ANFIS CONTROLLER FOR EFFICIENT POWER FLOW AND STABILITY IN AC/DC MICROGRIDS WITH SOLID-STATE TRANSFORMER

M.Kavya[1], P. Rizwan[2], Y. Manasa[3]

[1] PG-Scholar, Department of EEE, JNTUA College of Engineering, Anantapuramu, India.
[2, 3] Assistant Professor, Department of EEE, JNTUA College of Engineering, Anantapuramu, India.

ABSTRACT: This paper presents an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller for optimizing power flow and stability in AC/DC hybrid microgrids integrated with a Solid-State Transformer (SST). The decentralized nature and intermittency of renewable energy sources introduce voltage fluctuations and power imbalances, affecting grid performance. To address these challenges, an ANFIS-based controller is proposed to enhance power flow coordination between the SST, AC microgrid, DC microgrid, and energy storage, effectively minimizing DC bus voltage fluctuations. The controller dynamically regulates power flow and minimizes Total Harmonic Distortion (THD), ensuring smooth operation under varying load and generation conditions. A comparative analysis with Artificial Neural Network (ANN) and Fuzzy Logic Controllers demonstrates the superior performance of the ANFIS approach in achieving lower THD and improved grid stability. Simulation results validate the proposed method’s effectiveness in enhancing power quality, optimizing energy distribution, and prolonging the lifespan of energy storage systems. This research highlights the potential of ANFIS in next-generation smart grid applications.

Keywords: Smart grid, Dual Active Bridge (DAB), Super capacitor, Solar PV, DC load, AC load, Inverter, AC Distributed Generation (DG), ANFIS Controller.

I. INTRODUCTION

The increasing global demand for energy and the growing integration of renewable energy sources have introduced new challenges in power system stability and efficiency. The intermittent nature of renewable energy [1] [2], along with the decentralization of power generation, often leads to voltage fluctuations and power imbalances, affecting the security and quality of power networks. Hybrid microgrids, consisting of both AC and DC subsystems, have emerged as a promising solution to enhance grid flexibility and reliability. Among various control strategies, intelligent techniques such as the ANFIS have gained significant attention due to their ability to handle uncertainties and optimize power distribution dynamically. Solid-State Transformer (SST) technology further enhances microgrid performance by enabling efficient power conversion and improving grid resilience. Traditional power transformers, while effective, lack the flexibility required to manage modern power systems with high renewable energy penetration. SSTs provide advanced functionalities, such as voltage regulation, bidirectional power flow, and improved fault isolation, making them an essential component of future smart grids [3] [4]. However, ensuring stable operation in an AC/DC hybrid microgrid integrated with an SST requires an intelligent control strategy capable of dynamically adapting to fluctuating load and generation conditions.

Conventional control approaches, such as proportional-integral (PI) and fuzzy logic controllers, have been widely used for energy management in microgrids. While fuzzy logic-based controllers improve decision-making in uncertain environments, they still have limitations in handling complex nonlinear systems. Similarly, Artificial Neural Network (ANN) controllers exhibit strong learning capabilities but often require extensive training data and computational resources. In contrast, [5] ANFIS combines the strengths of both ANN and fuzzy logic by integrating adaptive learning with rule-based decision-making, making it a robust choice for microgrid control. In this paper, an ANFIS-based controller is proposed to enhance power flow coordination between the SST, AC microgrid, DC microgrid, solar and energy storage [6], effectively minimizing DC bus voltage fluctuations. The controller optimally manages energy distribution by dynamically adjusting power flows, thereby improving grid stability and reducing total harmonic distortion (THD) [7]. The proposed method ensures seamless integration of renewable energy sources while maintaining the reliability of the hybrid microgrid under varying operating conditions.

The ANFIS-based controller is its ability to learn from historical data and adapt to real-time power variations, ensuring optimal energy management. Unlike conventional controllers, which rely on fixed control parameters, the ANFIS approach continuously fine-tunes its decision-making process based on real-time grid conditions. This adaptability allows for better power quality regulation, reduced energy losses, and extended lifespan of energy storage systems. To validate the effectiveness of the proposed ANFIS controller, a comparative analysis is conducted against traditional ANN and fuzzy logic controllers. The performance is evaluated based on key metrics, including THD reduction, voltage stability, and system efficiency. Simulation results demonstrate that the ANFIS controller outperforms conventional methods by achieving lower THD, improved power balance, and enhanced grid stability.[8] [9] These findings highlight the potential of ANFIS in revolutionizing microgrid control strategies [10].

Section II provides an in-depth overview of the system, including its design and functional elements. Section III describes the methodology employed, detailing the application of the ANFIS controller. Section IV discusses the simulation outcomes and analyses, assessing the effectiveness of the proposed method across various operational scenarios. Finally, Section V concludes the paper by highlighting the main insights and suggesting potential areas for further investigation.

II. SYSTEM DESCRIPTION

A. REGULATION OF THE RECTIFIER STAGE

The rectifier stage is responsible for converting AC power into DC while ensuring stable voltage regulation, power factor correction, and minimal harmonic distortion. It plays a vital role in maintaining power quality and system efficiency in an AC/DC hybrid microgrid [11]. The control strategy implemented for the rectifier involves multiple layers, including current regulation, voltage stabilization, and harmonic mitigation. To achieve these objectives, the rectifier employs a cascaded H-bridge (CHB) topology, which facilitates multi-level voltage conversion. This topology helps in reducing total harmonic distortion (THD), enhancing waveform quality, lowering switching losses, and improving overall efficiency.

A single-phase d-q vector control method is used to regulate the rectifier's operation. By transforming AC quantities into a rotating reference frame, this control approach allows for independent control of active and reactive power. The d-q transformation simplifies the control structure and enhances the precision of voltage and current regulation, enabling efficient power conversion. The rectifier also incorporates a PI controller for DC-link voltage regulation. This controller continuously adjusts the switching pattern based on the voltage error to maintain a stable DC output despite fluctuations in load demand. The PI control law dynamically modifies the rectifier’s duty cycle, ensuring that voltage deviations are minimized.

Harmonic mitigation and power factor correction are critical functions of the rectifier stage. To achieve high power quality, an active filtering mechanism is implemented, which reduces current harmonics and synchronizes the rectifier with the grid [12]. This synchronization minimizes reactive power consumption and improves the overall power factor. Additionally, a feedforward compensation technique is employed to counteract sudden load variations, enhancing the rectifier’s responsiveness and maintaining voltage stability under dynamic conditions [13]. To further improve system reliability, real-time fault detection and protection mechanisms are integrated into the rectifier’s control strategy. These mechanisms continuously monitor voltage and current levels, triggering protective actions in case of overvoltage, overcurrent, or unbalanced conditions. Fast-response circuit breakers and intelligent fault isolation techniques are incorporated to ensure safe and stable rectifier operation.

B. CONTROL OF THE DAB CONVERTER

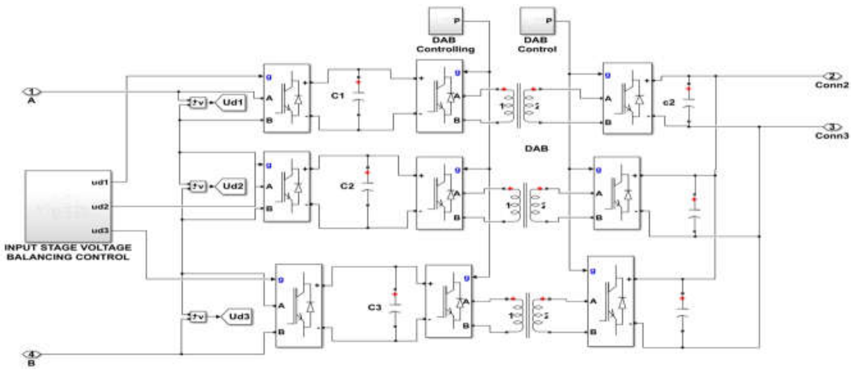


Fig.1 Dual Active Bridge Converter

The Dual Active Bridge (DAB) converter facilitates bidirectional energy transfer in an AC/DC hybrid microgrid as depicted in the fig.1, ensuring high-frequency isolation and efficient power conversion. It consists of two active H-bridge circuits on the high- and low-voltage sides, linked by a high-frequency transformer. Phase-shift modulation controls power transfer, optimizing efficiency and adaptability to load variations. The input-stage control aims for unity power factor and balanced DC-link voltage. Figures 2 and 3 depict single-phase current control and balancing control, respectively.

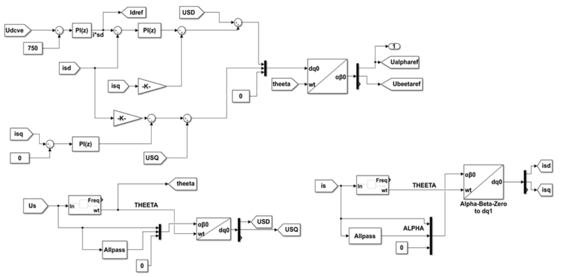


Fig.2 single-phase decoupled current control

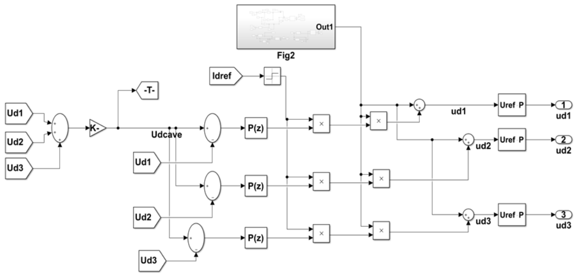


Fig.3 Input-stage voltage balancing mechanism

Phase-shift modulation, the main control method for the DAB converter, modifies the phase difference between the voltage waveforms of the primary and secondary bridges to control power flow. The quantity of power passed between the two sides can be adjusted by changing this phase shift. This method lowers switching losses, improves system stability, and guarantees effective energy exchange. To preserve DC bus voltage stability, the DAB converter also uses voltage droop management. By dynamically modifying the converter's power output in response to variations in load demand, this control technique reduces voltage fluctuations and enhances system performance.

To enhance efficiency and reduce power losses, adaptive control techniques are integrated into the DAB converter. These techniques optimize switching sequences, minimize conduction losses, and improve the converter’s response to transient changes in power demand. Furthermore, soft-switching mechanisms are employed to reduce switching losses and improve thermal performance. These methods ensure that the converter operates within optimal efficiency ranges while maintaining reliability under varying operating conditions

The DAB converter ensures real-time fault detection by monitoring voltage, current, and transformer temperature, deploying overcurrent protection and thermal management. Fault isolation strategies prevent component damage, ensuring uninterrupted operation in AC/DC hybrid microgrids. Fast-response control algorithms mitigate sudden load variations, maintaining stable power transfer under dynamic conditions. Phase-shift modulation, voltage droop control, and adaptive optimization enhance efficiency and reliability. Soft-switching mechanisms and real-time fault detection further improve performance. As a key component in modern power management, the DAB converter enables seamless bidirectional energy transfer and voltage stability.

C. REGULATION OF INVERTER STAGE

The inverter stage is a crucial component in the AC/DC hybrid microgrid [14] [15], responsible for converting DC power back into AC to supply local loads. It ensures stable voltage and frequency regulation, making it essential for seamless power distribution and load management. The inverter functions as the interface between the DC bus and the AC microgrid, ensuring that the power supplied to the AC loads maintains the required quality and stability [16]. The primary objectives of inverter control include voltage and frequency regulation, power sharing among multiple inverters, harmonic mitigation, and smooth transitions between grid-connected and islanded operating modes [17] [18].

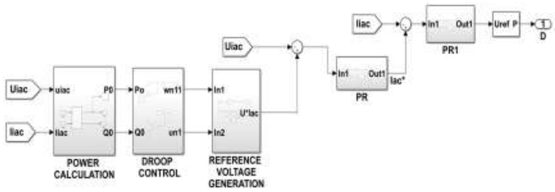


Fig.4 Block diagram of the inverter stage controller

To achieve precise voltage and frequency control, the inverter employs a dual-loop control structure, consisting of an inner current control loop and an outer voltage control loop as shown in the fig.4. The inner current loop regulates the output current by comparing it with a reference value and applying Pulse Width Modulation (PWM) control to adjust the inverter switches accordingly. The outer voltage loop maintains the desired AC output voltage by adjusting the reference signal for the current controller. A Proportional-Resonant (PR) controller is used instead of a traditional PI controller to improve tracking accuracy for sinusoidal waveforms, minimizing steady-state errors and ensuring better dynamic performance.

Another critical aspect of inverter control is droop control, which is widely used for load-sharing applications in microgrids. Droop control mimics the behaviour of synchronous generators in conventional power systems by adjusting the inverter output frequency and voltage in response to changes in active and reactive power demand. The control equations for frequency and voltage droop are given as:

$$\omega = \omega_0 - k_p\,(P - P_0) \ldots\ldots \quad (1)$$

$$V = V_0 - k_q\,(Q - Q_0) \ldots\ldots.. \quad (2)$$

Where ω and V are the frequency and voltage of the inverter, P and Q are the active and reactive power outputs, and kp and kq are the droop coefficients.

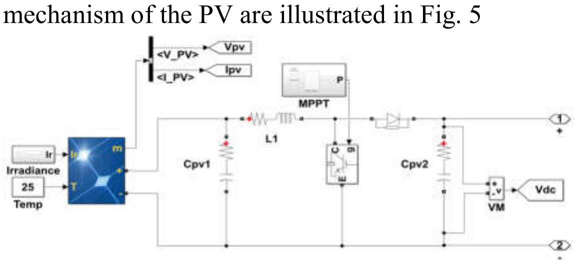
This approach allows multiple inverters operating in parallel to autonomously share the load without requiring a central controller. To enhance inverter efficiency and power quality, harmonic mitigation techniques are employed. Since inverters generate Pulse Width Modulation (PWM) are implemented to minimize Total Harmonic Distortion (THD). Additionally, virtual impedance control is integrated to improve stability and prevent circulating currents among parallel inverters.

The inverter mode transits between grid-connected and islanded operations. In grid-connected mode, the inverter synchronizes its voltage and frequency with the main grid, injecting power based on demand. During islanded operation, the inverter assumes grid-forming responsibilities, maintaining stable voltage and frequency independent of external support.

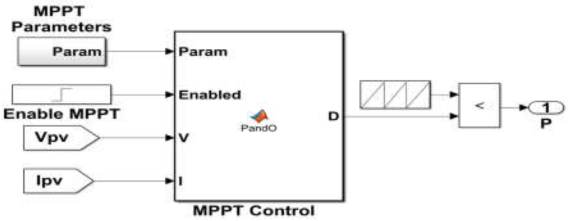
Real-time fault detection in inverter control includes overcurrent protection, thermal monitoring, and fast fault isolation to prevent damage. Intelligent fault ride-through ensures operation during disturbances, maintaining grid stability. The inverter stage enables efficient DC-to-AC conversion, voltage and frequency regulation, and robust load sharing in AC/DC hybrid microgrids. Advanced control strategies like PR controllers, droop control, and harmonic mitigation enhance stability and power quality. Integrated fault protection ensures reliable operation, making the inverter crucial for modern power management systems.

D. STRUCTURE AND CONTROL OF PV

The Photovoltaic (PV) system enables efficient solar energy integration by converting the fluctuating DC output from PV panels into a stable DC bus voltage. The PV converter maximizes power extraction, regulates voltage variations, and ensures balanced energy distribution within the hybrid microgrid. To improve efficiency and adaptability, a Maximum Power Point Tracking (MPPT) controller is implemented [19]. The topology and control mechanism of the PV are illustrated in Fig. 5



(a) PV Simulink model



(b) Controller of MPPT

Fig.5 Configuration and control strategy of the PV-based dc-dc converter

The PV system connects to the DC microgrid via a boost converter [20] [21], which elevates the fluctuating PV voltage to the required DC bus level. This converter comprises a switching device, an inductor, a diode, and a capacitor, all working together to regulate the output voltage. The power semiconductor's switching operation is governed by Pulse Width Modulation (PWM), ensuring efficient energy conversion

To extract the maximum available power from the PV array, MPPT algorithms are implemented. Conventional methods like Perturb and Observe P&O adjust the duty cycle based on real-time power variations but suffer from slow tracking speed and oscillations. The MPPT controller, on the other hand, uses a combination of fuzzy logic inference and artificial neural networks to adaptively determine the optimal duty cycle, resulting in superior tracking speed and accuracy.

The MPPT controller is integrated into the system to improve tracking efficiency and dynamic response. MPPT learns and adapts to varying irradiance and temperature conditions, making real-time adjustments to duty cycle. The control equation for duty cycle D of the boost converter is given by:

$$D = 1 - \frac{V_{pv}}{V_{dc}} \ldots\ldots \quad (3)$$

Where Vpv represents the PV panel voltage and Vdc is the desired DC bus voltage. ANFIS refines this duty cycle calculation by predicting the optimal perturbation step size based on historical data, ensuring faster convergence to the Maximum Power Point (MPP).

E. ENERGY STORAGE SYSTEM

This enables efficient charging and discharging of energy storage devices and is showed in fig.6 a. It ensures reliable operation under fluctuating power conditions. To enhance performance, an ANFIS control is implemented, improving dynamic response, optimizing power flow, and extending the lifespan of storage elements which is shown in the fig.6 b.

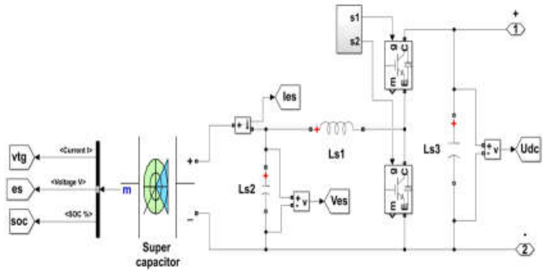


Fig.6(a) Simulink model of super capacitor

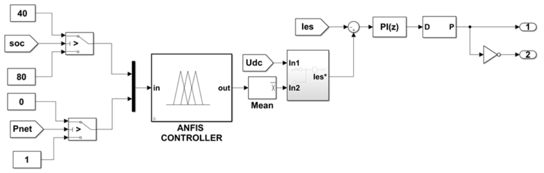


Fig.6(b) ANFIS control unit

A conventional droop control method is often used to modulate power output based on state-of-charge (SOC) and bus voltage variations. However, fixed droop coefficients can result in inefficient energy distribution under dynamic conditions. To address this limitation, an ANFIS-based adaptive droop control is integrated, allowing real-time adjustments to the droop coefficient based on SOC, power demand, and grid conditions. The control equation is given by:

$$Vdc = V_{dc,ref} - m_{adaptive} (P - P_0) \ldots\ldots \quad (4)$$

Where madaptive is dynamically tuned by ANFIS to optimize power sharing. This intelligent adaptation improves load response, minimizes overcharging/discharging risks, and enhances the overall efficiency of storage system.

F. ENERGY MANAGEMENT STRATEGY

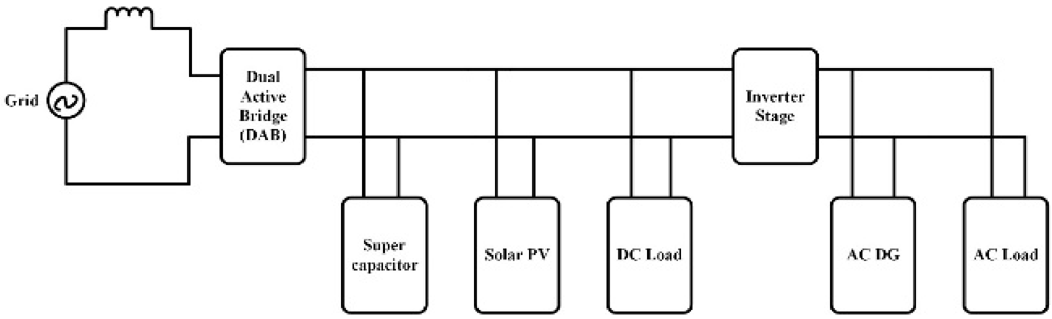


Fig.7 Power Transfer Dynamics in Grid-Connected Mode

The Energy Management Strategy (EMS) [22] in an AC to DC hybrid microgrid is ensuring efficient power distribution, voltage stability, and economic operation. The EMS is responsible for dynamically coordinating power generation, storage, and consumption while adapting to fluctuating renewable energy availability and load variations. To enhance system performance, an ANFIS-based energy management framework is integrated, allowing real-time decision-making and adaptive control for optimal energy utilization. Figure 7 illustrates the possible power flow scenarios of the SST in grid-connected mode.

III. ANFIS METHOD

The ANFIS combines the strengths of fuzzy logic and ANN to enhance the performance of power converters in AC/DC hybrid microgrids. While Fuzzy Logic Controllers (FLC) offer rule-based decision-making and ANN controllers provide learning capabilities, they both have limitations in handling complex, nonlinear power system dynamics effectively. The ANFIS controller overcomes these drawbacks by self-learning optimal control parameters, making it highly adaptive to varying load conditions, grid disturbances, and power quality requirements. This capability allows ANFIS to dynamically adjust control actions, leading to improved power flow management and harmonic suppression.

One of the major advantages of the ANFIS controller is its ability to reduce Total Harmonic Distortion (THD) significantly compared to FLC and ANN-based controllers. Traditional FLC-based droop control relies on predefined rules that may not optimally adapt to rapid variations in grid voltage and current, leading to suboptimal harmonic mitigation. Similarly, ANN controllers require extensive training datasets and struggle with real-time adjustments under rapidly changing conditions. In contrast, ANFIS continuously refines its rule set using real-time data and past system behaviour, ensuring precise control over switching signals and minimizing voltage and current distortions. This results in a cleaner power output with lower THD, enhancing power quality and system stability.

Moreover, the ANFIS-based controller improves dynamic response and transient stability by making real-time predictions and adjustments based on the operating conditions of the microgrid. Conventional droop controllers and fuzzy logic controllers exhibit slower response times and introduce oscillations during load fluctuations, leading to voltage deviations and frequency instability. The ANFIS controller, however, predicts system behaviour and fine-tunes its control parameters adaptively, ensuring a faster transient response, smoother voltage regulation, and efficient power-sharing among distributed energy resources (DERs). This results in better performance under both steady-state and transient conditions, reducing stress on power electronic devices and enhancing the lifespan of energy storage systems. The ANFIS controller surpasses both FLC and ANN-based controllers by offering lower THD, superior dynamic adaptability, and improved transient stability. By leveraging the learning ability of neural networks and the decision-making capability of fuzzy logic, ANFIS ensures optimal harmonic mitigation, reduced switching losses, and enhanced energy efficiency in AC/DC hybrid microgrids. This makes ANFIS an ideal choice for high-performance power management, ensuring better power quality and reliability compared to traditional controllers.

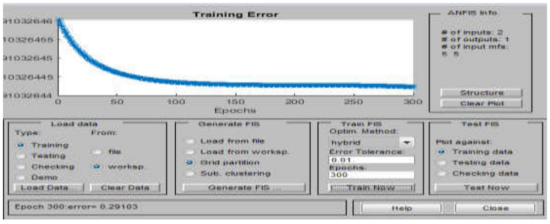


Fig. 8 ANFIS training error

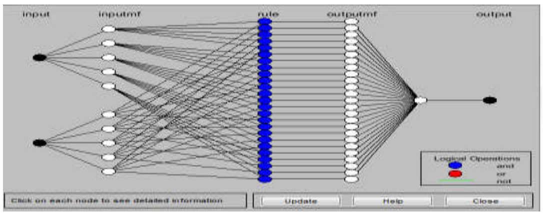


Fig. 9 ANFIS structure

IV. SIMULATION RESULTS AND DISCUSSION

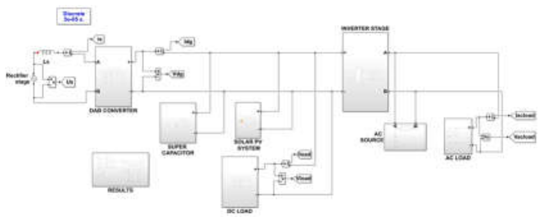
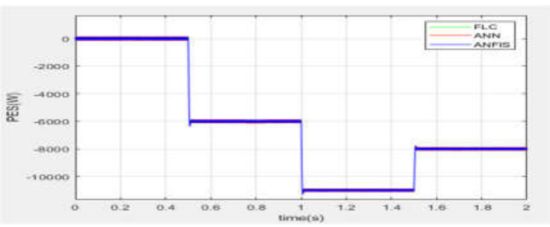
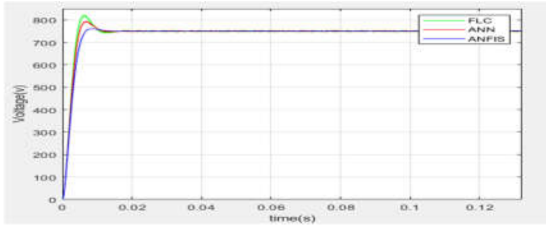


Fig.10 simulation model of ANFIS topology

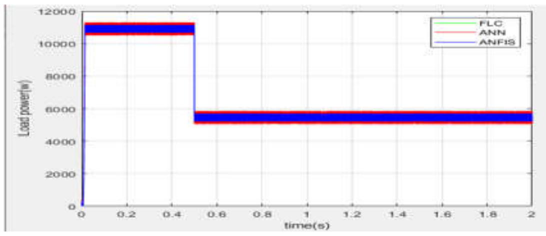
Case-1



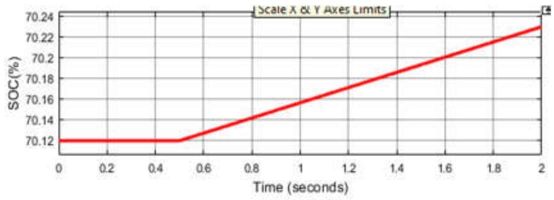
(a) Energy storage power



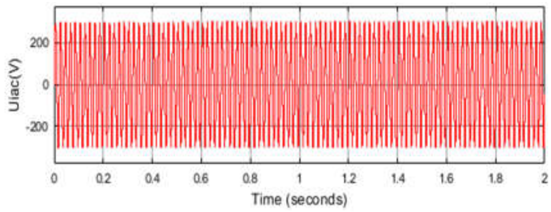
(b) Dc link voltage



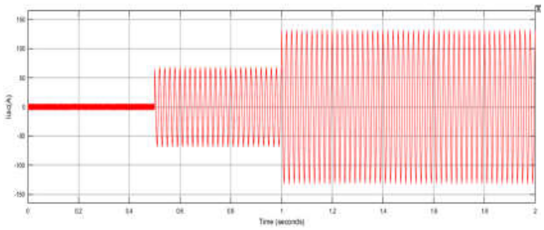
(c) Load power



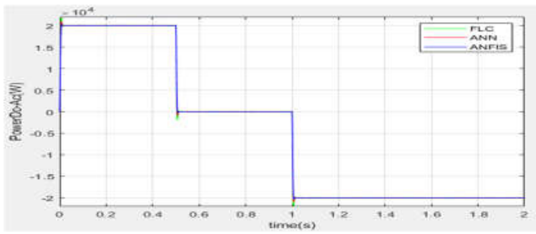
(d) SOC



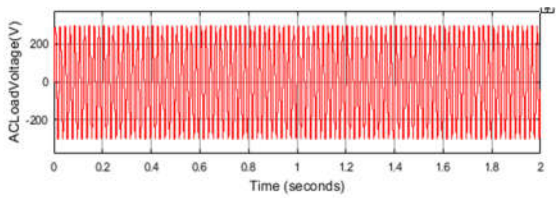
(e) Inverter voltage



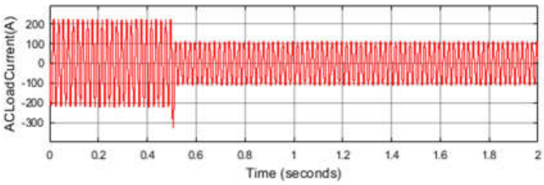
(f) Inverter current



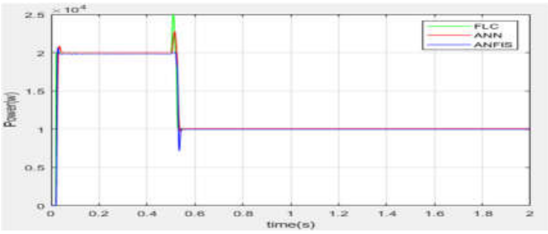
(g) Inverter power



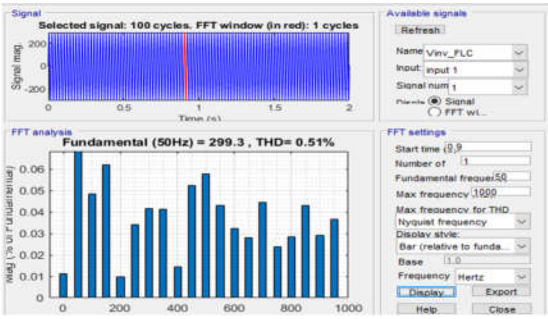
(h) Load ac voltage



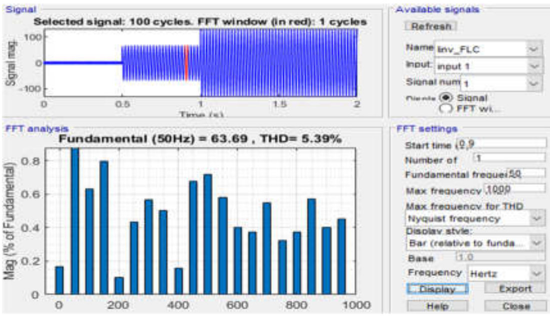
(i) Load ac voltage



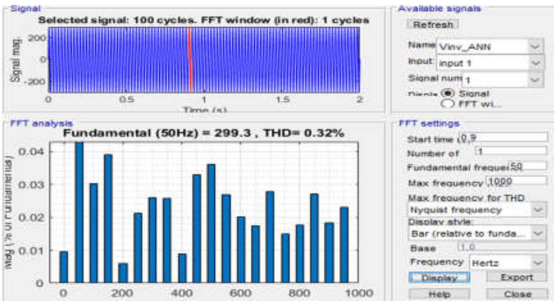
(j) Load ac power



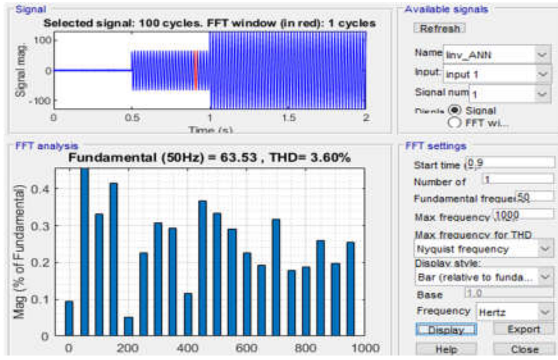
(k)Voltage of Inverter FLC THD %



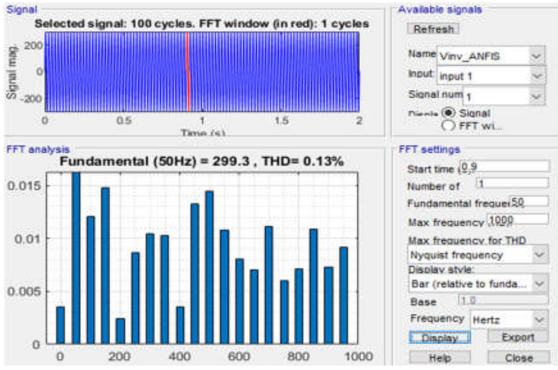
(l)Current of Inverter FLC THD %



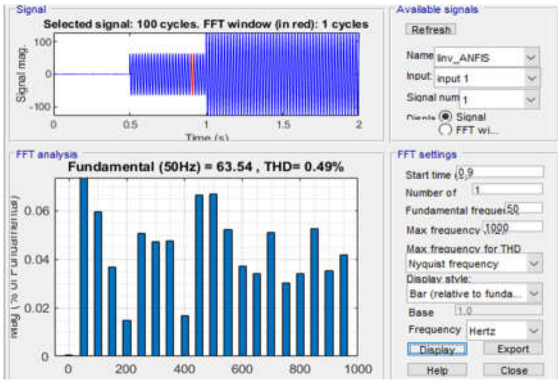
(m)Voltage of Inverter ANN THD %



(n)Current of Inverter ANN THD %



(o)Voltage of Inverter ANFIS THD %

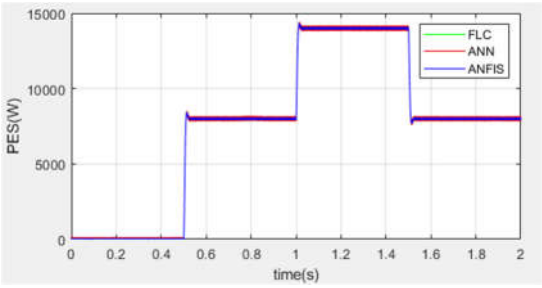


(p) Current of Inverter ANFIS THD %

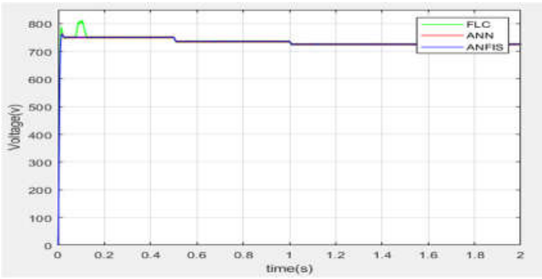
Fig. 11(a) to (p) shows the voltage and power variation profile of each unit in the dc and ac microgrid and its THD values

In Case 1, the THD values for inverter voltage and current were recorded for all three controllers. The results indicate that FLC exhibited the highest THD values, with an inverter voltage THD of 0.52% and an inverter current THD of 5.39%. The ANN controller showed an improvement, reducing the THD to 0.32% for inverter voltage and 3.60% for inverter current. However, the ANFIS controller significantly outperformed both, achieving a drastic reduction in THD to 0.13% for inverter voltage and 0.49% for inverter current. The substantial improvement achieved by the ANFIS controller can be attributed to its adaptive learning capability, which allows it to fine-tune its control parameters dynamically based on real-time system conditions. Unlike FLC, which relies on predefined rules that do not always optimize performance under varying load conditions, and ANN, which requires a fixed training dataset, ANFIS continuously learns and adjusts, ensuring precise harmonic compensation and voltage regulation.

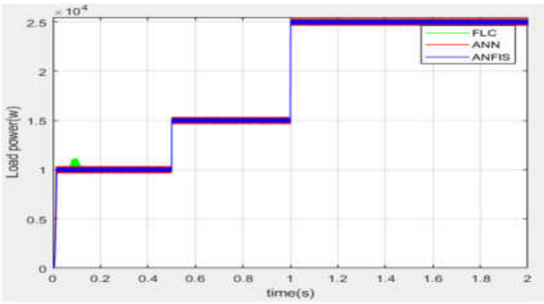
Case-2



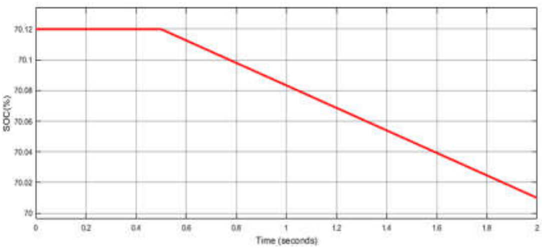
(a) Energy storage power



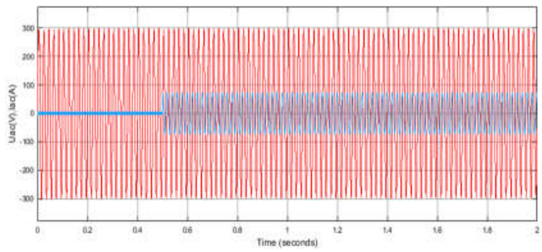
(b) Dc link voltage



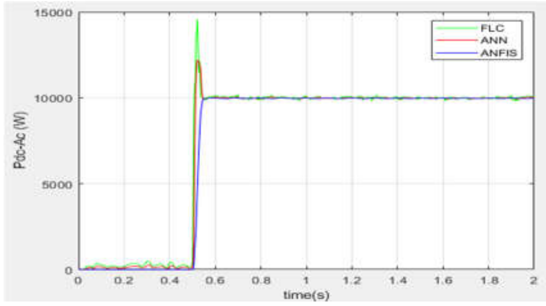
(c) Dc load power



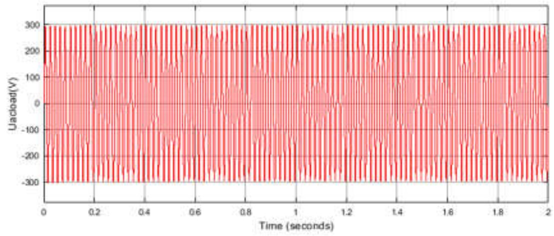
(d) SOC



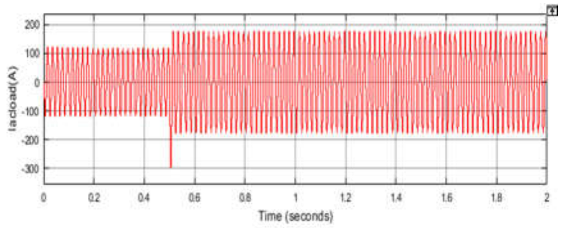
(e) Vac & Iac



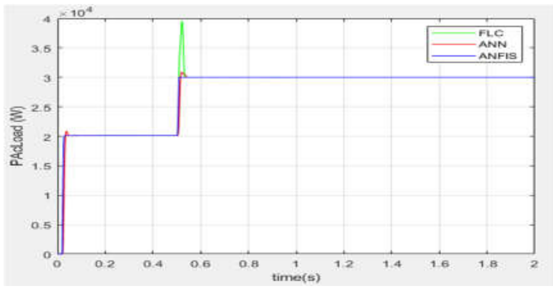
(f) Ac load power



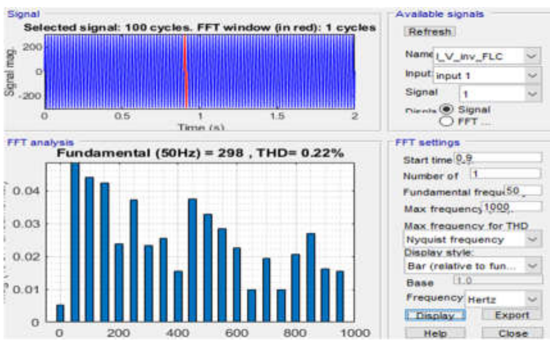
(g) Load ac voltage



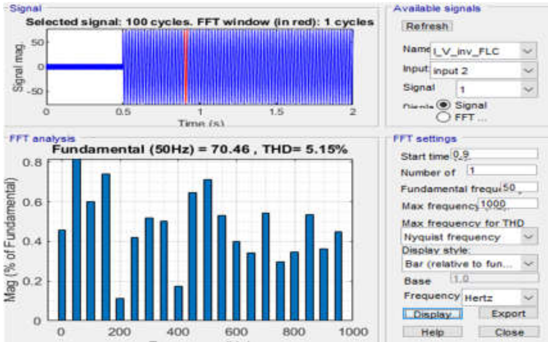
(h) Load ac current



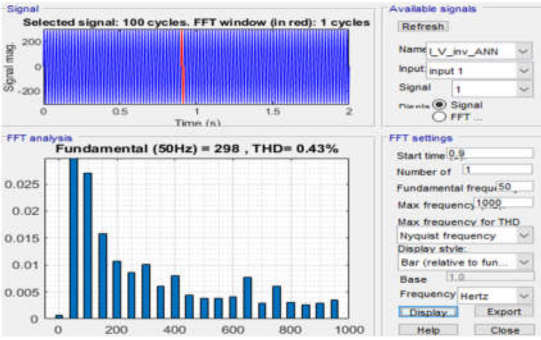
(i)Ac load power



(j) Voltage of Inverter FLC THD %

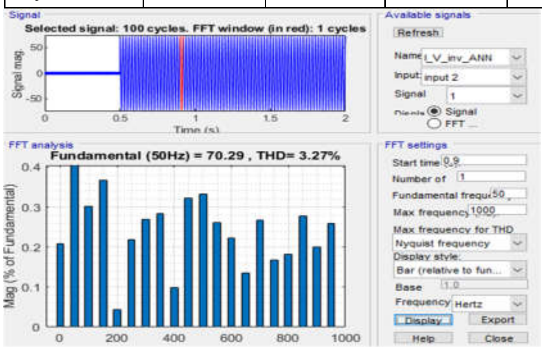


(k) Current of Inverter FLC THD %

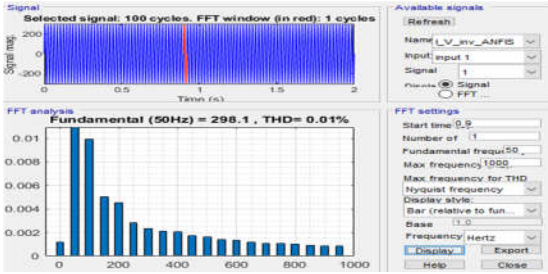


(l)Voltage of Inverter ANN THD %

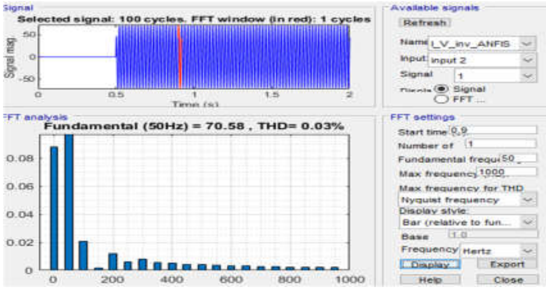
Controller	Case 1		Case 2	
Fuzzy Logic Controller	Inv Voltage-0.52	Inv Current-5.39	Inv Voltage-0.22	Inv Current-5.15
Artificial Neuron Networks	Inv Voltage-0.32	Inv Current-3.60	Inv Voltage-0.43	Inv Current-3.27
Adaptive Neuro-Fuzzy Inference System	Inv Voltage-0.13	Inv Current-0.49	Inv Voltage-0.01	Inv Current-0.03



(m) Current of Inverter ANN THD %



(n)Voltage of Inverter ANFIS THD %



(o) THD of inverter voltage

Fig. 12 (a) to (o) shows the outcomes of voltage and power variation profile of each unit in the dc and ac microgrid with THDs

In Case 2, where the microgrid experiences dynamic load variations, a similar pattern was observed. The FLC controller again exhibited high THD, with 0.22% for inverter voltage and 5.15% for inverter current. The ANN controller improved upon this, bringing the THD values down to 0.43% for inverter voltage and 3.27% for inverter current. However, the ANFIS controller achieved the lowest distortion levels, with a remarkable reduction to 0.01% for inverter voltage and 0.03% for inverter current.

This further validates the superiority of ANFIS in handling dynamic system conditions. While FLC struggles with adapting to rapid load changes and ANN has limited generalization outside its training data, ANFIS dynamically optimizes switching signals, ensuring minimal harmonics and superior voltage regulation. The near-zero THD in Case 2 demonstrates how effectively ANFIS suppresses harmonic distortions, making it the most efficient controller among the three.

Table-1 THD Comparison Table

From the comparative THD results across both cases, it is evident that:

*FLC shows the highest THD, making it less effective for high-quality power applications.

*ANN reduces THD compared to FLC but still lacks the adaptability to achieve optimal power quality in varying conditions.

*ANFIS achieves the lowest THD in all scenarios, demonstrating its ability to minimize voltage and current distortions, improve grid stability, and ensure high-efficiency power conversion.

*The significant THD reduction with ANFIS results in improved power quality, reduced stress on power components, and enhanced overall system reliability, making it the preferred controller for modern AC/DC hybrid microgrids.

V. CONCLUSION

This study analysed the performance of an ANFIS-based controller in an AC/DC hybrid microgrid, demonstrating its superiority over Fuzzy Logic (FLC) and Artificial Neural Network (ANN) controllers. The ANFIS controller significantly reduced THD, achieving 0.01% inverter voltage THD and 0.03% inverter current THD, compared to the higher distortions observed in FLC and ANN. By dynamically adjusting control parameters in real-time, ANFIS ensured better harmonic mitigation, faster transient response, and enhanced voltage regulation. Additionally, the ANFIS-based adaptive droop control improved energy storage efficiency, optimizing charge-discharge cycles and reducing power losses. Unlike FLC, which struggled with load variations, and ANN, which required extensive training data, ANFIS self-learned optimal control actions, making it more reliable and efficient. The ANFIS controller provided the best power quality, reduced grid stress, and ensured stable power flow, making it ideal for next-generation smart grids. Future research could explore real-time hardware implementation and extending ANFIS for multi-microgrid coordination. The results confirm that ANFIS is a powerful and intelligent solution for enhancing stability, efficiency, and energy management in modern power systems.

VI .REFERENCES

[1] N. A. Ludin et al., "Prospects of life cycle assessment of renewable energy from solar photovoltaic technologies: A review", Renew. Sustain. Energy Rev., vol. 96, pp. 11-28, Nov. 2018.

[2] P.García, C. A. García, L. M. Fernández, F. Llorens and F. Jurado, "ANFIS-Based Control of a Grid-Connected Hybrid System Integrating Renewable Energies Hydrogen and Batteries, vol. 10, no. 2, pp. 1107-1117, May 2014.

[3] R.A. Mastromauro, M. Liserre, Dellaquila and A., "Control Issues in Single-Stage Photovoltaic Systems: MPPT Current and Voltage Control", vol. 8, no. 2, pp. 241-254, May 2012.

[4] S. Koohi-Kamali, N. A. Rahim, and H. Mokhlis, ‘‘Smart power management algorithm in microgrid consisting of photovoltaic, diesel, and battery storage plants considering variations in sunlight, temperature, and load,’’ Energy Convers. Manage. vol. 84, pp. 562–582, Aug. 2014.

[5] A.M. Kassem, ‘‘Modeling, analysis and neural MPPT control design of a PV generator powered DC motor-pump system,’’ WSEAS Trans. Syst., vol. 10, no. 12, pp. 399–412, Dec. 2011.

[6] G. Mamatha, ‘‘Perturb and observe MPPT algorithm implementation for PV applications,’’ Int. J. Comput. Sci. Inf. Technol., vol. 6, no. 2, pp. 1884–1887, 2015.

[7] P Karuppusamy, AM Natarajan and KN Vijeyakumar, "An adaptive neuro-fuzzy model to multilevel inverter for grid connected photovoltaic system", vol. 24, no. 05, pp. 1550066, Jun 2015.

[8] S. Singh, M. Singh, and S. C. Kaushik, ‘‘Optimal power scheduling of renewable energy systems in microgrids using distributed energy storage system,’’ IET Renew. Power Gener. vol. 10, no. 9, pp. 1328–1339, Oct. 2016.

[9] N. T. Mbungu, R. Naidoo, R. C. Bansal, and M. Bipath, ‘‘Optimisation of grid connected hybrid photovoltaic–wind–battery system using model predictive control design,’’ IET Renew. Power Gener., vol. 11, no. 14, pp. 1760–1768, Dec. 2017.

[10] K. Basaran, N. S. Cetin, and S. Borekci, ‘‘Energy management for ongrid and off-grid wind/PV and battery hybrid systems,’’ IET Renew. Power Gener. vol. 11, no. 5, pp. 642–649, Apr. 2017.

[11] N. Mahmud, A. Zahedi, and A. Mahmud, ‘‘A cooperative operation of novel PV inverter control scheme and storage energy management system based on ANFIS for voltage regulation of grid-tied PV system,’’ IEEE Trans. Ind. Informat., vol. 13, no. 5, pp. 2657–2668, Oct. 2017.

[12] S. Kewat, B. Singh, and I. Hussain, ‘‘Power management in PV-batteryhydro based standalone microgrid,’’ IET Renew. Power Gener. vol. 12, no. 4, pp. 391–398, Mar. 2018.

[13] T. Ma and M. S. Javed, ‘‘Integrated sizing of hybrid PV-wind-battery system for remote island considering the saturation of each renewable energy resource,’’ Energy Convers. Manage. vol. 182, pp. 178–190, Feb. 2019.

[14] H. Razmi and H. Doagou-Mojarrad, ‘‘Comparative assessment of two different modes multi-objective optimal power management of micro-grid: Grid-connected and stand-alone,’’ IET Renew. Power Gener., vol. 13, no. 6, pp. 802–815, Apr. 2019.

[15] Y. E. G. Vera, R. Dufo-López, and J. L. Bernal-Agustín, ‘‘Energy management in microgrids with renewable energy sources: A literature review,’’ Appl. Sci., vol. 9, no. 18, pp. 1–28, Sep. 2019.

[16] J. Hong, J. Yin, Y. Liu, J. Peng, and H. Jiang, ‘‘Energy management and control strategy of photovoltaic/battery hybrid distributed power generation systems with an integrated three-port power converter,’’ IEEE Access, vol. 7, pp. 82838–82847, 2019.

[17] M. K. Senapati, C. Pradhan, S. R. Samantaray, and P. K. Nayak, ‘‘Improved power management control strategy for renewable energy-based DC micro-grid with energy storage integration,’’ IET Gener., Transmits. Distrib. vol. 13, no. 6, pp. 838–849, Mar. 2019.

[18] P. S. Kumar, R. P. S. Chandrasena, V. Ramu, G. N. Srinivas, and K. V. S. M. Babu, ‘‘Energy management system for small scale hybrid wind solar battery based microgrid,’’ IEEE Access, vol. 8, pp. 8336–8345, 2020.

[19] S. Gupta, R. Garg and A. Singh, "ANFIS-Based Control of Multi-objective Grid Connected Inverter and Energy Management", J. Inst. Eng. India Ser. B, vol. 101, pp. 1-14, 2020.

[20] A. Rajabi, A. Rajaei, V.M. Tehrani, P. Dehghanian, J.M. Guerrero and B. Khan, "A Non-Isolated High Step-Up DC-DC Converter Using Voltage Lift Technique: Analysis Design and Implementation", IEEE Access, vol. 10, pp. 6338-6347, 2022.

[21] A. Asadi, M.S. Karimzadeh, X. Liang, M.S. Mahdavi and G.B. Gharehpetian, "A Novel Control Approach for a Single-Inductor Multi-Input Single-Output DC–DC Boost Converter for PV Applications", IEEE Access, vol. 11, pp. 114753-114764, 2023.

[22] M.H. Ibrahim, S.P. Ang, M.N. Dani, M.I. Rahman, R. Petra and S.M. Sulthan, "Optimizing Step-Size of Perturb & Observe and Incremental Conductance MPPT Techniques Using PSO for Grid-Tied PV System", IEEE Access, vol. 11, pp. 13079-13090, 2023.