FOREX Publication
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International Journal of
Electrical and Electronics Research (IJEER)
Research Article | Volume 11, Issue 4 | Pages 1188-1203 | e-ISSN: 2347-470X

Multiple Grid-Connected Microgrids with Distributed Generators Energy Sources Voltage Control in Radial Distribution Network Using ANFIS to Enhance Energy Management

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ABSTRACT- Voltage conditions and power quality for customers and utility equipment are significantly impacted by the addition of microgrid-generating sources within distribution networks. Designing the right control for distributed generators for the various generating units of a Microgrid is important in enabling the synchronization of renewable energy generation sources, energy storage unity, and integration of Microgrids into a radial distribution network. This research provides control mechanisms based on an adaptive technique employing ANFIS, to reduce fluctuation of voltage and current difficulties faced when multiple renewable energy sources and storage systems are incorporated into a distribution network. A step-by-step Voltage Source Converter (VSC) Controller was designed for controlling the DC voltage power sources used. The ANFIS training, test system modeling, and the distributed energy source were modeled in MATLAB/SIMULINK 2021a Software. Four microgrids were developed each consisting of a Photovoltaic plant, Wind Turbine, and Battery Storage System. Non-critical and critical loads were considered during the system testing. The simulated result reveals that the proposed control system works effectively in maintaining a constant system voltage of 340VAC which significantly mitigates system voltage and current fluctuation without using any static synchronous compensator (STATCOM) and power system stabilizers.

Keywords: ANFIS, Distributed Generators, Microgrid, Radial Distribution network, Voltage Source Converter.

ARTICLE INFORMATION
Author(s): Ebenezer Narh Odonkor, Peter Musau Moses, Aloys Oriedi Akumu;
Received: 10/10/2023; **Accepted**: 11/12/2023; **Published**: 23/12/2023;
e-ISSN: 2347-470X;
Paper Id: IJEER 1010-06;
Citation: 10.37391/IJEER.110441
Webpage-link:
https://ijeer.forexjournal.co.in/archive/volume-11/ijeer-110441.html

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1. INTRODUCTION

In recent times utility distribution network operations based on power supply to crucial industrial loads, domestic loads, and crucial commercial operations can be significantly costly due to a variety of outages and service disruptions. Power quality supply especially constant voltage supply is crucial to be maintained at the customers end when renewable energy sources like wind and solar are integrated into distribution networks [1]. Based on the growth of electricity generation using distributed generators having renewable sources integrated into power networks, in [2], [3] the authors investigated an effective power control technique for inverter-based distributed generation (DG) in an islanded microgrid, taking into account voltage and frequency control, dynamic response, and steady-state response, during island operation of Microgrid. A voltage-frequency (VF) control with a hybrid intelligent search technique, such as Particle Swarm Optimization (PSO) and Genetic Algorithm (GA), was used in reference [4] to maintain system operation voltage and frequency. Enhancing power generation and conversion as well as maintaining the constant voltage and frequency (V-f) of Microgrid with renewable energy sources, a hybrid MPPT approach based on PSO-ANFIS was utilized in reference [4] to control the active and reactive power (P-Q) utilizing the least root mean square error (RMSE) in PV power generation. Mitigating low-frequency and under-voltage stability issues of integrated DGs in a distribution network, an Adaptive Neuro-Fuzzy Inference System(ANFIS) based Phase lock loop (PLL) driven droop controller was proposed in [5].

In [6], the primary goal of power quality supply by lowering the cost of the energy acquired from the utility grid with a method of detecting islanding based on maximum power point tracking (MPPT) was introduced. Authors in [7] presented an energy management system (EMS) for the day-ahead dispatch of battery storage systems (BSS) in distributed generating systems involving direct current (DC) networks with a multi-period power flow approach and a master-slave strategy based on

parallel implementations of the particle swarm optimizer (PPSO) but did not considered voltage issues that affect power flow.
To improve the efficiency of a variable-speed wind energy conversion system, the work in [8] offers a unique application of a hybrid adaptive neuro-fuzzy inference system (ANFIS)-based genetic algorithm (GA)-based control scheme. Power control in AC Isolated Microgrids having Renewable Energy Sources was suggested in another study [9] with an emphasis on regulating the voltage on the terminals of the battery by managing the power generated by the energy sources. Genetic Algorithm-Adaptive Neuro-Fuzzy Inference System (GA-ANFIS) controller for regulating voltage during power generation was also presented in [10]. Addressing power quality issues, increasing power usage, and boosting the effectiveness of the network of interconnected Microgrid distribution systems, a power control approach utilizing an adaptive network-based fuzzy inference system was developed in reference[11]. In [12], the authors suggested a Cascaded Multi Level Inverter (CMLI), Boost Converter with Cascaded Feed Forwarded Neural Network (CFFNN) MPPT Controller to enhance Power Quality (PQ) for Linear, Non-Linear, and Unbalanced Loading Conditions and reduce Total Harmonic Distortion (THD) to aid in improving quality of power. In the study [13], [14], a hybrid energy storage system (HESS) with a PV microgrid was controlled using ANFIS controller and Genetic Algorithm (GA) control techniques, which monitored and determined the ideal quantity of power or energy for the HESS needed to be operated in deficit and excess modes of a Microgrid without considering voltage issue. Lessening power oscillations and properly balancing power produced and demand energy supply is necessary, hence researchers in paper [15] developed an energy management system for microgrids with an ANFIS control scheme using a Heuristic Algorithm with a battery storage system.

It was suggested in reference [16] a cost-based EHO-based droop control technique for power management in hybrid-based AC-DC microgrids without considering the effect of voltage variations when renewable energy sources are used in hybrid AC-DC Microgrid. Increased interest in renewable energy due to growing environmental safety concerns led to the adoption of wind turbines (WT) which required careful control of the blades to harness the full potential of wind energy, therefore in [17] an Advanced Intelligent Genetic Algorithm was used to optimize the blade pitch angle controller, yet no consideration were taken for varied wind that will affect voltage fluctuation. To handle voltage fluctuation issues of wind plants a Fuzzy-PID-based pitch angle controller was introduced in [18]. Moreover, a fuzzy-based predictive controller was used to control the pitch angle of a wind turbine with variable speed [19] yet voltage issues were neglected in this study. To precisely track the desired pitch angle trajectory and account for model uncertainties and uncertain disturbances, an adaptive robust integral sliding approach to pitch angle control of an electro-hydraulic servo pitch system for wind turbines was proposed in [20]. This work [21] proposed an innovative adaptive Rotor Speed Recovery (RSR) technique that restores the rotor speed during turbulence using the aerodynamic power enhanced by wind gusts and stabilizes the turbine during wind lulls by following a suboptimal power curve with voltage fluctuation considered.

In article [22], the authors present a Resilience-Oriented Bidirectional ANFIS Framework for connected Microgrid Management systems with Renewable Energy Sources such as Photovoltaic, Wind Turbines, Batteries, and Intelligent Load Control, while electrical networks that are integrated with storage power sources, voltage consistency in the integrated networks with optimal battery charge management controller-based hybrid GA-ANFS for PV-wind microgrid was presented in this paper[23]. In [24], the authors implemented a switching mechanism using the Emperor penguin based on an adaptive fuzzy neuro inference system (EP-ANFIS) controller to ensure efficient storage unit control in a Microgrid with PV-WT System, and Smart battery controller using ANFIS [25]. Extracting the optimum power from a photovoltaic (PV), wind plant, and battery bank using ANFIS with fractional order PID (FO-PID) controller for a smart DC-microgrid was introduced in [26]. In reference [27], a High Voltage Direct Current (HVDC) connection and an Adaptive Neuro-Fuzzy-based Damping Controller (ANFDC) were suggested for controlling the dynamic behavior of the system with Hybrid Integration of Wind Farms and Batteries in a Grid-Connected Microgrid. In this work, the authors did not consider voltage variation issues that could affect power quality and customers.

In another research [28], the authors detailed that using a hybrid ANFIS-PSO and digital Infinite Impulse Response (IIR) filter-based proportional-resonant current controller, a distributed hybrid DC/AC microgrid (MG) can be controlled cooperatively to quickly and with no oscillation tracking to extract the maximum power from both the inverter and boost converter of the solar photovoltaics (PV) systems neglecting voltage issues that might result from system oscillations. Addressing power issues that arise when using renewable energy sources, the effectiveness of the ANFIS, an ANFIS and artificial bee colony (ABC) algorithm was utilized with solar systems maximum power point tracking (MPPT) and inverter control in [29]–[31] to investigate maximum power harvesting. For the microgrid network to operate properly and achieve voltage and frequency regulation, particularly during an islanded mode of operation, maintaining power balance under unpredictable circumstances is of major concern. As a result, power balance, voltage, and frequency regulation to reduce the transition fluctuations, and quick switching operations are necessary for renewable energy sources synchronizing with the main grid [32]. Other authors utilized Support Vector Machines (SVMs) in [33], [34] to provide a new anti-islanding protection technique for Low-Voltage (LV) networks with Voltage-Sourced Converter (VSC) to mitigate system voltage transient when Plug-in hybrid electric vehicles(PHEVs) are integrated into distribution networks. In reference [35], [36] a novel fluctuating voltage injection approach based on a Pearson correlation coefficient was proposed as a hybrid strategy for islanding detection with zero percent non-detection zone and low influence on power quality and minimized turbulence when power is received by Plug-in electric vehicle (PEV) batteries due to power exchange [36].

Addressing the non-uniform irradiation issue with multi-string PV, this study [37] introduced an improved Multi-Dimensional Cuckoo (MDC) algorithm for maximum power extraction (MPE) by integrating duty cycle control for multiple renewable energy sources in a grid-connected system to maximize power from all sources and solve the linearly growing cost issue. Voltage sag and swell mitigation using a hybrid control mechanism-based DVR in solar PV-based were presented in [38] using a proportional-integral (PI) controller with a fuzzy logic controller (FLC). For reducing the deviations in PV plants caused by changes in temperature, grid integration using ANFIS for Hybrid DG and Storage Units to Control and Manage Power was suggested in reference [39]. Mitigating the detrimental impact of an unbalanced load in microgrid networks, an ANFIS-based add-on controller for imbalance voltage compensation in low voltage microgrids was developed in reference [40] while enhancing the Dynamic Voltage Stability of a Wind Power System Connected to the Grid with an ANFIS Controlled Static Var Compensator were introduced in [41]. The authors in [42] use the application of a Fuzzy Logic Controlled Static Var Compensator (SVC) for voltage control and Ferranti effect mitigation in transmission systems. However, a hybrid series active power filter was used in reference [43] to enhance Power Quality with ANFIS Controller, and using Nonlinear Autoregressive Neural Network [44], Neuro-based controllers that reduce oscillation [45] for Grid-Connected Microgrid with Solar PV and Wind Turbine. In [46], the ANFIS approach for reconfiguring Distribution Networks was established with the goals of keeping the feeder power balanced, lowering active power loss, and minimizing node voltage volatility. It was emphasized in [47] that, utilizing reactive power injection or absorption might decrease voltage profile variation in low-voltage distribution networks. Different techniques for voltage control were suggested such as ANFIS-PSO-based STATCOM [48], D-STATCOM, fuzzy-based controllers in [49], [50] for improving AC-DC Microgrid voltage stability and improving power quality.

It is vital to stress that to improve power quality (active and reactive power) management, voltage control, and frequency control of microgrids different authors employ one or more of different optimization techniques, artificial intelligent (AI) with a Static Synchronous Compensator (STATCOM) to provide or absorb reactive current thereby regulating the voltage at the point of connection to a power grid. From the above literature, it is clear that using only ANFIS to maintain system voltage of grid-connected microgrids in a radial distribution network has received relatively less attention. Therefore, in this proposed work, the main aim is to develop a control system for the various distributed energy sources (wind turbine, PV, and battery storage system) using ANFIS due to its adaptive nature to regulate and maintain voltage and current of energy sources integrated into low voltage distribution network.

The main contributions of this paper are as follows;

1) Using an adaptive technique based on ANFIS to mitigate fluctuation of voltage and current issues posed when multiple REs and storage systems are integrated into a distribution network.
2) Design a Voltage Source Converter (VSC) for a DC power source using an Adaptive Controller.
3) Develop multiple microgrids using modeled distributed generators and integrate them into a test 34-bus radial distribution network.

The following is an outline of the remaining sections of this paper: *Section 2* presents materials and methods. *Section 3* details simulation results and *Section 4* discussion section. The conclusion of the proposed research is presented in *Section 5*.

2. MATERIALS AND METHODS

The proposed hybrid grid-connected microgrid is shown in *figure 1* and is made up of four (4) Microgrid which are integrated with distributed generation (DG) power sources such as photovoltaic (PV) plants, wind turbines (WTs), battery energy storage systems (BESS), and connected loads into the test system. The controllers, distributed energy sources, and the test system were modeled in MATLAB/SIMULINK Software. The DC sources (PV and Battery) were connected to the distribution network through DC/AC converters controlled with ANFIS while the AC renewables source (wind turbine) was connected directly without any converter, however, its pitch angle was controlled using ANFIS. The DC-generating units are linked to a utility grid by DC-DC boost converters using ANFIS. Based on the control loops and system voltage, the VSC's function is to convert 500 VDC to VAC and maintain constant system power without fluctuations. Two forms of control loops were used, that is external control loops and internal control loops. To maintain the DC voltage at 260V, an external control loop is used. In order to maintain constant power, the internal controls loop is used to adjust the active current component (Id), which is the output of the external DC voltage controller, and the reactive current component (Iq), which is kept at zero. The *Vd* and *Vq* voltage outputs of the current controller are then converted to three modulating signals reference (Vabc-ref).

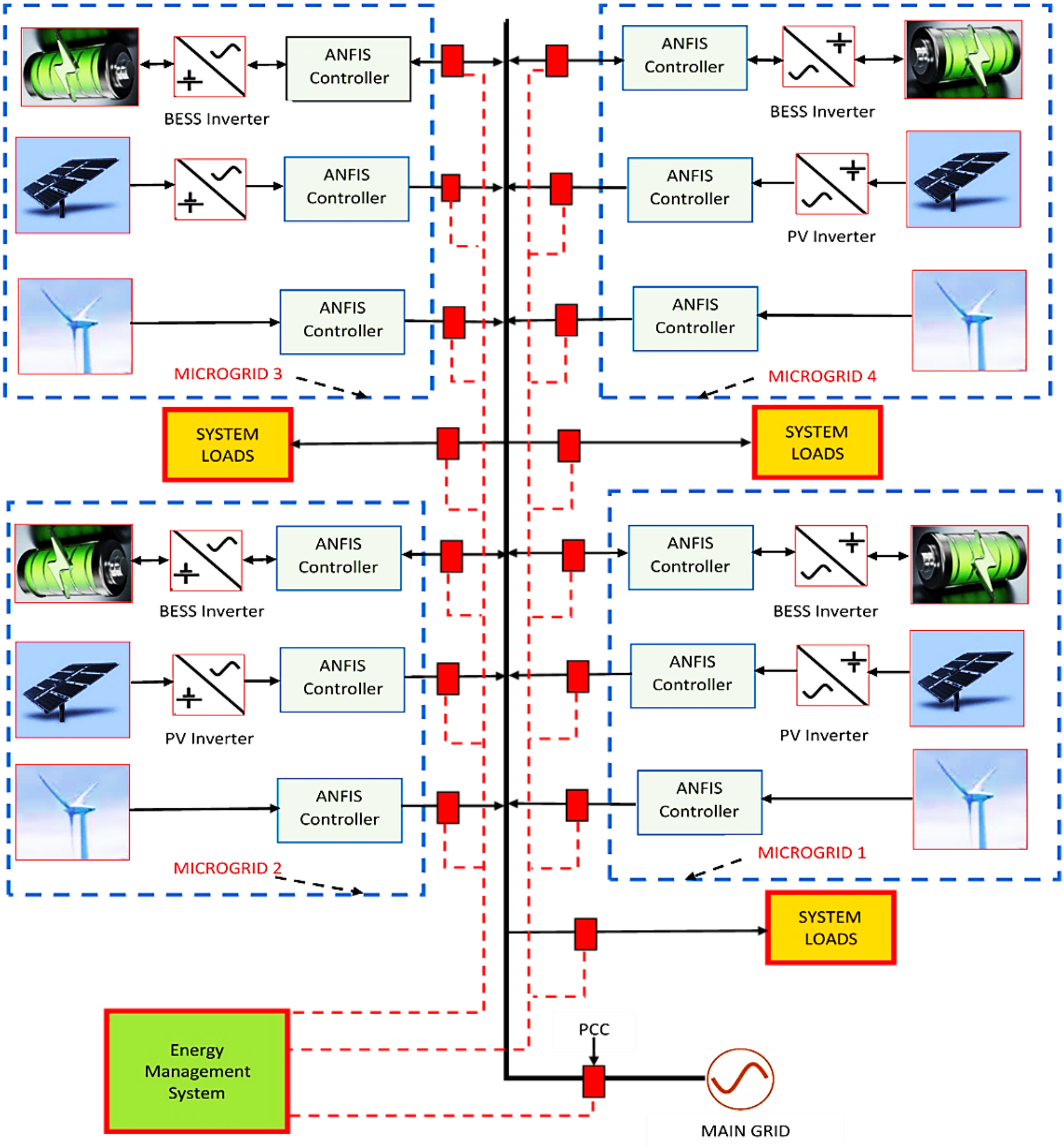

Figure 1: Proposed grid-connected Microgrid

2.1 Design of PV Plant Controller

2.2.1 Voltage Source Converter (VSC) Controller Design

The controller is implemented using ANFIS control techniques. It was designed to ensure stability, robustness, and good transient response to voltage and current when a Microgrid changes mode of operation. In achieving this a voltage source inverter and current source inverter were designed considering power rating. In this work, control objectives include maintaining output voltage and current, by regulating the output power and managing power flow. For the proposed system providing accurate phases and frequency control synchronization of different sources used, a Phase Locked Loop (PLL) control application was used in this work, for Grid synchronization with renewable energy sources and power converters. The designed Phase Locked Loop (PLL) control system was used to synchronize the generated power with the national utility by ensuring smooth and adaptive power injection to the main grid (radial distribution network) from renewable energy sources without any deviation in grid phase-to-phase voltage and phase-to-phase current. The designed Phase Locked Loop (PLL) controller is shown in *figure 2*. To maintain the output voltage magnitude and current in the proposed system, a current control system was implemented as shown in *figure 3* which was used to regulate the output current to achieve precise load control. Additionally, a Control Strategy using a voltage dependent current (VDC) controller was designed as shown in *figure 4* having a voltage control mechanism. This controller can adapt to system voltage and current accordingly with the help of the introduction of the ANFIS in maintaining a constant phase-to-phase voltage and phase-to-phase current enabling specific power output dispatched in the distribution network.

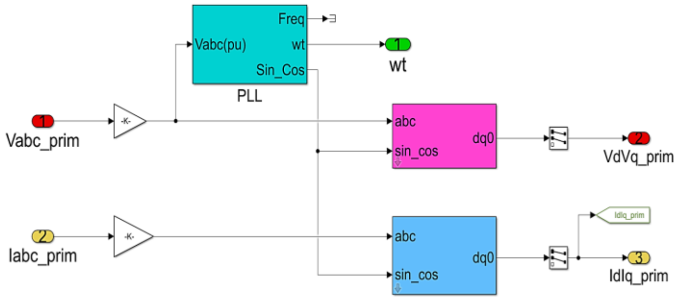

Figure 2: Proposed Phase Locked Loop (PLL) control system

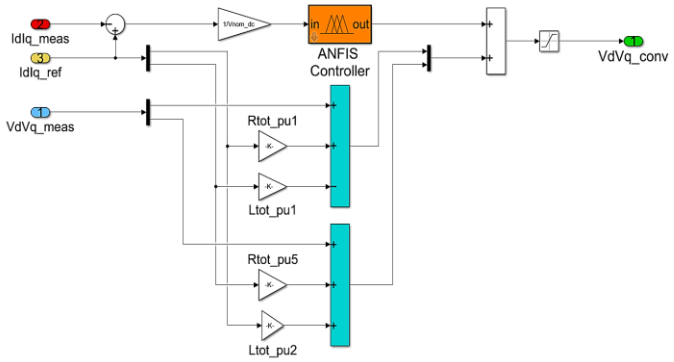

Figure 3: Proposed ANFIS Current control system

2.1.2 Voltage-dependent Current (VDC) Controller Design

The Voltage-Dependent Current controller was designed to control the voltage loop of renewable energy systems, particularly those that involve power conversion and energy storage. This system plays a significant role by regulating the voltage of the direct current (DC) bus in the proposed systems. The VDC controller ensures that the DC bus voltage remains within safe and optimal limits, preventing under-voltage or over-voltage conditions that could damage the power electronics. For optimal power conversion processes of the solar panel and the wind turbine output to usable AC power or charging and discharging batteries, depends on maintaining the proper voltage levels hence the use of a VDC controller to maintain the voltage at the optimal point for efficient power conversion. *Figure 4* shows the Voltage Dependent Current (VDC) controller design using MATLAB/SIMULINK. Battery charging and management are some of the advantages of the VDC controller used in this research work to manage the charging and discharging of batteries used to ensure that the batteries are charged to the appropriate voltage levels by preventing overcharging or undercharging could reduce battery lifespan.

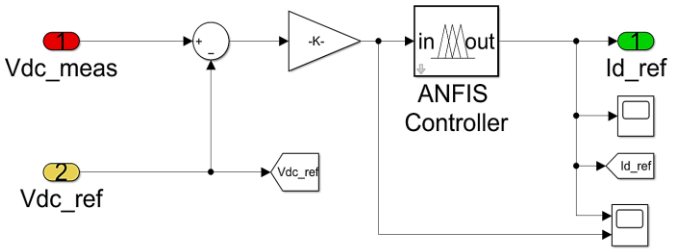

Figure 4: Proposed ANFIS Voltage Controller

Since the proposed microgrids involved alternating current (AC) power generation sources such as wind turbines and solar inverters, reference frame transformations are important for controlling and regulating the generated power. Park transformation was used for the abc to dq transformation mathematically by converting the three-phase AC quantities (a, b, c) into a two-coordinate rotating reference frame (d, q) [3]. The dq reference frame is particularly useful for controlling the active and reactive power components independently, which is crucial for maintaining stable operation and efficient power conversion in microgrid networks [2]. The equations for transforming current and voltage are similar, therefore in this work, the current equations were considered. For the VI transformations, an assumption was taken such that Ia+Ib+Ic=0, where Ia is the value of the current of phase A, Ib is the value of the current of phase B, and Ic is the value of the current of phase C of the three-phase current respectively. The following Equations, (1) and (2) were used to convert three-phase current to direct and quad current. *Figure 5* shows the proposed Uabc ref generator developed.

$$I_d = \frac{2}{3}\left[I_a cos\theta + I_b \cos\left(\theta - \frac{2}{3}\pi\right) + I_c \cos\left(\theta + \frac{2}{3}\pi\right)\right] \qquad (1)$$

$$I_q = \frac{2}{3}\left[I_a sin\theta + I_b \sin\left(\theta - \frac{2}{3}\pi\right) + I_c \sin\left(\theta + \frac{2}{3}\pi\right)\right] \qquad (2)$$

Where: I_d is the d or direct current, I_q is the q or quad current and is the mechanical rotor position in radians. The values of Id and Iq are derived from equations (3) and (4)

$$I_d = I_\propto cos\theta + I_\beta sin\theta \qquad (3)$$

$$I_q = I_\propto sin\theta + I_\beta cos\theta \qquad (4)$$

where $I_\propto = I_a$ and $I_\beta = \frac{1}{\sqrt{3}} I_a + \frac{2}{\sqrt{3}} I_b$

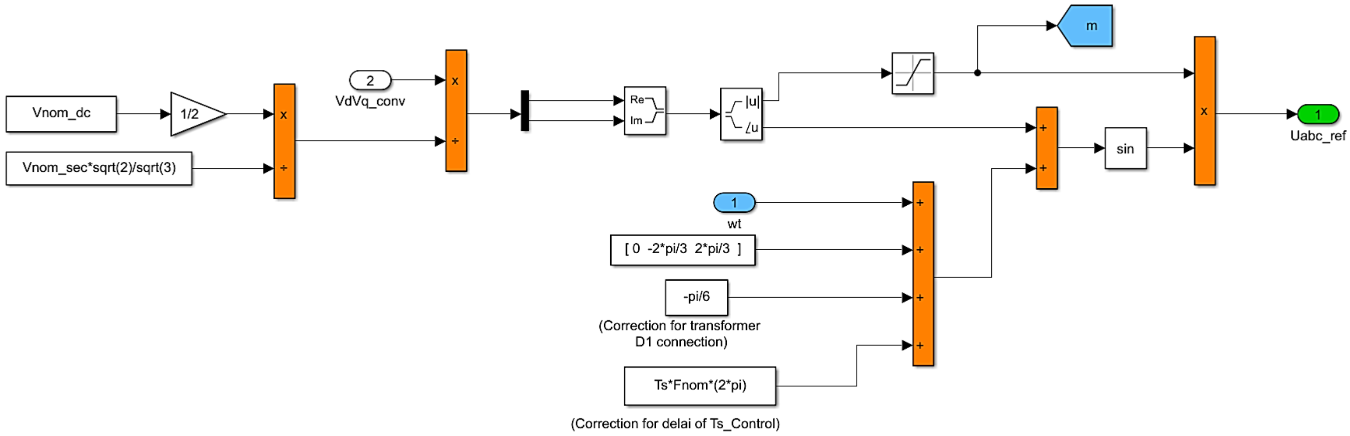

Figure 5: Proposed Uabc ref Generator

Combining the above designs of the Phase Locked Loop (PLL), VDC regulator, current regulator, and ABC to DQ Transform, a complete voltage source converter (VSC) controller was formed as shown in *Figure 6*. For systems simplification of the design, a subsystem was created from the design as indicated in *figure 7*. The parameters used to design the voltage source converter (VSC) controller are tabulated in *table 2*.

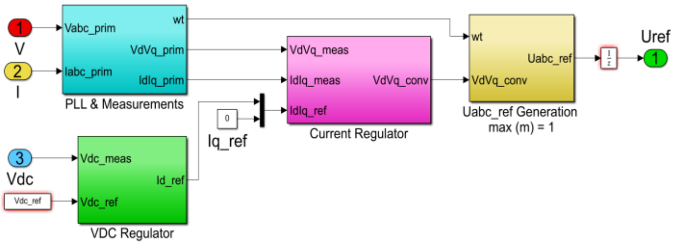

Figure 6: Proposed Voltage Source Converter (VSC) Controller

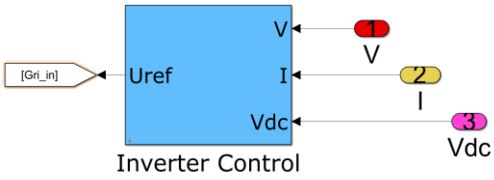

Figure 7: Subsystem of the proposed Inverter Controller

Table 1: Voltage source converter (VSC) controller parameters

Parameters	Values
Nominal Power (Pnom)	2600e3VA
Frequency	50Hz
Nominal Primary Voltage (Vnm_prim)	500V
Nominal Secondary Voltage (Vnm_Sec)	420V
Nominal DC bus voltage	500V
Output Line Voltage	400V
Output frequency	50Hz
Nominal Efficiency	97%
Total transformer leakage impedance (pu/Pnom)	
Resistance (Rxfo)	0.002
Inductance (Lxf)	0.06
Choke impedance	
Resistance(R)	1e-3ohm
Inductance(L)	45e-6H
DC voltage (VDC) regulator gains	
Proportional gain (Kp)	7
integral gain (Ki)	800
Current regulator gains	
Proportional gain (Kp)	0.3
integral gain (Ki)	20
DC/AC Converter Mask Model Values	
Output Line Voltage	400V
Output frequency	50Hz
Nominal Efficiency	97%

2.1.3 Maximum Power Point Tracking (MPPT) design based on perturb and observe Algorithm

Maximum Power Point Tracking (MPPT) is a critical concept in renewable energy systems, especially in photovoltaic (PV) systems and wind turbines for harvesting the maximum power[4]. In this work, the objective of using the MPPT is to extract the maximum available power from the renewable energy source (solar) by dynamically adjusting the operating point. This is achieved by continuously tracking the maximum power point (MPP) of the source under changing environmental conditions (varying solar irradiance). MPPT controller is used to adjust the operating parameters such as voltage and current to ensure that the system operates as close to the maximum power point (MPP) as possible by maximizing energy harvesting efficiency. The design of the above-mentioned was done in MATLAB as shown in *figure 8*. The perturb and observe algorithm was considered during the design of the Maximum Power Point Tracking (MPPT) controller due to its capability of efficient energy harvesting, adaptation to changing conditions, and real-time operation. The complete proposed photovoltaic plant model used in this work is shown in *figure 9*.

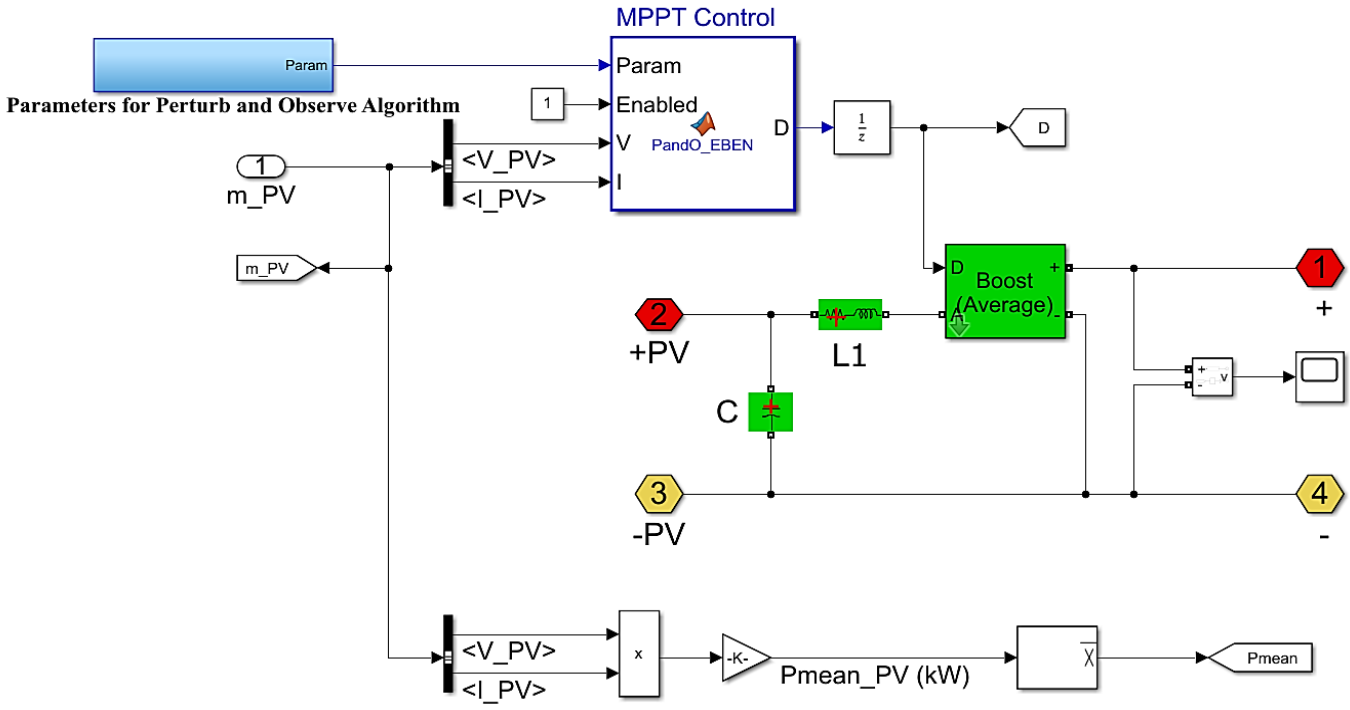

Figure 8: Proposed Maximum Power Point Tracking (MPPT) design

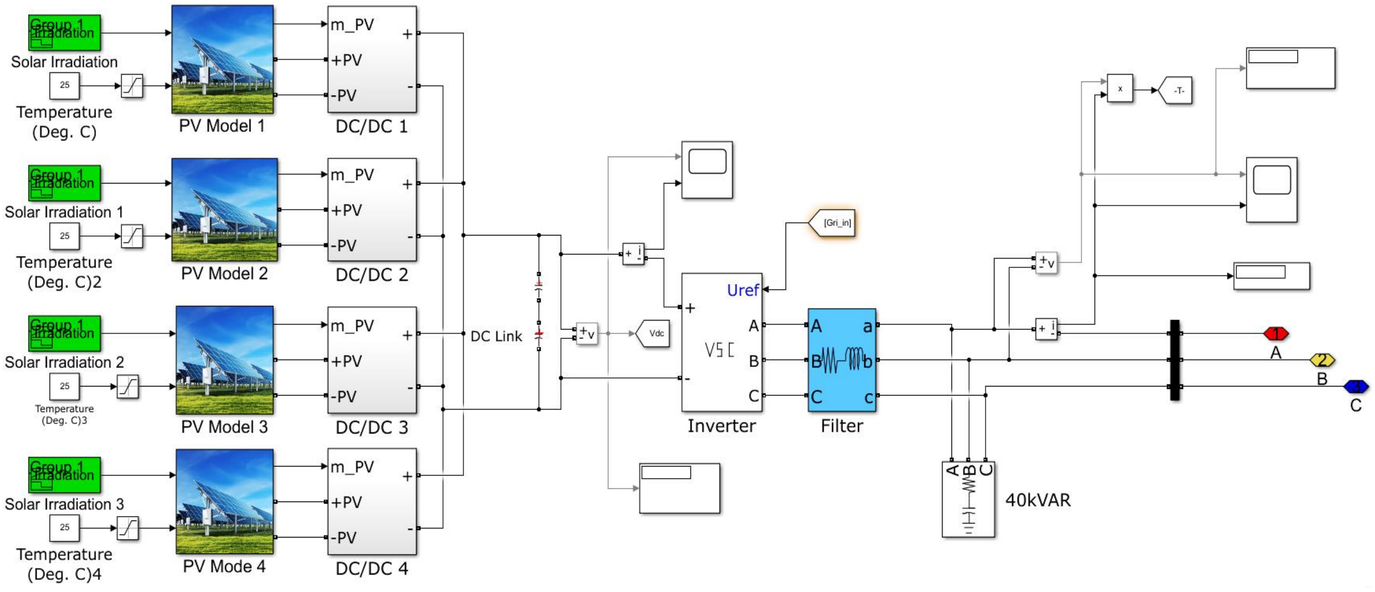

Figure 9: Complete design of the Photovoltaic Plant

2.2 Design of Wind Turbine and Control System

2.2.1 Two-mass drive system design using ANFIS

The two-mass drive system is a crucial component in modern wind turbine designs, enabling efficient and reliable conversion of wind energy into electricity suitable for the grid and maintaining system stability with maximum power extraction [51]–[53]. The necessity to deal with flexible modes brought on by intermittently fluctuating wind speed and low-speed shaft stiffness is what drives the employment of the two-mass concept in this study. In this work, the two-mass drive system with ANFIS controller was used in wind turbine coupling to a generator due to its adaptive nature to system condition changes. Its advantages are speed adaptation, torque conversion, mechanical decoupling, efficiency improvement, vibration damping with torque smoothing, enhanced generator performance, reduced mechanical stress, increased energy capture, improved grid stability and system protection. It was considered in this work because of its mechanism that helps optimize the balance between the dynamic nature of wind forces and the steady power output desired for stable energy generation. The proposed design of the two mass-drive train is shown in *figure 10*

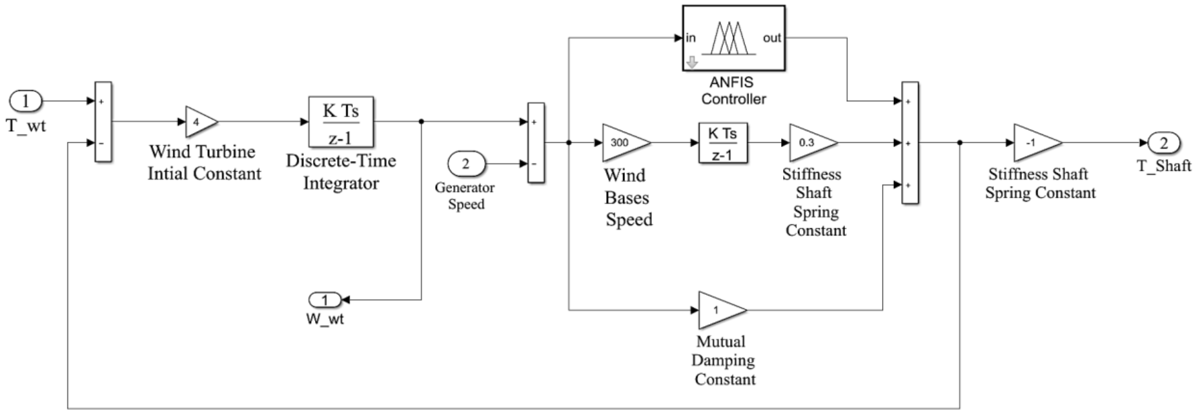

Figure 10: Proposed Two mass-drive train model with ANFIS Controller

2.2.2 Proposed design of pitch angle controller using ANFIS

The pitch angle controller plays a vital role in controlling the speed and power output of the turbine. With this, an adaptive pitch angle controller was developed to adapt and adjust the pitch angle based on variations in wind speed, and regulate the turbine speed and power generation [17]–[20]. In this study, the main reasons for the introduction of a pitch angle controller with ANFIS in wind turbine speed control are the advantages that it offers as power limiting, power regulation, speed control, load reduction, yaw control interaction, and emergency shutdown control. Based on the above-mentioned advantages a pitch angle controller with ANFIS is designed in SIMULINK as shown in *figure 11* and a complete model of the proposed Wind turbine is presented in *figure 12*.

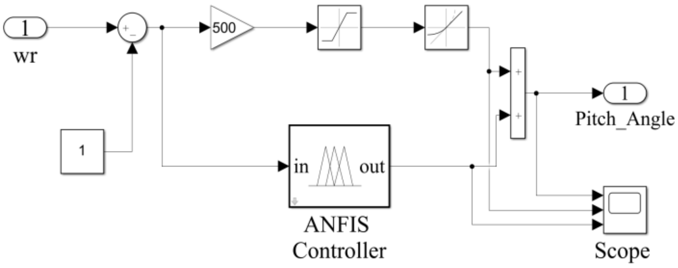

Figure 11: Proposed Pitch Angle Controller using ANFIS

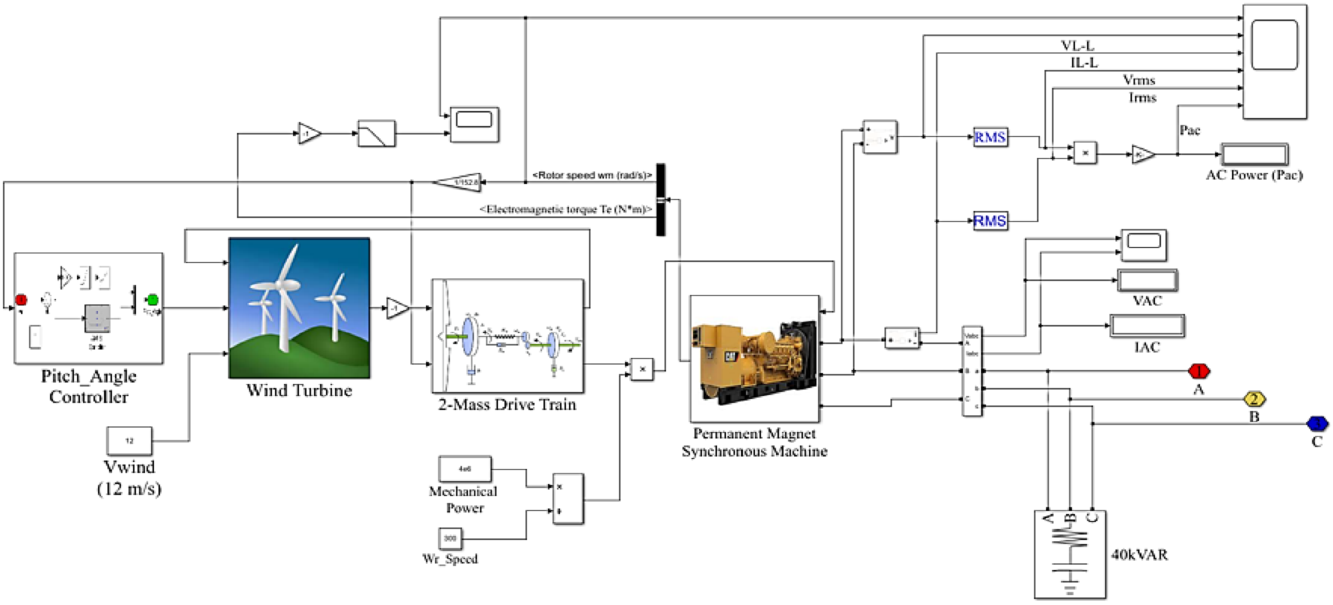

Figure 12: A complete model of the proposed Wind Plant

2.3 Battery Energy Storage System Design

2.3.1 Battery energy storage system controller design

To aid in connecting the storage system to the radial distribution network, a bidirectional buck/boost converter and DC/AC converter were designed. A bidirectional buck/boost converter is crucial for efficiently managing power flow and facilitating bidirectional energy transfer in applications such as energy storage systems, renewable energy integration, and grid-tied systems. In this work, the above-mentioned converter was modeled and used due to its capability in power charging systems, particularly in energy storage systems (Battery). The designed converter can both step down (buck) and step up (boost) voltage, allowing power to flow bidirectionally between the energy sources and the load to manage the energy storage charging and discharging, managing Bi-directional power flow, voltage matching when the source voltage is different from the load voltage, for ensuring efficient energy transfer without risking damage to the components, with Grid integration by adapting the voltage levels and ensure the power is fed into the grid with the right characteristics, conforming to grid requirements and regulations(parameters). DC/AC converter was used to convert the DC voltage into AC voltage which is interfaced with the grid network. The proposed battery system control system is presented in *figure 13* while the design of the storage system with the DC/AC converter is presented in *figure 14*. The complete model of the storage system is shown in *figure 15*. Combining all the above controllers and the power sources modeled in MATLAB, the complete proposed grid-connected Microgrids integrated into a distribution test system is shown in *figure 16*.

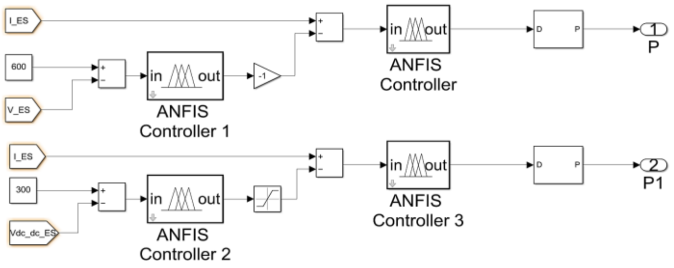

Figure 13: Proposed battery energy storage control system

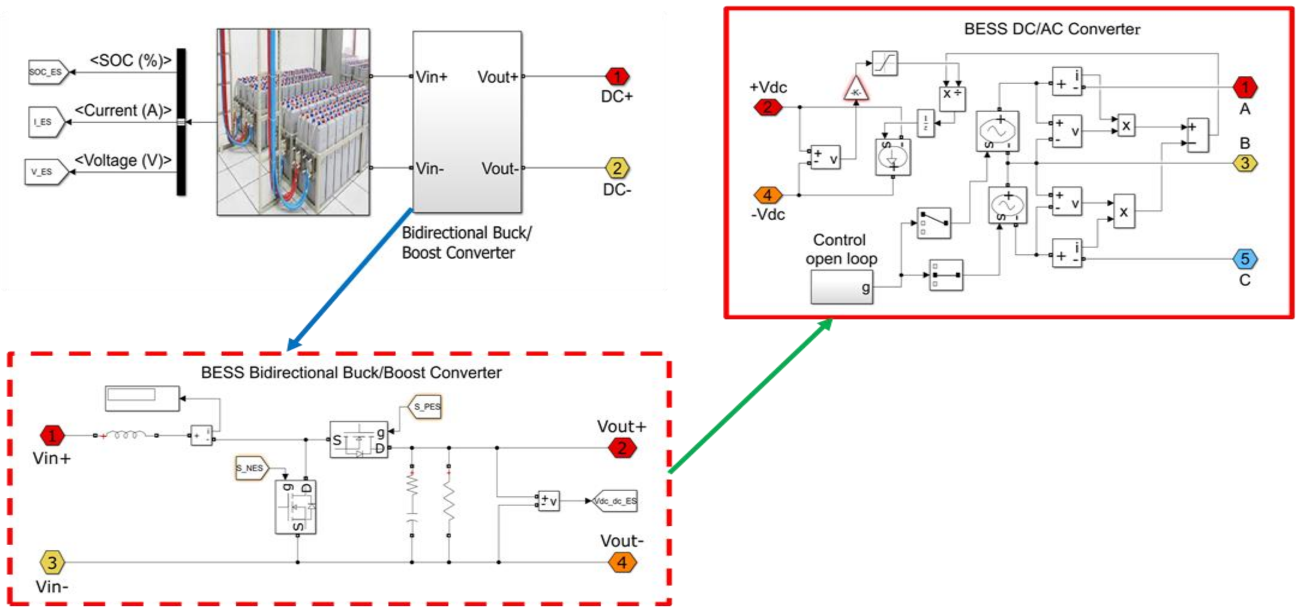

Figure 14: Design of the storage system with DC/AC converter

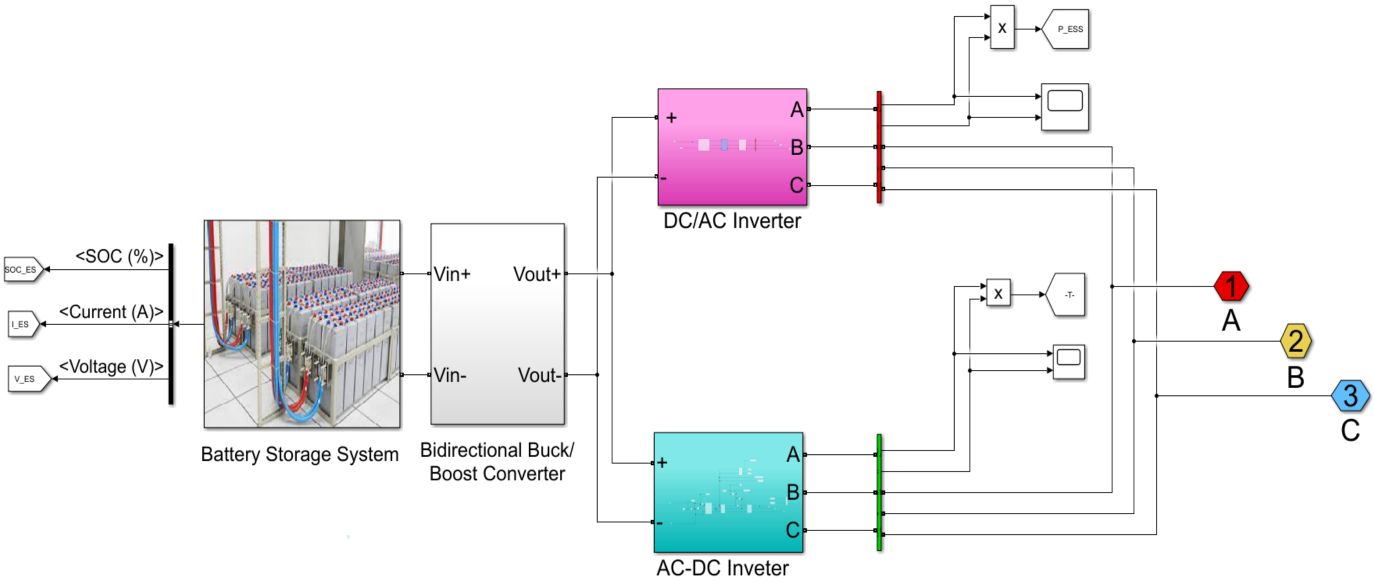

Figure 15: Complete model of the proposed storage system

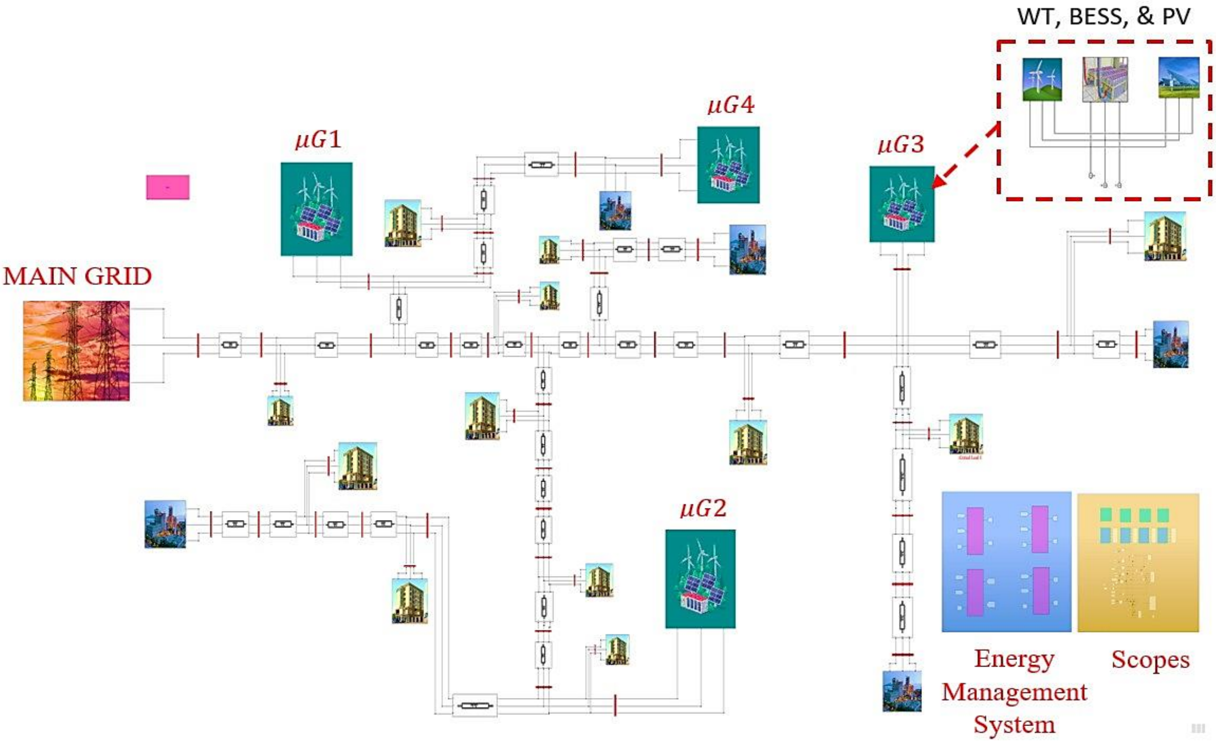

Figure 16: Proposed radial distribution network with four Microgrids

2.4 Mechanism of operation of proposed ANFIS controller

The distribution network architecture currently in use for grid operation lacks an adaptive controller to use ANFIS to manage Microgrid power resources integrated into the grid network for automatically controlling and maintaining voltage level without utilizing reactors, STATCOM, and compensators for quick response for voltage control to ensure grid stability. In order to address the aforementioned issue, the ANFIS controller, which can adapt to system changes while keeping a consistent output, is proposed in this research. With this mentioned, *figure 17* displays the control flowchart for the multiple grid-connected Microgrid voltage control of the suggested grid network. The model operation of the ANFIS controller is depicted in this figure. Activating the microgrids' ANFIS-based controllers to adapt and maintain constant system supply voltages to prevent deviations in the voltage profile prior to connecting each Microgrid to the distribution network allows for control and maintenance of the integrated Microgrid's voltage. This flowchart defines the order in which the Microgrid elements should be connected and activated. The general voltage control of the suggested distribution network is modeled mathematically by this. Obtaining the reference voltage level should be done first. Upon reaching the system reference voltage (Vref), the ANFIS controller will utilize this information to initiate the control mechanism, which will involve adapting, maintaining, and connecting Microgrids automatically.

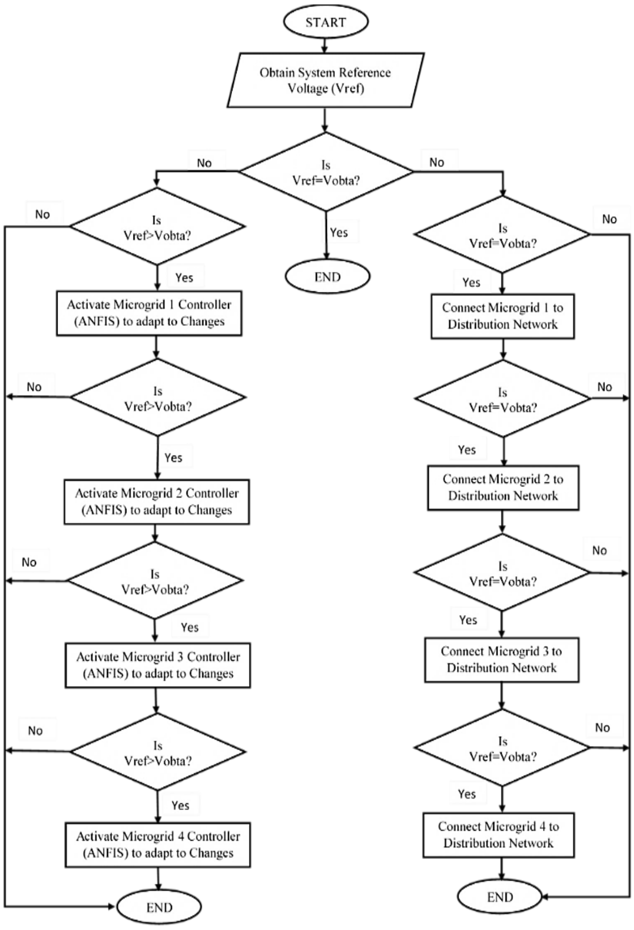

Figure 17: Flowchart of the proposed Multiple grid-connected Microgrids voltage control

2.4.1 Steps for System Actualization

1) Initialized system operation
2) Obtain the distribution network reference voltage.
3) Obtain system load demand
4) Connect an available power source
5) Check variation of system voltage (Sag or Swell) based on system load and power supply by Microgrid(s) connected.
6) Obtain system voltage status for sag or swell in the network.
7) Microgrid controller with ANFIS adapted to the system voltage variation.
8) Activate the ANFIS controller at the DGs which is connected to the system to observe voltage sag and swell.
9) Normal system voltage is obtained.
10) End

3. SIMULATION RESULTS

This work was aimed at evaluating the effectiveness of the ANFIS-Based Controller of keeping system voltage and current of integrated distributed generators energy sources (PV, WT, and BESS) of grid-connected microgrids power supply in radial distribution network without adding any compensator(s). the power distribution of all the generators was simulated in MATLAB/SIMULINK using a 24-hour duration during the simulation period. But for clarity of the current and voltage graphs presented in this work, the scope time was set to 0.1 seconds. The simulated results are presented in *figures 18, 19, 20, 21,22,23 and 24*.

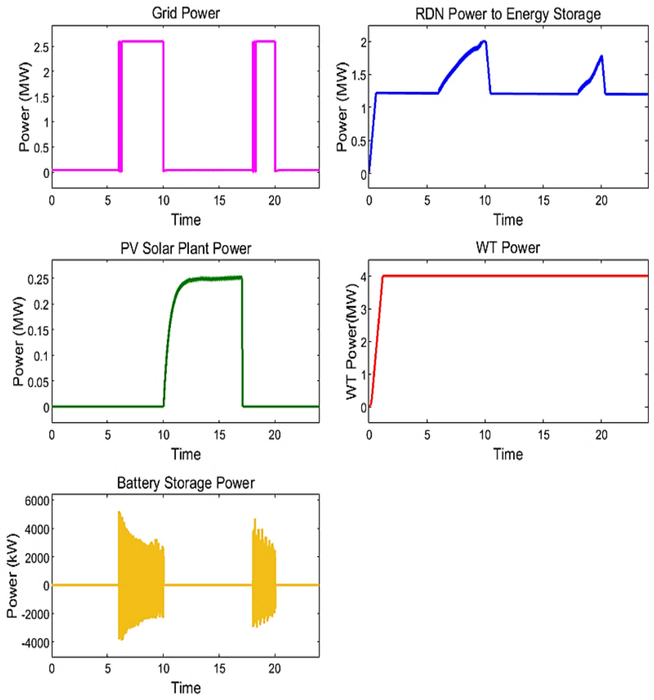

Figure 18: Power distribution of grid-connected Microgrids DGs

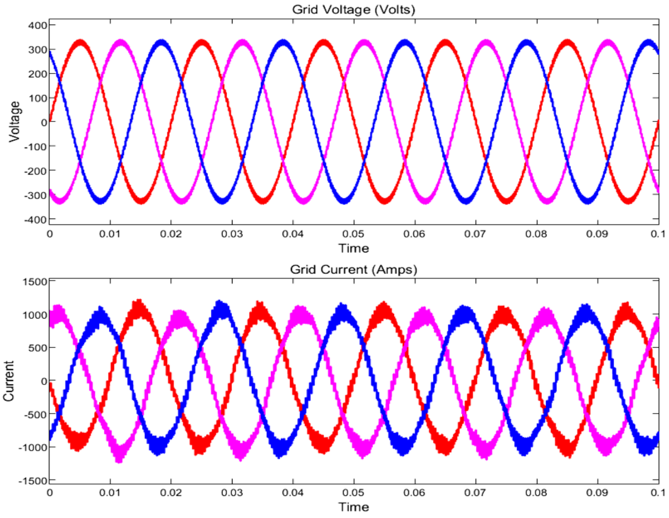

Figure 19: Distribution network voltage and current characteristics

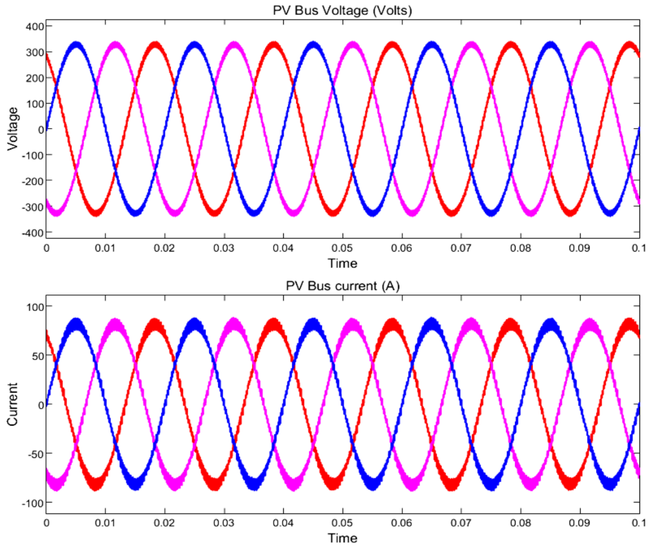

Figure 20: Bus voltage and current characteristics of the PV Plant

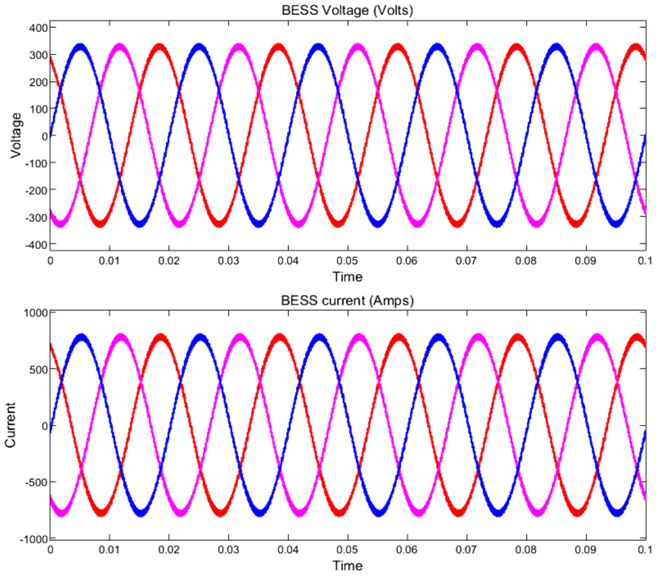

Figure 21: Bus voltage and current characteristics of the BESS

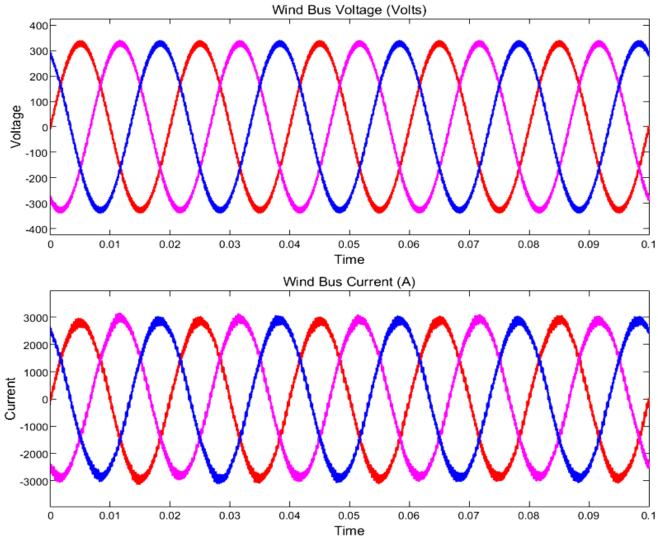

Figure 22: Bus voltage and current characteristics of the Wind Turbine

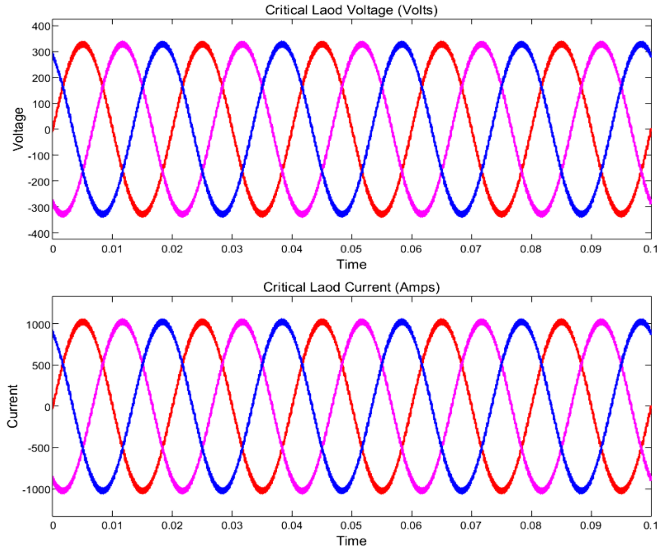

Figure 23: Voltage and current characteristics of Critical Load

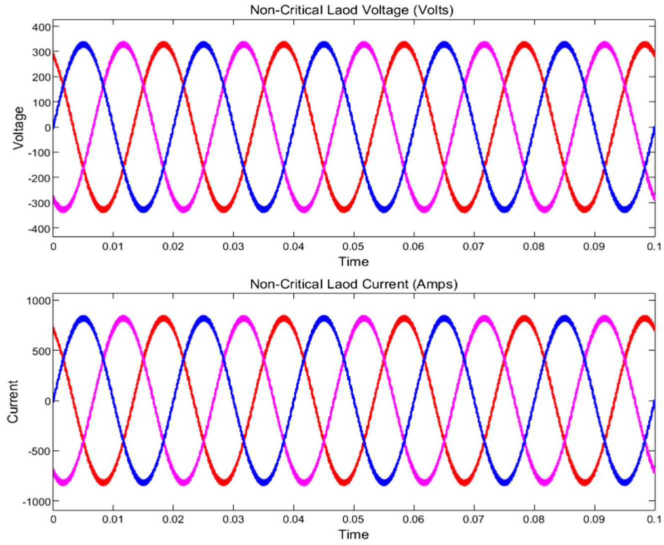

Figure 24: Voltage and current characteristics of Non-Critical Load

4. RESULTS AND DISCUSSION

In evaluating system performance based on the dispatching of the above-mentioned energy sources, some operational conditions scenarios were considered such that; when enough power is available from all the sources to supply system load demand (PLD), when there is excess power supply than connected load demand, and when there is low power supply than system load demand. Based on the above-mentioned scenarios, the ANFIS controller adapts to system behavior and supply power accordingly either under grid-connected mode or islanded mode. Two loads were considered in this work, that is critical load and non-critical load to aid in evaluating how each load will be supplied with voltage and current. Since PV power is mostly dependent on sunshine, the major power taken into account in this study is the power produced by wind turbines (WT). As a result, the ANFIS controller was utilized to dispatch the available power sources based on the load demand (PLD) connected to the network. The simulated results are presented in figures (18) to (25) and table 2 and 3 respectively. In *figure 18*, the grid power and battery storage power are shared during the peak demand period of the day, that is, between the hours of 06:00h to 10:00h and 18:00h to 20:00h with the grid supplying maximum power of 2.5MW, the battery storage system supplies around 4000kW power to maintain power balance in the system.

In the Microgrids the PV plants supply 0.25MWp power between the hours of 10:00h to 17:00h, using the MPPT control technique in harvesting the available solar irradiation to produce the necessary power required as indicated in *figure 18*. The wind turbines supply 4MW, this was a constant supply because of the use of the adaptive controller (ANFIS) for controlling the pitch angle for optimum adjusting the turbine blades in varied wind conditions and also controlling the drive train that coupled the wind turbine to the generator. When the power dispatching from the microgrid sources was evaluated, it was discovered that the power from the radial distribution network (RDN) was power from the wind turbines of about 1.2MW, which were stored between the hours of 00:00h to 06:00h before the grid power started to supply power, where the storage power increases to 2MW during the peak hours after the grid started supplying power. But even though the PV plants were supplying power between 10:00 and 17:00, a consistent power of 1.2 MW was maintained between the hours of 00:00 to 06:00, 10:00 to 17:00, and 20:00 to midnight. This was accomplished through the application of the suggested ANFIS controller, which was used to regulate the charging and discharging of the batteries used in this work and to guarantee the sharing of power among the numerous grid-connected microgrids in the distribution network, as depicted in *figure 18.* The summarized data obtained during the simulation on the distributed generators are therefore presented in *table 2*.

In the quest to evaluate the current and voltage flow in the entire distribution network using the proposed ANFIS Controller, the flow voltage and current in grid distribution are presented in *figure 19* while the various distributed energy sources, critical loads, and non-critical loads voltage and current flow are shown in *figures 20, 21, 22, 23 and 24* respectively. It was realized that a constant voltage of 340VAC was maintained in all the above-mentioned graphs with different current supplies based on the demand of the load connected. The 1000A current was supplied and maintained throughout the entire network but the bus voltage and current distributed energy sources (PV, WT, and BESS) are 340VAC and 100A for photovoltaic plants as depicted in *figure 20*, 340VAC and around 600DCA of the battery energy storage system as in *figure 21* before connected through the Voltage source converter (VSC) controller where the VSC now control these parameters to meet grid network parameters (voltage and current) for proper synchronization while the bus voltage and current of the wind turbine was 340VAC and 3000A respectively as shown in *figure 22*. Using the proposed controller, further evaluation of voltage and current supply to the above-mentioned loads were realized that, for critical loads considered a 340VAC and 1000A were supplied to that load as shown in *figure 23*, and for the non-critical loads, a voltage of a 340VAC and a current around 800A were supplied as shown in *figure 24*. In all these simulation scenarios, the time of 0.1 seconds was used in setting the scope time for clarity of graphs. It is clear from the results presented that the proposed ANFIS Controller and the VSC effectively control the various DC power sources (PV, and BESS) voltage and that of the AC voltage of the Wind Turbine for achieving a constant distribution network voltage of 340VAC for successful synchronizing the districted generators to the grid network without fluctuation in phase voltages. It must be emphasized that the were varied current values based on the load requirement yet no fluctuation in phase currents was recorded during the simulation. With the help of VSC, power supply voltages are maintained within an acceptable range of 340VAC for use with other electrical parts. Power flow to the loads is present using *figure 25* which shows the minimum and maximum power for non-critical and critical loads as 520kW and 450kW, 540kW and 470kW respectively with the summarized data obtained presented in *table 3*. This means that the proposed controller can supply power based on the required needs of a customer.

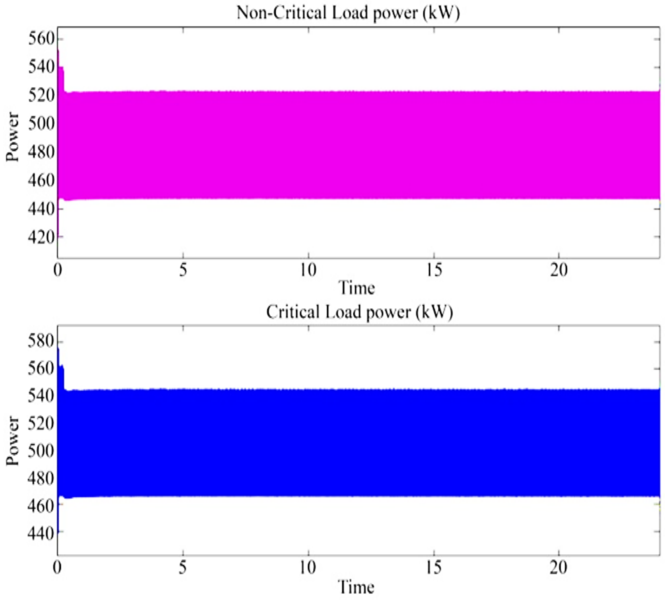

Figure 25: Critical and Non-Critical Load Power Supply

Table 2: Simulation results obtained on distributed generators

	AC Voltage(V)	AC Current(A)	Power (MW)
Grid Distribution Network	340	1000	2.5
PV	340	100	0.25
WT	340	3000	4
BESS	340	600	6

Table 3: Simulation results obtained on system loads

	AC Voltage (V)	AC Current (A)	Maximum Power (kW)	Minimum Power (kW)
Critical load	340	1000	540	470
Non-Critical	340	800	520	450

4.1 Comparative Analysis with Existing Methods

For connected PV-WT systems that operate on both ON and OFF the grid, an efficient storage unit, and Emperor Penguin-based Adaptive Neuro-Fuzzy Inference System (EP-ANFIS) controller were designed in [24] to regulate the voltage obtained from RES, the results obtained were presented in *Figures 5 and 6* of [24] for off-grid mode and on-grid mode respectively. Considering the proposed technique of the paper [24], during the off mode of their system, the voltage, current, and power profile have some ripples. However, during the on-grid, smooth signals were recorded. The difference in the two modes of operation is that the variation in signals reduces the performance of their system as compared with what is proposed in this work where under both conditions of operation voltage and current were not varying. Using a cost-based EHO-based droop control technique for power management using a hybrid ANFIS PID-based AC-DC microgrids in [16], the varying power affects system voltage as shown in *figure 7* of [16]. However, when the wind turbine voltage increases, the generated power increases and further slightly decreases as presented in *figure 6* of [16]. Fuzzy-ANFIS Controllers were used to enhance grid power quality and the result on load voltage and current were presented in *Figure 20* of [12] which also indicated that such technique can be used to control system voltage and current. Meanwhile using only, the ANFIS controller in this paper performed effectively by controlling not only load Voltage and Current but the entire power generation sources and distribution network Voltage and Current as represented in *figures 19 to 24*. Again, *figure 11* presented in [54], there were variations of voltage from 0.9131 p.u. to 0.9335 p.u., with average voltage recorded as 0.9604 p.u. in a voltage profile for combined light, medium, and peak load conditions as compared to the performance of the proposed method used in this paper where constant voltage profile of 340V was maintained.

From the above discussion, some of the advantages of this proposed method over the existing one are the less cost involved and the space of installation that could be utilized in real-time application as a result of not using compensators in this work. The disadvantages realized are the longer period required for training data and simulation of such a large network in MATLAB/SIMULINK to complete. The limitation realized is the huge simulation data obtained which is not added in this paper. The proposed controller was limited to low voltage system and therefore it was not applied to a high-voltage network (transmission network) to verify its performance and compare it with the low-voltage network result obtained. Therefore, future works should focus on applying to a transmission network as well with some optimization techniques and the result should be compared with other results obtained when applied to a distribution network.

5. CONCLUSION

Maintaining power distribution network voltage and current based on an Adaptive control has been presented in this manuscript using ANFIS to develop controls for the various distributed generators power sources (PV, WT, and BESS) used in this paper. Voltage source control is designed for the DC sources used. The test system was modeled and simulated using MATLAB/SIMULINK. The grid-connected Microgrid proposed can operate in both grid-connected mode and Islanded mode without affecting system operation. The system was tested in these modes during the simulation of the network. Four microgrids were developed and integrated into the network system through the various points of common coupling. The novelty of this paper is the proposed adaptive control based on the ANFIS mechanism used to adapt system changes and maintain a constant system-generated voltage of 340VAC without any variations during different modes of operations of Microgrids. The control system is simple to design and will require a small installation space and less cost in a real-time implementation as compared with the technologies found in other papers utilizing compensators. It is found that the control method succeeds by synchronizing multiple microgrids to the utility grid without any fluctuations in distribution network phase-to-phase voltage and phase-to-phase current supply. In order to provide reliable system performance under a variety of contingencies and dynamic events, future work is also required to build and implement the control methods and apply to a transmission network by including optimization techniques. The findings offer a starting point for more investigation into the application of strong controls for upcoming grids with a predominance of renewable energy sources.

Author Contributions

Ebenezer Narh Odonkor: Conceptualization, designed, Modeled, simulated, evaluated system performance, and wrote the paper.
Dr. Peter Musau Moses: supervise, analyze, and edit the paper
Dr. Aloys Oriedi Akumu: supervise, analyze, and edit the paper

Funding Source

This work was funded by the Pan Africa University (PAU).

Acknowledgments

The authors are grateful to the Pan African University Institute for Basic Sciences, Technology and Innovation (PAUSTI) for the support.

Conflicts of Interest

The authors declare no conflict of interest.

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