the following steps: generation of data sets, data pre-processing, selection of membership functions and hybrid learning optimization. The simulation model for the proposed methodology is developed using MATLAB/Simulink, which involves the integration of PV and Wind energy resources through DC-link along with MPPT control, three level inverter, filter and grid interface. The performance of the proposed approach is analysed using various operating conditions including different levels of irradiance, wind speed and loads.

2.1 Development of ANFIS Intelligent Controller

ANFIS controller incorporates learning abilities of artificial neural networks along with fuzzy logic for an adaptive control system for the hybrid photovoltaic-wind energy system. Unlike PI, FOPID, and fuzzy-PI controllers, the ANFIS controller learns the behavior of the nonlinear system and adapts to varying operating conditions. The inputs considered by the controller are the error of DC link voltage (e) and change in the error (Δe). The output of the controller is the control signal for DC-AC inverter switching. The adaptive control will assist

in maintaining DC-link voltage stability and reducing power fluctuations in the system.
Figure 1 Solar PV-Wind Hybrid Energy System.

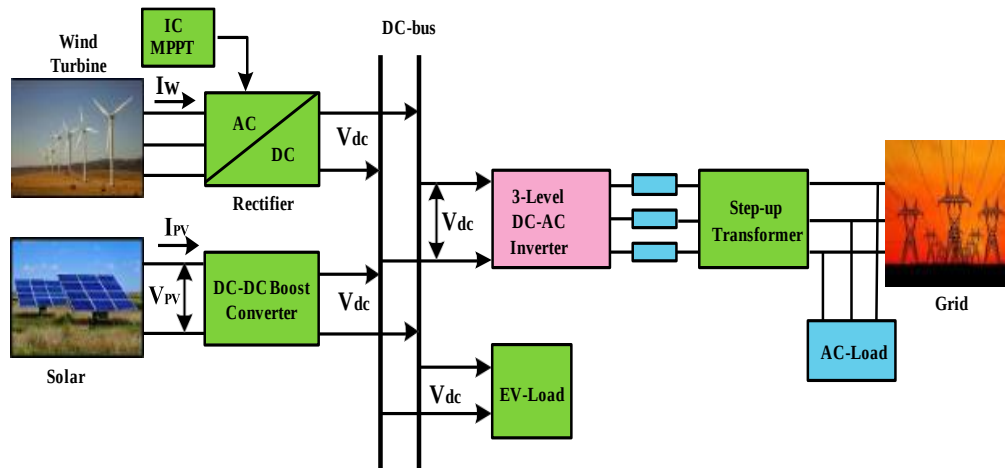


Figure 1 Solar PV-Wind Hybrid Energy System

2.2 ANFIS Architecture

- **Fuzzification Layer:** The voltage error (e) and voltage error rate of change (Δe) are fuzzified by using Gaussian membership functions.
- **Rule Layer:** Fuzzy IF-THEN rules are applied on the fuzzified input variables and the firing strengths of each rule are calculated.
- **Normalization Layer:** The firing strengths are normalized in order to ascertain the proportion of each fuzzy rule toward the output.
- **Defuzzification Layer:** The normalized fuzzy data is defuzzified in order to produce numerical control actions needed for the inverter.
- **Summation Layer:** All the rule outputs are summed up in order to produce the ANFIS control signal.

2.3 ANFIS Training Methodology

Training of the Adaptive Neuro-Fuzzy Inference System (ANFIS) process is a critical stage in the designing of the intelligent controller for the combined photovoltaic-wind energy system. Correct training will enable ANFIS to properly establish the nonlinear relationship between the inputs of the system (voltage error and its change) and the desired control output. Training process consists of several steps which include the following: dataset creation, data pre-processing, membership functions selection and hybrid learning algorithm application. Each step is important in order to increase the efficiency of the controller under various operation conditions such as changes in solar irradiation, wind speed and load.

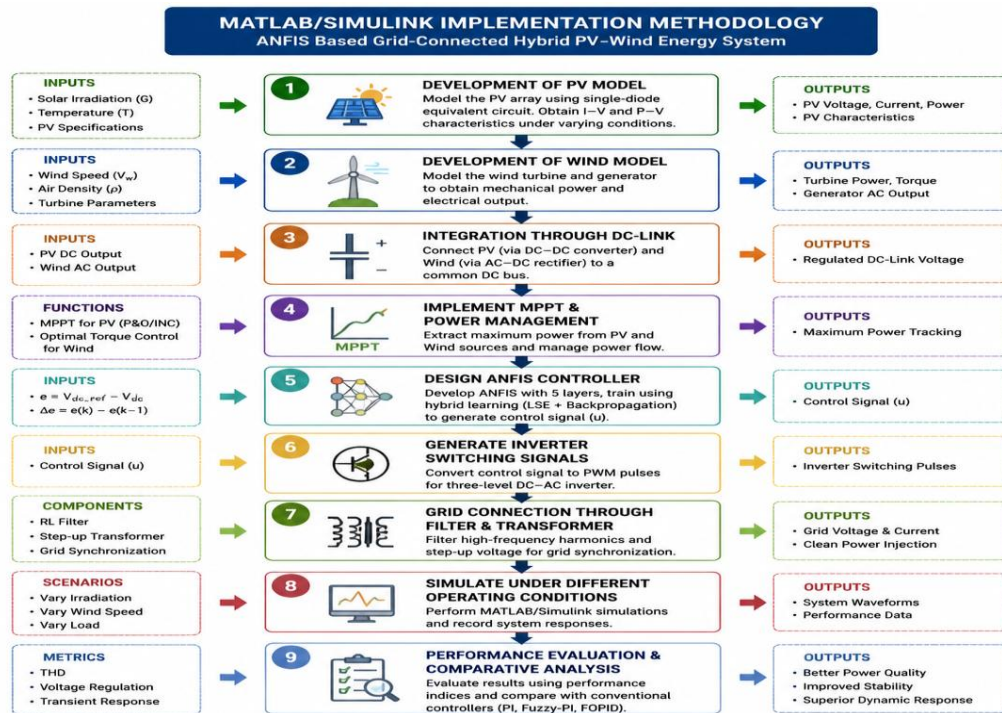


Figure 2 MATLAB/SIMULINK Implementation Methodology of ANFIS-Based Grid-Connected Hybrid PV-Wind Energy System

The Figure 2 above illustrates the MATLAB/Simulink development technique for the ANFIS based grid-connected PV-wind hybrid energy system. First of all, modeling of PV and wind energy resources is done, and both the energy resources are connected through common DC link, followed by maximum power extraction through MPPT. ANFIS controller developed in this paper uses the error in DC link voltage along with the change in error for producing control action using hybrid learning scheme. The control action produced is then converted into switching signals for control of three-level DC-AC inverter. The output from inverter is passed through RL filter and transformer for injecting into the grid. Lastly, the performance of the system is analysed based on its efficiency during changing conditions of irradiance, wind speed, and load demand using THD, voltage regulation, and transient response analysis with comparison to traditional controllers.

2.4 Dataset Generation

The procedure of ANFIS training involves the generation of a database containing all possible cases for the operations of the hybrid renewable energy systems. In the present approach, the database was generated through the simulations carried out using the MATLAB/Simulink program. The change in the values of the solar irradiation, wind speed, and the load conditions was performed while simulating the systems. The change in the values of the solar irradiation is due to the variation of the value of the solar irradiation throughout a day, between different seasons, and as a result of presence of the clouds. Variation in the value of the wind speed is also considered in order to model the real wind

conditions. Moreover, the variation in the values of the load is also considered in order to make the database diversified and enable the controller to respond to the sudden load change.

2.5 Data Pre-processing

This database forms the foundation of the learning process in which multiple operational scenarios are considered. Following the creation of the dataset, the pre-processing stage comes into play in order to ensure that the training process will be as good as possible. Here are the steps involved in the pre-processing process:

- **Normalization:** The input and output datasets are normalized, meaning that their values will be scaled to certain values (usually between 0 and 1) in order to avoid numerical problems and to ensure that each input has the same weight in the learning process.
- **Filtering:** All the noisy and inaccurate data is filtered in order to avoid mis-learning of the algorithm and to increase the speed of convergence.
- **Training and Testing:** The processed dataset is divided into two parts – the training part that will be used for the adjustment of ANFIS parameters, and testing one that will provide us with the information about generalization capabilities of the controller and its ability to operate in new conditions.

As already mentioned, pre-processing is a vital step in the process, because the quality of the input data affects the quality of ANFIS training.

III. Results and Discussion

The performance of the adaptive controller using ANFIS for the grid-integrated hybrid photovoltaic wind energy system is analyzed based on dynamic operating conditions such as load variations, EVs charging requirements, voltage control at DC link, response of inverter, grid currents, and THD analysis. From the results, it can be seen that the performance of the adaptive controller in terms of power flow is adequate with fast settling and minimal oscillations for changes in load. There are minimal fluctuations in DC-link voltage as well as synchronized and balanced responses of the inverter output and grid current. Additionally, the proposed adaptive controller provides the lowest value of THD at 1.91% as compared to 2.20% by FOPID and 3.50% by fuzzy-PI. Overall, the outcomes confirm the potential of ANFIS in improving voltage regulation, performance, and the process of integrating the system in the power grid.

3.1 Load Current Change

Figure 3 mentioned below shows the change in Load-1 current (I_{load_1}) with respect to time when there is a sudden load change. The x-axis represents the time in seconds, and the y-axis represents the load current in amperes. At the initial period, between 0.2 s to 0.5 s, the load current remains almost constant at about 1 A, implying that the system is working under the steady state condition with a constant load. From 0.5 s, a sudden increase in load occurs, leading to an immediate increase in the load current. There is a sudden increase in load current from about 1 A to about 8 A in a very short transient period. After a sudden load change, the load current immediately becomes constant at about 8 A up to 0.8 s. There are no oscillations and overshoots in the process, which indicate good control over power flow.

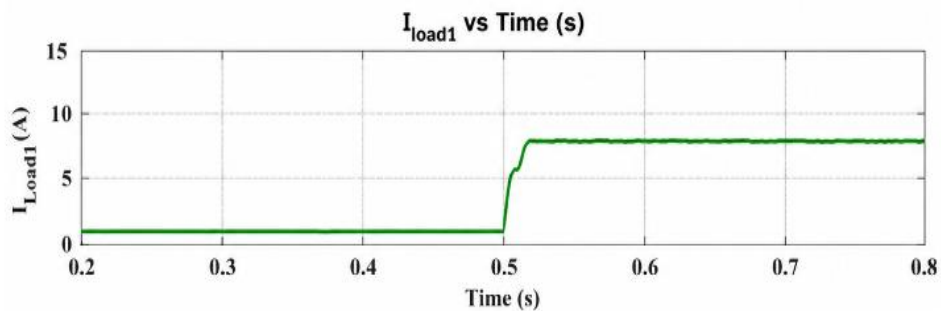


Figure 3 Load Current Response During Step Change in Electrical Demand (I_{load1})

3.2 EV Load Current Change

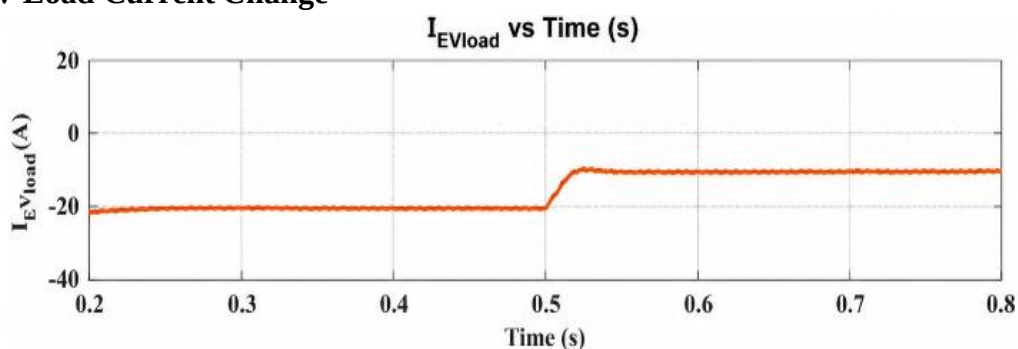


Figure 4 Electric Vehicle Load Current Response Under Step Load Variation (I_{EVload})

The above graph in Figure 4 depicts the response of the load current of the electric vehicle I_{EVload} to time. The time is plotted along the x-axis in seconds, whereas the charging current of the electric vehicle is depicted along the y-axis in amperes. At the beginning, from 0.2 s to 0.5 s, the charging current of the electric vehicle is almost constant and is about -20 A. However, after 0.5 s, there occurs a change in the operational state. The current of the electric vehicle starts increasing from approximately -20 A to nearly -10 A within a very short duration of transient period. Later on, the charging current of the electric vehicle becomes almost constant again with little variations and settles down to about -10 A at around 0.55 s to 0.8 s. The minus sign of the current of EV load suggests that energy is fed into the EV battery (charging process). The gradual nature of switching and the fast stabilization of the system in the wake of changes in the load are indicative of the effectiveness of the developed control approach in dealing with the charging requirement of the EVs. The control scheme has regulated the transfer of energy among renewable energy sources, DC-link, and EV load in a stable manner with minimal oscillations.

3.3 DC-Link Voltage

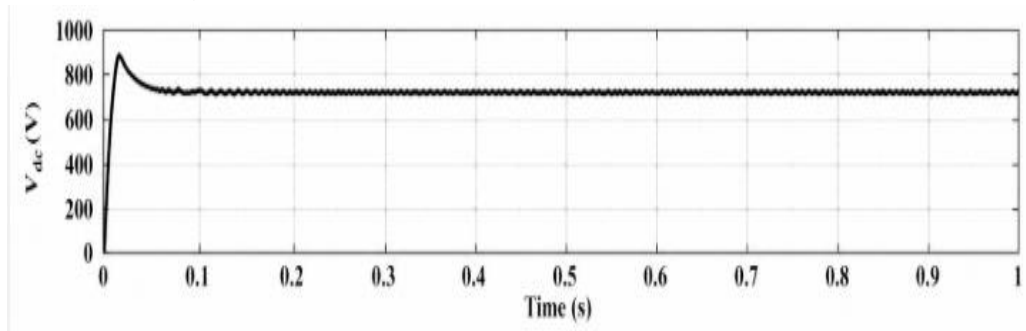


Figure 5 DC-Link Voltage Response (V_{dc} vs. Time (s))

The above Figure 5 provides an illustration of the DC-link voltage (V_{dc}) response of the hybrid renewable energy system versus time. The time is shown along the x-axis while the y-axis shows the DC-link voltage value in volts. Initially, the DC-link voltage rises sharply from 0 V to reach a maximum value of 850–900 V due to charging of the DC-link capacitor and the transient at the start of the simulation. After attaining the maximum voltage value, there is a slight overshoot, and then the voltage begins to reduce. After approximately 0.1 s, the voltage stabilizes at a value between 700–720 V where it becomes almost constant for the rest of the simulation time. The DC-link voltage response is characterized by very minimal voltage ripples. The fast settling time, minimized overshoot, and steady state voltage indicate that the suggested control method is effective in sustaining the stability of DC link voltage. Controlled DC link voltage helps to achieve power balance among the renewable energy sources, converters, EV load, and grid interface. This capability is important in enhancing the reliability and efficiency of the hybrid photovoltaic-wind energy system.

3.4 Inverter Output Voltage

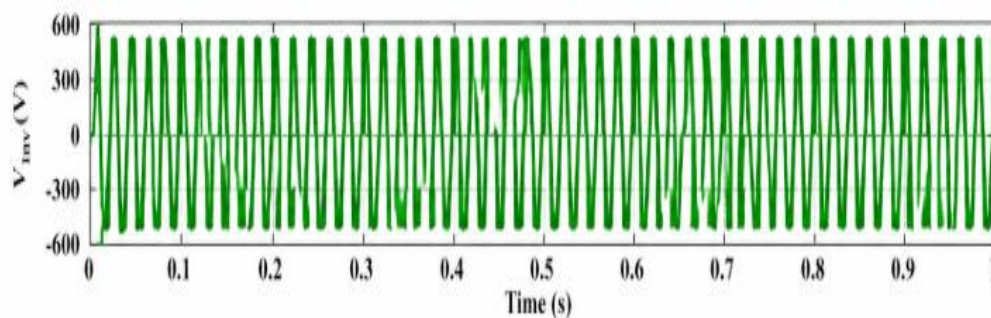


Figure 6: Inverter Output Voltage Response (V_{inv} vs Time (s))

The following graph in Figure 6 depicts the inverter output voltage (V_{inv}) waveform vs. time for the PV-Wind Hybrid Energy System. The horizontal axis is the simulation time in seconds, whereas the vertical axis corresponds to inverter voltage in volts. The above waveform depicts the periodic nature of alternating voltage waveform with peak value of approximately ± 500 to 600 volts, implying successful conversion of DC-link voltage to AC voltage using the inverter. The inverter voltage waveform is shown to be periodic and symmetric during the simulation time ranging from 0 to 1 second, showing proper

functioning of the inverter and its switching mechanism. This implies that the switching pulses of the inverter produced using the suggested controller control the output voltage. The constant sinusoidal waveform of the alternating voltage is a sign that the inverter functions correctly for power conversion and synchronization. The stability of the voltage waveform shows that the new ANFIS controller regulates the inverter under fluctuating conditions of renewable energy generation and load, hence improving voltage regulation and power quality.

3.5 ANFIS Grid Current

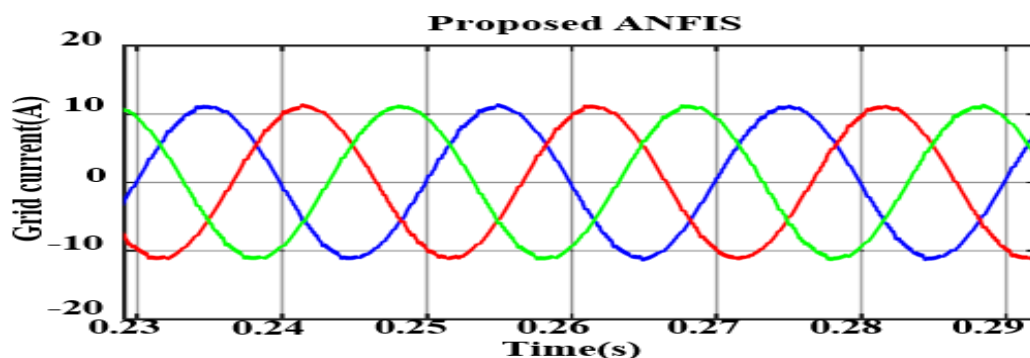


Figure 7 Grid Current Response with Proposed ANFIS Controller

Figure 7 shows the three-phase grid current wave form generated by the above mentioned ANFIS control approach. The x-axis shows time, while the y-axis shows the grid current in amperes. The wave form includes three sinusoidal current values with a peak value of around ± 10 -12A corresponding to the three phases of the grid connected hybrid renewable energy generation system. These waveforms are sinusoidal in nature and are symmetrical with almost constant amplitude throughout the entire observation period, which is from 0.23 seconds to 0.29 seconds. The three phase currents are shifted with an electrical phase angle difference of 120° , and this clearly shows that the phases are balanced and synchronized. This shows the efficiency of ANFIS controller in producing inverter switch timing signals. The steady and stable response of grid current clearly shows that the suggested control strategy based on ANFIS is successful in controlling the amount of power supplied to the grid. The capability of ANFIS to learn adaptively makes ANFIS capable of dealing with the nonlinearity of the system and variability of renewable energy production, thus ensuring reduced current fluctuations and increased power efficiency of the PV-Wind energy system.

3.6 THD Comparison

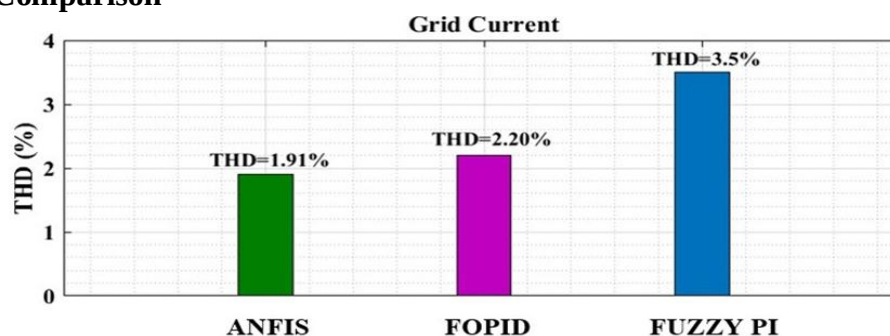


Figure 8 Comparison of Grid Current Total Harmonic Distortion (THD) Using Different Controllers

Figure 8 shows the Grid current total harmonic distortion (THD) of the proposed ANFIS controller, FOPID controller, and Fuzzy-PI controller are shown in the above figure. Total harmonic distortion (THD) is an essential parameter which is utilized for judging the quality of power in the grid-connected hybrid PV-wind energy system. A lower value of THD represents low harmonic distortion in the current. The newly introduced ANFIS controller has obtained the least value of THD, which is 1.91%, thereby showing better capability in harmonics reduction when compared to the other control methods. The FOPID controller yields the THD of 2.20% whereas the traditional fuzzy-PI controller gives the highest THD value of 3.5%. The low THD value is mainly due to the ability of ANFIS to learn from the environment and adapt to non-linear behavior of the system and generate optimal inverter switching signals. From the above results, it is clear that the proposed ANFIS control technique produces a good grid current quality because it reduces harmonic content and enhances inverter operation. The proposed controller shows significant improvement in THD with a reduction of around 13.2% as compared to FOPID and 45.4% as compared to Fuzzy-PI controller.

3.7 Discussion

The obtained results show that the proposed ANFIS-based controller can adaptively control a system more efficiently than the traditional controllers by controlling the nonlinearities in renewable energy production and load demand. The better stability of the DC-link voltage, less fluctuation, and balanced grid current indicate that ANFIS based inverter control is effective in ensuring efficient power conversion. The low value of THD achieved by the proposed controller indicates the ability of the controller to produce an optimal switching signal and improve the quality of grid power. This is owing to the learning and adaptation feature of ANFIS, whereby the controller adapts to the changing operating environment and hence improves the performance of the overall hybrid renewable energy system that is connected to the electrical grid.

IV. Conclusion

The study proposes an adaptive control technique based on NFIS for the grid-connected hybrid photovoltaic-wind energy generation system in order to enhance voltage regulation, power quality, and performance. The proposed control technique makes use of neural network learning and fuzzy inference features to deal with the nonlinearity in the renewable energy systems and provide optimized switching signals for the DC-AC inverter. It is evident from the performance analysis conducted under various operating conditions, including the effect of load changes, EV charging, response of DC-link voltage, inverter performance, and grid current characteristics that the proposed scheme is quite effective. The ANFIS controller is able to provide stable and smooth DC-link voltage with low fluctuations, maintain balance and synchronization in grid current and improved power conversion efficiency. Moreover, the grid current THD obtained with the proposed control technique is 1.91%, as compared to 2.20% with FOPID and 3.50% with fuzzy-PI controllers.

This is evident that the proposed control technique has superior performance in terms of reducing harmonics and improving power quality. The results prove the effectiveness of the proposed control framework for the improvement of hybrid PV-Wind energy generation system stability and performance. The proposed framework can be further extended through real-time hardware implementation, integration of advanced optimization algorithms, and experimental validation under practical renewable energy operating conditions.

References

- [1] Babu, T. M., Chenchireddy, K., Kumar, K. K., Nehal, V., Srihitha, S., & Vikas, M. R. (2024). Intelligent control strategies for grid-connected photovoltaic wind hybrid energy systems using ANFIS. *International Journal of Advances in Applied Sciences*, 13(3), 497-506.
- [2] Cholamuthu, P., Irusappan, B., Paramasivam, S. K., Ramu, S. K., Muthusamy, S., Panchal, H., ... & Khan, B. (2022). A grid-connected solar PV/Wind turbine based hybrid energy system using anfis controller for hybrid series active power filter to improve the power quality. *International Transactions on Electrical Energy Systems*, 2022(1), 9374638.
- [3] Aloo, L. A., Kihato, P. K., Kamau, S. I., & Orenge, R. S. (2023). Modeling and control of a photovoltaic-wind hybrid microgrid system using GA-ANFIS. *Heliyon*, 9(4).
- [4] Banu, J. B., Muthuramalingam, M., & Nammalvar, P. (2022). ANFIS based double integral sliding mode control for a grid-integrated hybrid power system. *Optik*, 270, 170013.
- [5] Bhavani, N. V. A., Singh, A. K., & Kumar, D. V. (2024). Modeling of GAO-ANFIS controller based hybrid solar photovoltaic and wind power system with seven-level converter. *Energy Storage and Saving*, 3(4), 259-269.
- [6] Mehta, M., & Mehta, B. (2024). Control strategies for grid-connected hybrid renewable energy systems: Integrating modified direct torque control based doubly fed induction generator and ANFIS based maximum power point tracking for solar PV generation. *e-Prime-Advances in Electrical Engineering, Electronics and Energy*, 8, 100575.
- [7] Elymany, M. M., Enany, M. A., & Elsonbaty, N. A. (2024). Hybrid optimized-ANFIS based MPPT for hybrid microgrid using zebra optimization algorithm and artificial gorilla troops optimizer. *Energy Conversion and Management*, 299, 117809.
- [8] Ishaque, M., Laghari, J. A., Bhayo, M. A., Chandio, S., & Mahariq, I. (2024). Hybrid ANFIS-PI-Based robust control of wind turbine power generation system. *International Transactions on Electrical Energy Systems*, 2024(1), 2389751.
- [9] Renjith, A., & Selvam, P. (2023). Efficient maximum power tracking technique in grid connected PV-wind system. *Electric Power Systems Research*, 214, 108955.
- [10] Prasad, D., Kumar, N., Sharma, R., Malik, H., Márquez, F. P. G., & Pinar-Pérez, J. M. (2023). A novel ANROA based control approach for grid-tied multi-functional solar energy conversion system. *Energy Reports*, 9, 2044-2057.



- [11] Babu, N. (2024). Power quality enrichment and power management using an adaptive control scheme in Microgrid System. ECTI Transactions on Electrical Engineering, Electronics, and Communications, 22(3).
- [12] Karmaker, A. K., Hossain, M. A., Pota, H. R., Onen, A., & Jung, J. (2023). Energy management system for hybrid renewable energy-based electric vehicle charging station. IEEE Access, 11, 27793-27805.
- [13] Brahmane, A. V., & Deshmukh, S. R. (2023, July). Artificial intelligence-based energy management system for renewable energy sources. In 2023 4th International Conference on Electronics and Sustainable Communication Systems (ICESC) (pp. 727-731). IEEE.
- [14] Karri, S. R., Gugulothu, R., & Bhookya, N. (2023, January). Control and Energy Management of DC Nano Grid-Connected Solar PV, Fuel cell and Battery Energy Storage System. In 2023 International Conference on Power Electronics and Energy (ICPEE) (pp. 1-6). IEEE.
- [15] Rahman, A., Adhena, H. H., Georgious, R., & Garcia, P. (2022). Implementation of an Energy Management System for Real-Time Power Flow Control in AC Microgrid. arXiv preprint arXiv:2209.06377.
- [16] Bhavya, R., Manjuladevi, P., Santhoshini, E. S., Ramya, M., & Dhanapal, R. (2023, April). Development and improving energy management system in smart grid through integration with renewable energy system with AI and internet of things. In 2023 International Conference on Inventive Computation Technologies (ICICT) (pp. 398-403). IEEE.
- [17] Nakip, M., Çopur, O., Biyik, E., & Güzeliş, C. (2023). Renewable energy management in smart home environment via forecast embedded scheduling based on Recurrent Trend Predictive Neural Network. Applied Energy, 340, 121014.
- [18] Kumar, A., Alaraj, M., Rizwan, M., & Nangia, U. (2021). Novel AI based energy management system for smart grid with RES integration. IEEE Access, 9, 162530-162542.
- [19] Taha, M. S., Abdeltawab, H. H., & Mohamed, Y. A. R. I. (2018). An online energy management system for a grid-connected hybrid energy source. IEEE Journal of Emerging and Selected Topics in Power Electronics, 6(4), 2015-2030.