An Intelligent Charging System for Grid-Integrated Electric Vehicles Using an ANFIS-Based Controller

MAHENDRA NAIDU GOTTAPU[1], Dr. Kottala Padma[2], Prof. T.R Jyothsna[3]
[1]*Andhra University College of Engineering (A) Andhra University*
[2]*Associate Professor, Department of Electrical Engineering, AU College of Engineering (A), Visakhapatnam-530003*
[3]*Professor & Head, Department of Electrical Engineering, AU College of Engineering (A), Visakhapatnam-530003*

***Abstract*—Electric vehicles (EVs) are rapidly emerging as a key component of sustainable transportation, driving the need for advanced charging infrastructure. This work presents a multifunctional charging system integrated with the grid, EV batteries, and household utilities, offering improved efficiency and adaptability. The proposed system consists of a voltage source converter (VSC) connected to the grid and a bidirectional converter that manages battery charging and discharging while maintaining a stable DC bus voltage for EV charging.**

To enhance system performance, an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller replaces the conventional PI controller, providing adaptive control, faster response, improved robustness against load variations and to estimate the active component of load current, further optimizing power management. The ANFIS-based control strategy enhances the system's dynamic response by accelerating error convergence and improving mean square error (MSE) performance. Simulation and simulation results validate the effectiveness of the proposed intelligent charging system, demonstrating improved accuracy, efficiency, and reliability in grid-integrated EV charging applications. simulation results demonstrates that the ANFIS outperforms traditional methods by achieving superior dynamic performance and accuracy. Specifically, the ANFIS will optimize system effectively and reduces Total Harmonic Distortion (THD) of the source current to 1.06%.

I. INTRODUCTION

1.1 Overview

In recent years, the environment and conservation have become major concerns. Therefore, the development of electric vehicles (EVs) is increasing at a rising pace as they are environment friendly. Electric Vehicles: 1) solve the problems of environmental pollution, 2) reduce the dependency on conventional resources, and 3) represent cultivating pillars for new industries. The electric transportation, two- and three wheelers, and buses pilot growth, their electricity utilization has almost tripled over the forecasted years. For a sustainable environment, the appropriate idea about the electric vehicle is mandatory, including its charging modes and the load profile across the grid , the Monte Carlo based simulation method is used to present an analysis on EVs, which shows that the charging profile plays a major role in the charging model of EVs and battery swapping helps in cutting down load demand from the grid. EV fields into domains, which are power electronics, battery technology, electric motor and charging/discharging systems.

It has also estimated rates of improvement per year, which are 18.3%in power electronics, 7.7% in electric motors, 23.8% in charging/discharging systems and 11.7% in batteries. Therefore, the development of a charging infrastructure and battery control are the key features and the EV batteries are charged with the grid connection.

The discussed the decentralized control of EVs and their charging impact on distribution networks. The outcome shows the reduction of fluctuations in the DC bus voltage and the total harmonics distortion (THD) of the current is also improved. The charging infrastructure can be either "on board" or "off board" depending upon the requirements.

1.2 Literature Review

The increasing adoption of electric vehicles (EVs) has necessitated advancements in charging infrastructure to enhance efficiency, reliability, and grid stability. Various studies have explored intelligent charging systems that integrate bidirectional power flow, renewable energy sources, and advanced control strategies. Bidirectional charging has been identified as a crucial technology to support vehicle-to-grid (V2G) and grid-to-vehicle (G2V) applications. Research in [1] emphasizes that bidirectional power flow allows EVs to act as distributed energy resources, contributing to grid stability and reducing peak demand. Studies such as [2] and [3] highlight the impact of EV penetration on power distribution networks, showing that bidirectional chargers can help mitigate voltage fluctuations and optimize energy management. a multifunctional [4] charging system is presented, which consists of a PV array as a renewable energy source to charge the EVs [5]. The researchers have also developed a controller for power quality improvements.

The multi-functional EV charging system connected to the grid can cater and support the needs of the EVs. The charger is also enabled with an EV2G and an electric vehicle to home (EV2H) to feed the loads when the grid is not connected to the system. However, it is still a challenge to develop a robust controller with fast response for EV2G and G2EV modes. An onboard charger [6],[7] is developed with power factor correction capability in [9],[10]. The charger consists of a low voltage DC to DC converter with G2EV andEV2G operating modes. S. Wang et al. [11], present the highly efficient charger with G2EV, EV2G, and with proposed EV2EV charging operations. In the V2V mode of operation, the efficiency achieved is 96.1%. In [12], the 2EV/EV2H/EV2G are developed with the bidirectional power flow capability using an electric scooter. The charge/discharge and energy management are discussed in [13], [14] carried out the review on the charging infrastructure and various charging levels for the plug-in-EVs.

Moreover, these multifunctional charging systems are operated in four non-identical configurations with respect to future smart grids: (1) The EV battery pack being charged by the grid from the G2EV mode; (2) The EV battery pack can inject stored energy back into the electrical power grid through the electric vehicle-to-grid (EV2G) mode [15]; (3) The charging system is operated in the vehicle to home mode (EV2H) mode [16]; (4) a multifunctional vehicle to vehicle (V2V) charging system is also the requirement for the current era [17], [18] proposed a coordinated control to help the penetration of EVs into the grid and support the grid frequency control during the fast EV's charging rates. In [19], [20], researchers have focused on the performance of the bidirectional battery chargers (BBCs).

More specifically, they consider a designed BBC for the charging of a particular EV and subsequently it is sized to match the specifications of that particular EV's battery. In [21], a voltage based scheme is discussed, which does not require any communication between EVs and the grid. However, the impact on grids with integration of EVs and power quality issues are not included in it. The quality of power during the EV2G and G2EV operating modes is also one of the major concerns during the grid interaction [22].

The increase of consumer nonlinear loads, for example, electric furnaces, power converter-based power supplies and LEDs, etc., at the point of common coupling (PCC), is the main cause in disturbing the quality of voltage and current in the distribution grid. In [23], a power quality control is proposed for the battery storage and PV array-based system. It enables the only active, only reactive, and simultaneous active and reactive power exchanges with the grid. This system is able to maintain the grid current THD below 5% in all operating modes. The optimal planning of Electric Vehicle charging stations into the grid/distribution feeder has become very important as it plays a significant role in quality management [24], [25] have presented an integrated traction machine and converter topology that enables the bidirectional power flow [26] between EV and DC/AC supply and/or the grid. Moreover, In [27], have proposed an efficient battery charging system, in which low-cost battery charging is imposed and at the same time degradation time of the Lithium- ion battery is also improved.

Therefore, battery energy storage technology is the core of the multifunctional charging system for EVs, which comprises a bi-directional converter and VSC tied to the grid. It plays the important role in monitoring the charging/discharging of the EV battery and battery swapping techniques, which are achieved by finite state machine (FSM) based logic in [28]. In the above model, different types of control methods are used to control the load current, DC link voltage and grid currents. Therefore, the adaptive controls are the key to controlling the charging system with improved transient response analysis [29]. The step size of the technique is updated under adaptively disturbances and noise. Therefore, these controllers are playing a crucial role as the charging system is subjected to dynamic conditions, charge/discharge and sudden load changes. In this paper, a multifunctional charging system [30] is presented with EV2G and G2EV modes along with the nonlinear load with adaptive technique.

The motivation for the project need to:

- Improve charging efficiency and power quality in grid-integrated EV systems.
- Enhance grid stability through intelligent bidirectional energy management.
- Seamlessly integrate renewable energy sources and household energy systems into EV charging infrastructure.
- Reduce economic barriers by optimizing energy use and minimizing operational costs.
- Contribute to the sustainable transportation ecosystem while supporting global de carbonization efforts.

1.4 Project work Objective

The primary objective of this thesis is to design, develop, and validate an intelligent, multifunctional charging system for grid-integrated electric vehicles (EVs) that ensures high efficiency, adaptability, and reliability under dynamic operating conditions. Specifically, the work aims to:

1. Develop an ANFIS-based control strategy to replace conventional PI controllers, enhancing adaptability, reducing steady-state error, and improving dynamic response in EV charging systems.
2. Implement a bidirectional power flow architecture to support grid-to-vehicle (G2V), vehicle-to-grid (V2G), and vehicle-to-home (V2H) operations, thereby improving energy management and grid stability.
3. Ensure seamless integration with renewable energy sources and household utilities to maximize the utilization of clean energy while minimizing dependency on conventional grid power.
4. Validate system performance through simulation analysis, demonstrating improved efficiency, robustness against load variations, and compliance with power quality standards.

By achieving these objectives, this research aims to contribute to the advancement of intelligent, grid-compatible EV charging systems capable of meeting the future demands of sustainable transportation and smart grid infrastructure.

II. SYSTEM CONFIGURATION

The topology of the charging system is shown in Figure.4.1. The configuration shows the integration of the grid with EV battery and nonlinear loads. The grid is supplying power to the nonlinear load which is constructed by using a diode bridge rectifier, followed by R and L. The grid is connected to the bidirectional converter through a common DC link capacitor via a voltage source converter (VSC). The VSC transforms the AC power of the grid side to DC power, which is further fed to the bidirectional converter to feed the EV battery. The bidirectional converter is connected to the EV battery with a smoothing inductor. The ripple circuits having intermediate resistance and very low capacitance are employed for the reduction of the high frequency noise from the grid voltages.

The Figure 4.1 shows:

Multiple EV Batteries (on the left, represented as car icons with battery symbols).

DC/DC Converters (the three identical buck-boost converter circuits with IGBTs and inductors) connected to the EV batteries.

A Common DC Bus (the vertical line connected to a capacitor).

A Three-Phase Inverter (the central orange box with six IGBTs/diodes) connected to the DC bus.

An AC Grid Connection (on the right, represented by the wavy lines).

Based on the description of the components typically found in that kind of diagram (Electric Vehicles, DC-DC Converters, a DC Bus, and a Three-Phase Inverter connected to the AC Grid), the image most likely illustrates the Working Principle of a Multi-Port Bidirectional DC Fast Charging Station with Vehicle-to-Grid (V2G) capability.

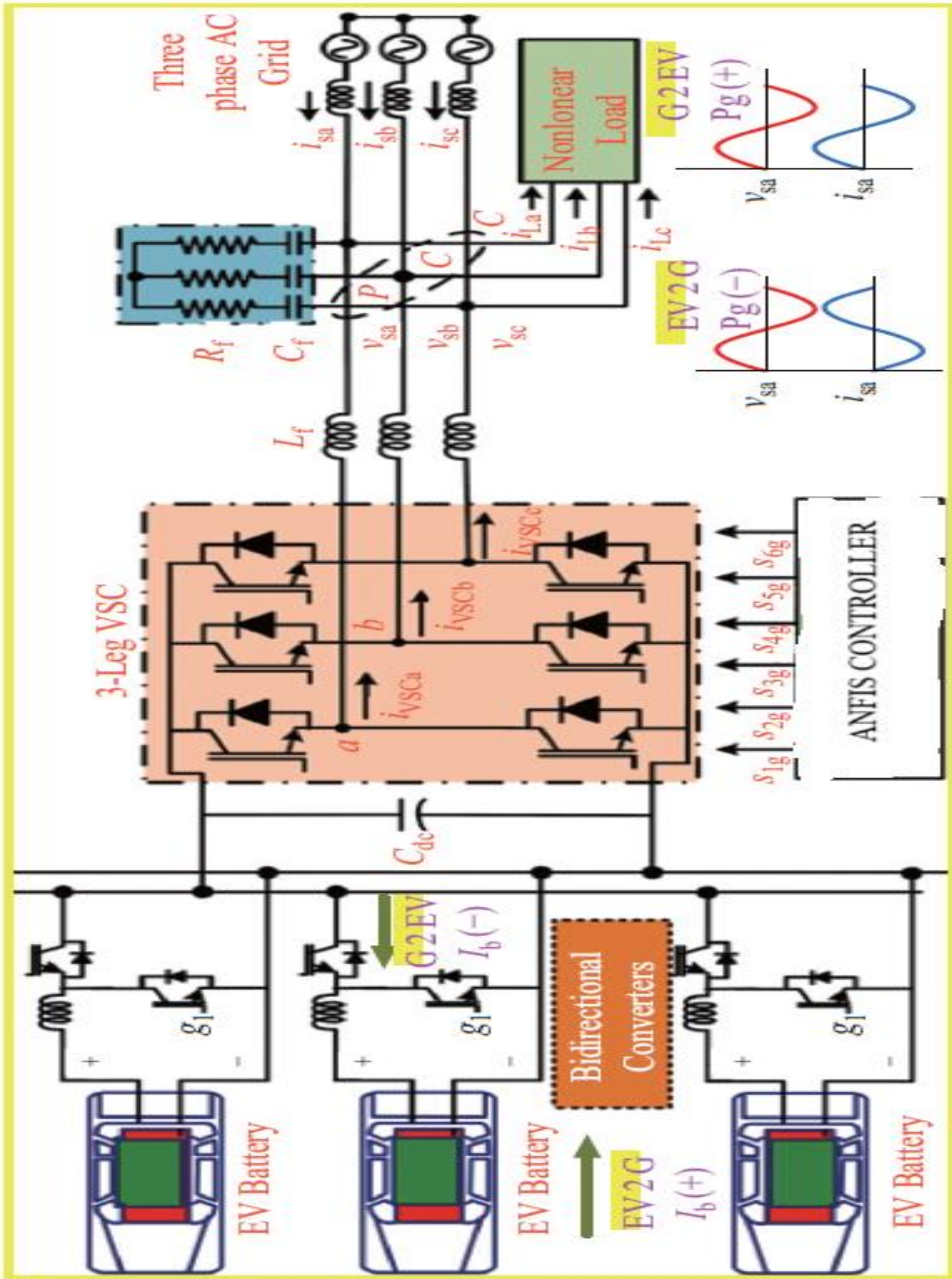

Figure 4.1 Circuit topology of Charging system

Here is a breakdown of how this system works:

III. KEY COMPONENTS

Component	Function
AC Grid Connection	The source of power (or sink for V2G power), typically a three-phase Alternating Current (AC) supply.
Three-Phase Inverter	The main power stage that connects the station to the AC grid. It acts as an AC-to-DC Rectifier during charging and a DC-to-AC Inverter during discharging (V2G).
Common DC Bus	A high-voltage Direct Current (DC) link that connects the central inverter to all the individual EV charging ports. This is the energy highway of the station.
EV DC/DC Converters	Bidirectional DC-to-DC power stages (often a non-isolated or isolated topology like a Dual Active Bridge) that connect each Electric Vehicle's battery to the common DC bus.
EV Batteries (Loads/Sources)	The batteries in the electric vehicles. They act as loads during charging (G2V) and as sources during discharging (V2G).

IV. MODES OF OPERATION

The system is designed to manage power flow in two principal ways:

A. Charging Mode (Grid-to-Vehicle or G2V)
This is the standard operation where the EV battery is charged from the power grid.
1. AC-to-DC Conversion: The Three-Phase Inverter operates as an Active Front-End (AFE) Rectifier. It takes three-phase AC power from the grid and converts it into a regulated, high-voltage DC power on the Common DC Bus. This stage typically performs Power Factor Correction (PFC) to ensure power quality.
2. DC Bus Power Delivery: The DC power is now available on the common DC bus.
3 DC-to-DC Conversion: The EV DC/DC Converter for a plugged-in vehicle operates in Buck (step-down) mode. It receives the high voltage from the DC bus and converts it into a specific lower DC voltage and current profile required by the EV's battery management system (BMS) for safe and fast charging.
4. Charging: DC power is delivered directly to the EV's battery.

B. Discharging Mode (Vehicle-to-Grid or V2G)
This is the advanced operation where the EV acts as a temporary power source to support the grid, often for a financial incentive or to balance grid fluctuations (like peak shaving).
1. DC-to-DC Conversion: The EV DC/DC Converter for the participating vehicle operates in Boost (step-up) mode. It takes the DC power from the EV battery and boosts its voltage to match the voltage of the Common DC Bus.
2. DC Bus Power Aggregation: The power from the EV battery is injected onto the common DC bus. If multiple cars are discharging, their power is aggregated here.
3. DC-to-AC Conversion: The central Three-Phase Inverter operates in Inverter mode. It takes the high-voltage DC power from the common bus (now supplied by the EVs) and converts it into grid-compatible three-phase AC power.
4. Power Injection: The AC power is synchronized with the grid and injected back into the utility network.

4.4.1 Modelling of ANFIS

In 1993, J.S. Roger Jang introduced the ANFIS, which is recognized as a fuzzy system and global estimator derived from the Takagi–Sugeno fuzzy model . This model functions as a Type 3 fuzzy inference system, where the rule outputs are formed by a linear mixture of input parameters and a constant term. The final result is calculated by averaging the weighted outputs of all the rules. ANFIS is a sophisticated integration of an artificial neural network and a fuzzy inference system, offering a powerful and integrated solution to complex engineering problems by leveraging the strengths of both models. Figure 4.3 presents a schematic diagram of the ANFIS architecture, demonstrating how the system effectively combines the learning capabilities of a neural network with the fuzzy logic system to model the output–input relationships of real-world systems.

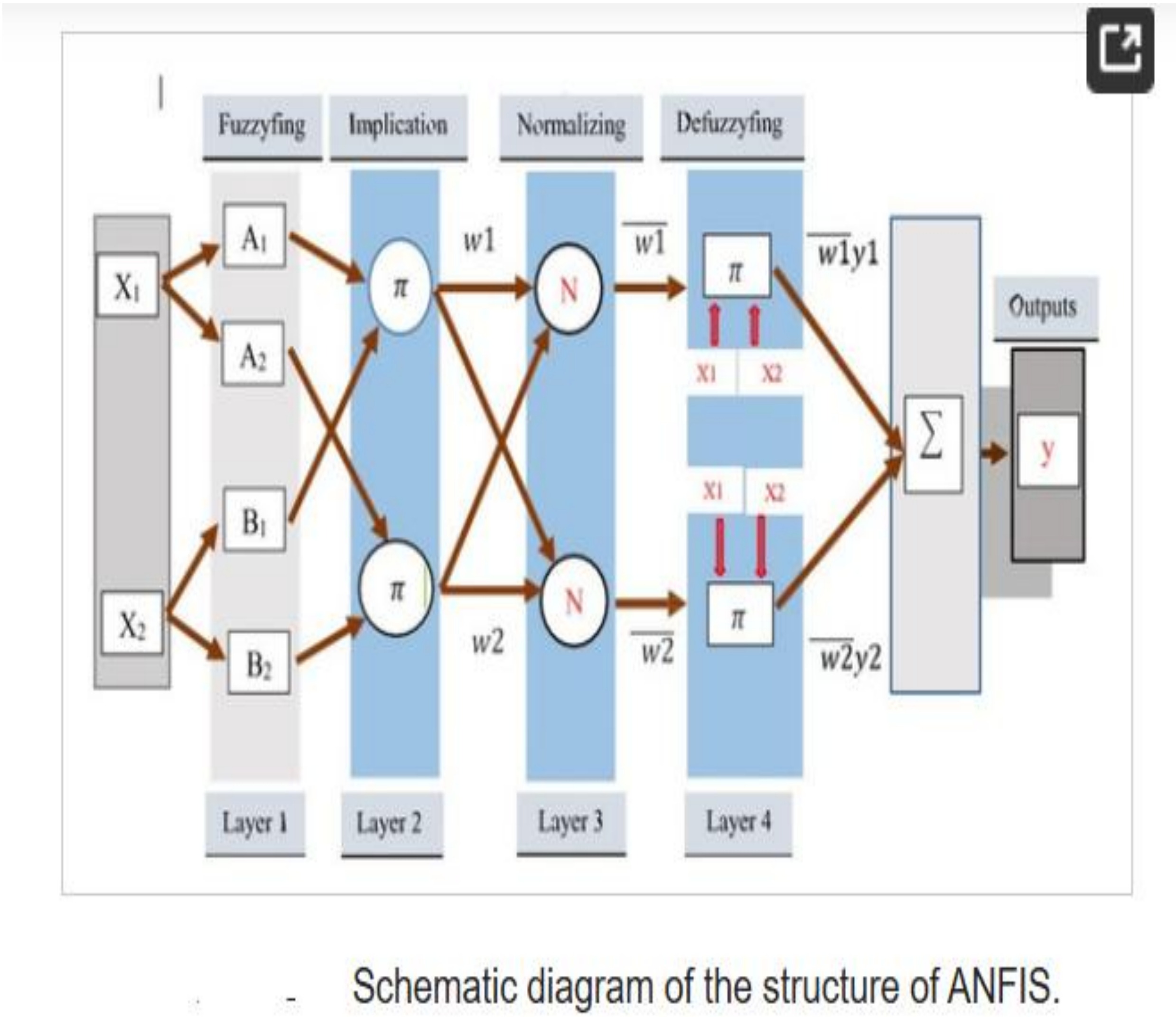

Figure 4.3 Schematic diagram of the structure of ANFIS

The fundamental ANFIS rule, that processes two inputs, X_1 and X_2, to generate a single output, y, is described as follows:

Rule 1: if X_1 is A_1 and X_2 is B_1, then the output is given by $y_1 = p_1X_1 + q_1X_2 + r_1$.

Rule 2: if X_1 is A_2 and X_2 is B_2, then the output is given by $y_2 = p_2 X_1 + q_2 X_2 + r_2$.

The parameters A_j and B_j correspond to each input fuzzy sets for the premise part, while the parameters p_j, q_j, and r_j are the linear variables in the consequent part. The ANFIS architecture for a single output–two input network consists of five distinct layers:

1.Fuzzification Layer: In this layer, each node j is considered an adaptive node, and the output is computed as

$$O_j^2 = \mu A_j(X_1), for \ \ j = 1, 2$$
$$O_j^2 = \ for \ \ j = 3, 4 \tag{4.12}$$

(1) Implication Layer: In this layer, the nodes are fixed and represented by π, meaning they function as simple multipliers. Each node's output introduces w_j, the rule firing strength, which is computed based on the incoming signals as

$$O_j^2 = W_j = \mu A_j(X_1)\,\mu B_j - 2(X_2), \quad for \ \ j = 1, 2 \tag{4.13}$$

2)Normalization Layer: In this layer, each node is a fixed node, labeled as N. The output signal w_j for the jth node is calculated by the division of the firing strength of the jth rule by the sum of all the rules' firing strengths:

$$O_j^3 = \overline{W_j} = \frac{W_j}{W_1 + W_2} \ for \ j = 1, 2 \tag{4.14}$$

(2) Defuzzification Layer: Each node j in this layer is adaptive, with the node function involving the parameters (p_j, q_j, r_j) and w_j. The firing strength is expressed as a normalized value, as follows:

$$O_j^4 = \overline{W_j} y_j = \overline{W_j}\left(p_j X + q_j X + r_j\right) for \ j = 1, 2 \tag{4.15}$$

(3) Combination Layer: The final layer consists of a single fixed node, labeled ∑, which sums all the input signals to compute the total final output as

$$O_j^5 = y = \sum_j (\overline{W_j} y_j) = \frac{\sum_j (W_j Y_j)}{\sum_j W_j} \tag{4.16}$$

4.4.2 Evaluation Parameter

ANFIS learning uses two algorithms to determine the membership function: the back propagation method and a hybrid algorithm that integrates the least squares method with gradient descent techniques. In particular, this study employs the gradient descent method to adjust nonlinear input parameters, while the least squares technique is used to fit nonlinear output parameters. This combined algorithm is recognized for its high efficiency . The root mean square error is calculated by squaring the gap between predicted and observed values, averaging this over the sample, and then taking the square root. Mathematically, this can be expressed as

$$R_{MSE} = \sqrt{\frac{1}{n}\sum_{k=1}^{n} [n(k) - \hat{n}(k)]^2} \tag{4.17}$$

Let n be the test vectors. Here, $\hat{n}(k)$ refers to the expected (measured) value, while $n(k)$ denotes the value generated. The RMSE follows a quadratic error rule, where the differences are first averaged and then squared. This approach assigns a relatively higher weight to larger errors .

4.5 Generating Fuzzy Inference System and Training of ANFIS

For V2V misalignment application, at first, the PI controller is developed to tune the system in the desired level. As the PI controller exhibits an oscillatory pattern in higher LTMs, the PI controller input (error in primary current) and output (phase angle of the inverter) are extracted from the simulation. The dataset is then used for training the ANFIS. In total, 80,000 data points are used to train the neural network. This is a SISO (single input–single output) network, In the wireless power transfer system for V2V charging, key feedback parameters such as received voltage, current, and power levels are monitored on the receiving side. These parameters serve as indicators of the system's performance, helping to identify any inefficiencies or misalignments that may occur during the power transfer process. Specifically, variations in these parameters can signal phase misalignment (dephasing) between the transmitting and receiving coils, which directly impacts the efficiency of the power transfer.

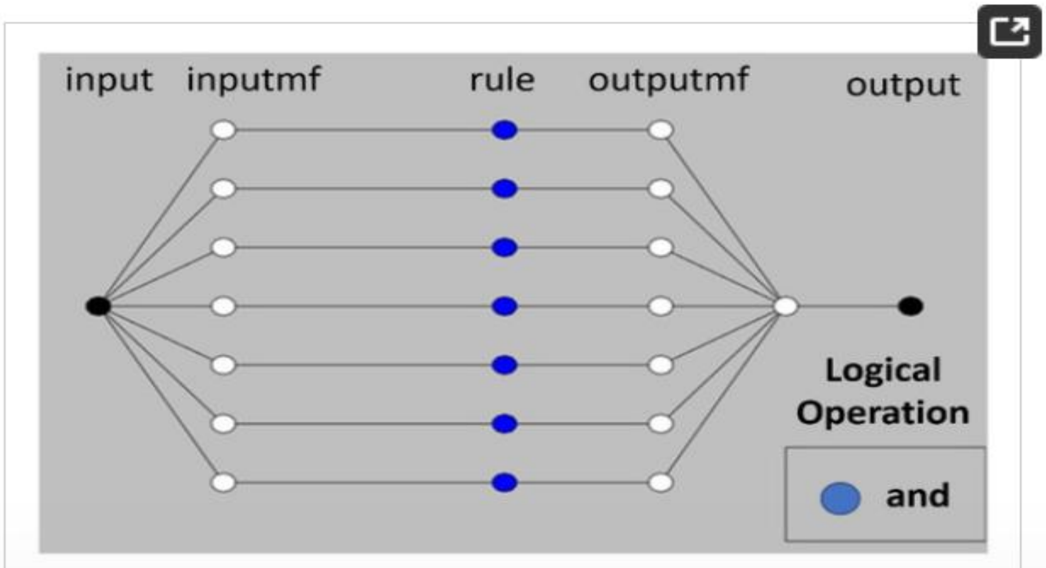

Figure 4.4 ANFIS Layout

The primary goal of the Adaptive Neuro-Fuzzy Inference System (ANFIS) algorithm is to utilize the feedback parameters to detect and resolve de phasing issues in real time. By continuously adjusting the phase and duty cycle of the PWM converter on the transmitting side, the algorithm ensures optimal alignment and efficient power transfer. The ANFIS algorithm dynamically compensates for misalignments and varying conditions, maintaining effective power transmission despite the challenges posed by the dynamic V2V charging environment.

Table 4.1 Comparison of various controllers

V. MODELING OF BI-DIRECTIONAL CHARGING SYSTEM

5.1 Introduction

The simulation diagram explains the detailed working principle of the Battery Energy Storage System (BESS) integrated with a grid-connected inverter and non-linear load. This system enables bidirectional power flow between the battery and the grid.

1. DC Power Generation (Battery Bank)

The system contains three batteries connected in parallel. The parallel configuration maintains a constant DC voltage while increasing total current capacity. The total available DC power serves as the input for the inverter. The battery bank acts as the energy storage component, which can discharge power to the grid or store energy during charging.

2. DC Link Capacitor (Cdc)

The DC link capacitor is connected across the battery output and inverter input. It functions as an energy buffer that stabilizes the DC voltage, filters out ripples, and ensures smooth operation during transient changes.

3. Inverter Operation (DC to AC Conversion)

A three-phase Voltage Source Inverter (VSI) converts DC power into AC using semiconductor switches controlled by Pulse Width Modulation (PWM). The inverter supports bidirectional operation—discharging power (V2G) and charging batteries (G2V). It generates three-phase AC voltage synchronized with the grid.

4. LC Filter

The inverter output contains switching harmonics due to PWM operation. An LC filter removes these high-frequency harmonics and ensures a pure sinusoidal AC waveform. It enhances power quality and reduces Total Harmonic Distortion (THD).

5. Grid and Non-linear Load

The filtered AC output connects to both the grid and a non-linear load. The non-linear load draws non-sinusoidal current, introducing harmonics, which the inverter compensates for. The system operates in two modes: (1) V2G – supplies power to grid/load, (2) G2V – charges batteries from the grid.

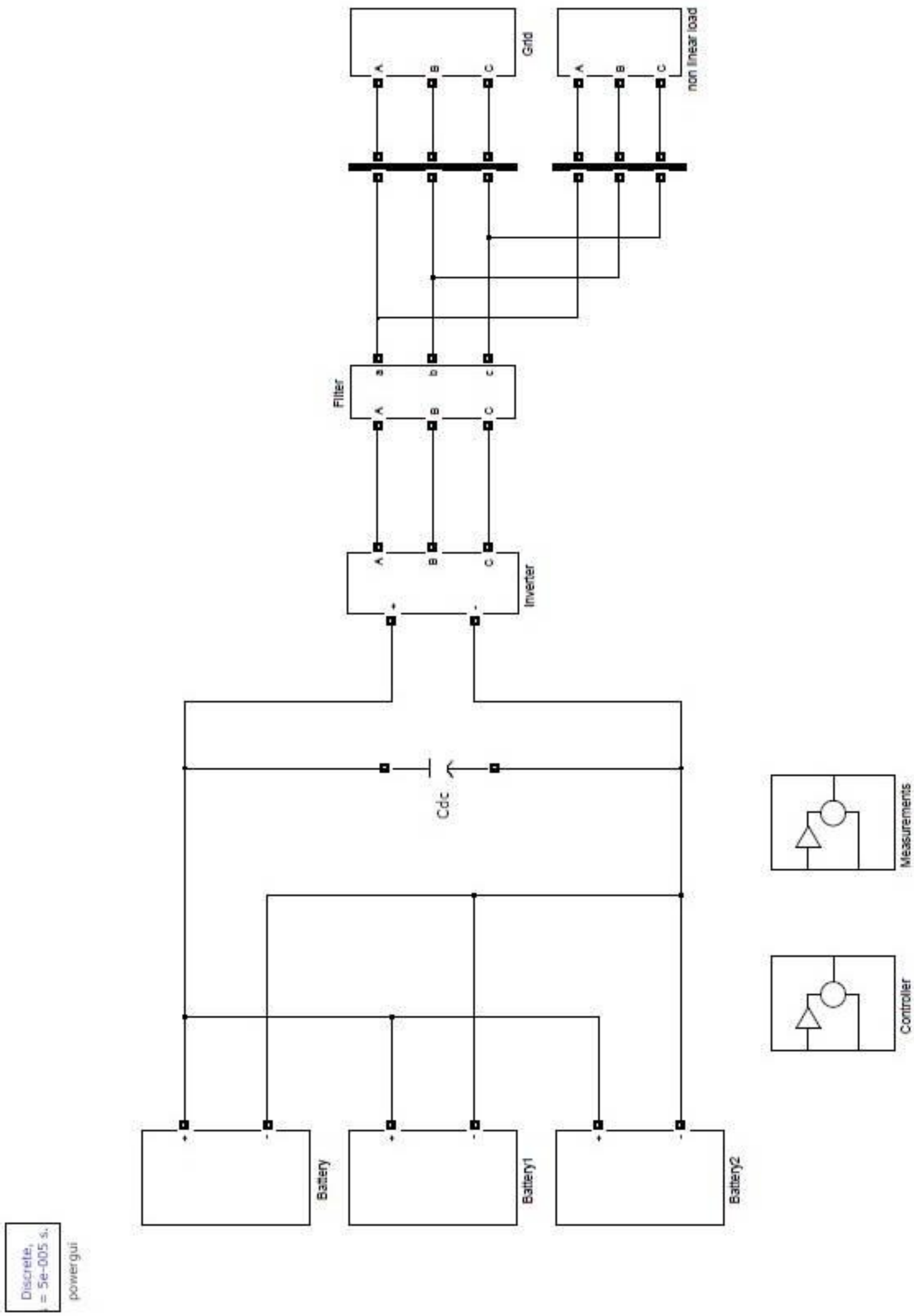

Figure 5.1 Simulation Diagram of Bi-directional charging system

5.2 Battery Charging Circuit.

- Battery/DC-DC Converter: Converts the battery's DC voltage to match the DC link voltage and controls power flow.
- Controller: Receives feedback of DC link voltage (Vdc) and battery current (Ibat). It generates gate signals (S1, S2) to regulate converter operation.
- Vdc_ref: The reference DC voltage set at 400 V.
- Sensors: Measure the instantaneous values of Vdc and Ibat for feedback control.

The controller continuously monitors Vdc and compares it with the reference Vdc_ref. Based on the deviation, it adjusts the duty ratio of switches (S1, S2) to regulate current flow (Ibat). This feedback control ensures stable DC link voltage and efficient battery management.

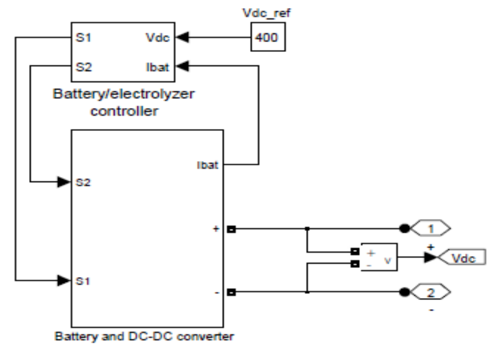

Figure 5.2 Battery Charging Circuit

Figure 5.3 represents Li-Ion Battery: Serves as the primary energy storage. The bi-directional nature allows the battery to be charged or discharged

Inductor (L3): Acts as the intermediate energy buffer. It stores energy in its magnetic field when a switch is ON and releases it to the load or battery when a switch is OFF. This action is essential for transforming the DC voltage level.

Switching Bridge (Q1, Q2, D1, D2): Consists of two power switches (likely MOSFETs) and their anti-parallel diodes. This half-bridge structure enables the two-way power flow. The switches are controlled by complementary PWM signals (S1 and S2)

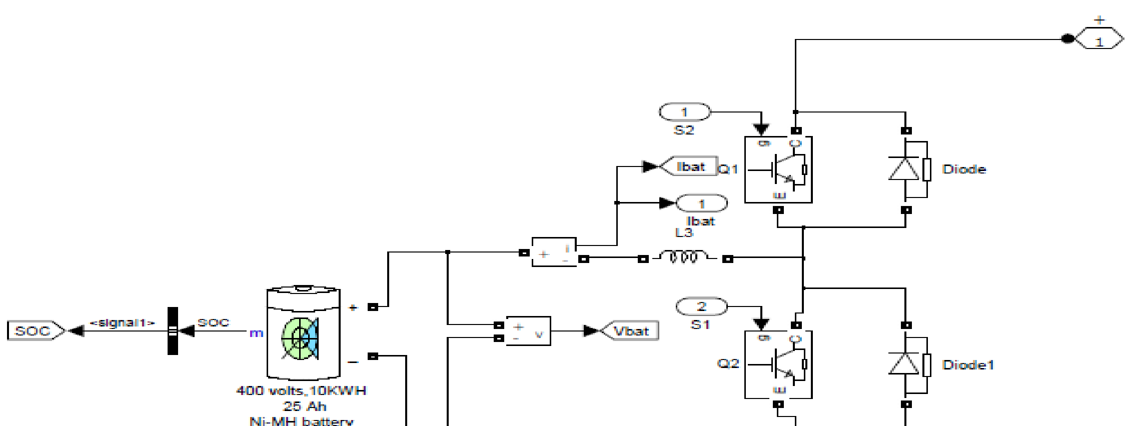

Figure 5.3 DC-DC Converter

Figure 5.4 Simulink model represents a two-input, single-output intelligent control or identification system based on the Adaptive Neuro-Fuzzy Inference System (ANFIS) architecture. The system uses two

key pieces of information to generate its output:
The instantaneous value of the input signal (u).
The instantaneous rate of change of the input signal (du/dt).
This is a common configuration in closed-loop control systems, analogous to the structure of a Proportional-Derivative (PD) controller, where the ANFIS block acts as a highly adaptive, non-linear controller.

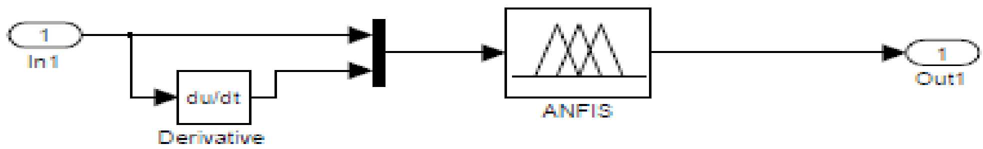

Figure 5,4 ANFIS Interface

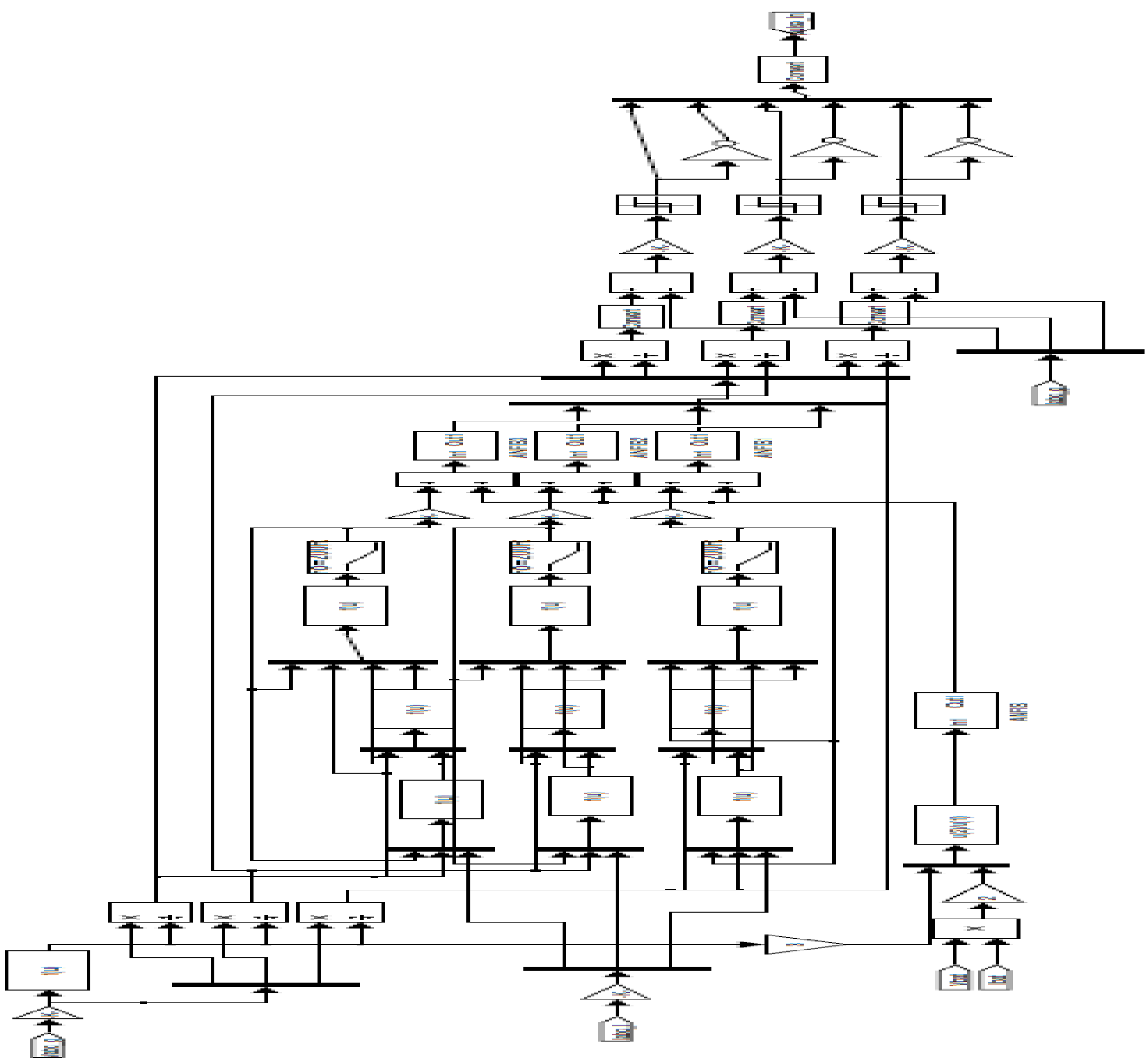

Figure 5.5 Proposed ANFIS Controller

VI. SIMULATION RESULTS

6.1 simulation Results

A configuration of the charging system, with grid, EV battery and non-linear loads is established from the MATLAB/ Simulink software. For investigating the behaviour of the developed model, the response of VSC and bidirectional converter-based charging system is analyzed for various dynamic conditions. The behaviour of the developed model is analyzed for the grid voltage as Vg, grid current as Ig, load current as iL, DC link voltage as Vdc, battery voltage Vb, battery current Ib. The simulated results are observed and recorded to validate the various operations.

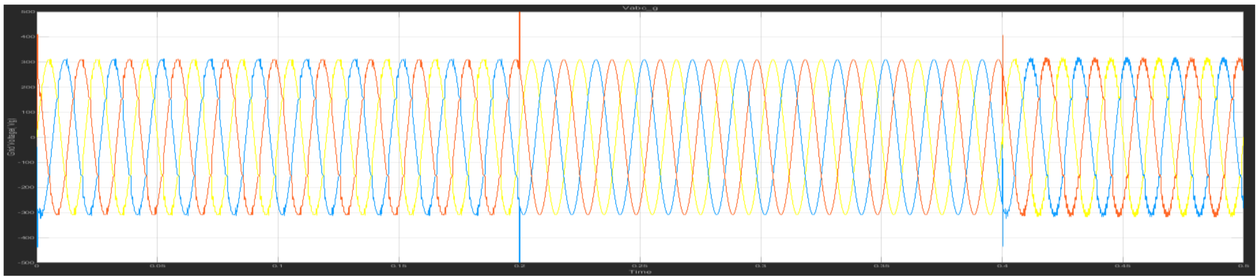

Figure 5.6 Dynamic performance of system Grid voltages(Vg)

Figure 5.6 waveform represents the input Grid voltage without applied the power transform from Grid to EV or EV to Grid. The input transistion time taken as t=0.5s, for further considering the SOC of battery it will changes its voltage from t=0.2s to t=0.4s.

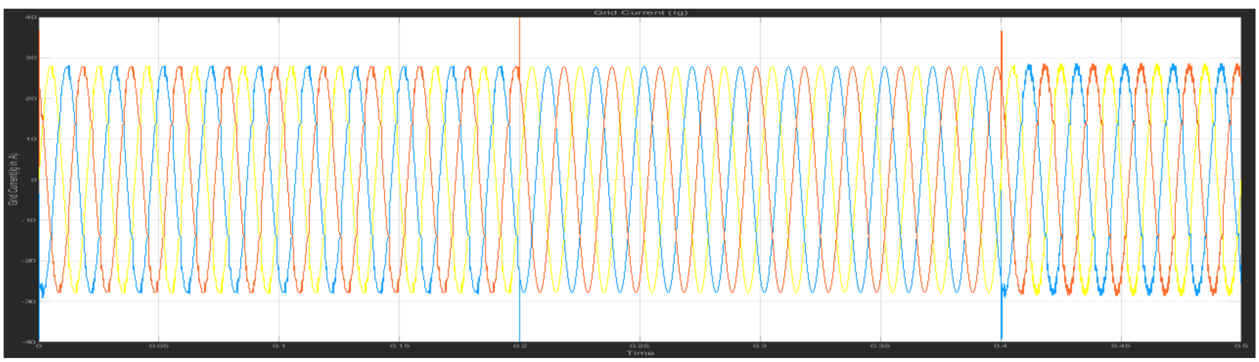

Figure 5.7 Dynamic performance of system Grid Currents(Ig)

Figure 5.7 waveform represents the input Grid current without applied the power transform from Grid to EV or EV to Grid. The input transistion time taken as t=0.5s, for further considering the SOC of battery it will changes its voltage from t=0.2s to t=0.4s. the input Grid current is zero when the charging system is on G2EV mode untile the SOC of battery is reaches to 60 percentage .

Figure 5.8 show the dynamic operating mode transition of the charging system from G2EV and EV2G and vice-versa. The behaviour is analyzed based on the grid voltage (vg), Load voltage (Vl). From the transition t=0 to t=0.2s the system is in G2EV mode of operation . in this state the grid voltage (Vg) is same as the input voltage. But the Inverter voltage is shows small negative value. And the battery is continuously charging. When the SOC of Battery is below 60 percentage the charging system is converted in to EV2G mode at a transition time of t=0.2s to t=0.4s. The transition of the charging system from G2EV to EV2G after 0.05 s. Moreover, after 0.05 s, the ig and vg both are in the opposite phase as the battery supporting the grid by supplying power to the grid. However, after 1 s, the transition of the system from EV2G to G2EV is presented in Figure. 5.8.

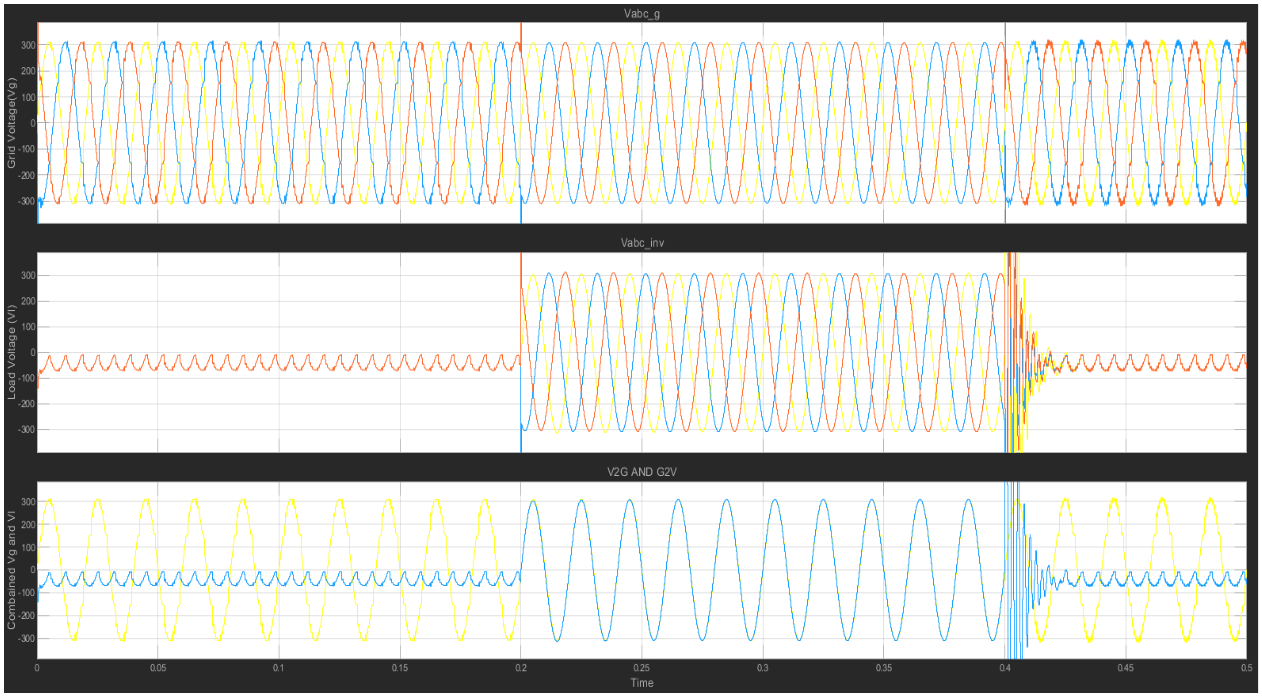

Figure 5.8 Load voltage during G2V and V2G

Moreover, in the G2EV mode, the battery current is negative, which means the battery is charged and (battery and load) are drawing power from the grid as vg and ig both are in the same phase. In these transitions, DC link voltage, and load current are constant. The battery current is positive/negative while the battery is discharged/charged. the switching of EV2G to G2EV is presented. The vehicle battery is initially in the charging position and suddenly it is switched to the discharging mode to reduce the burden on the grid.

Moreover, Figure. 5.9 presents the grid power, load power, battery power and SOC of the battery under EV2G to G2EV and G2EV to EV2G transition modes at 0.2 and 0.4 s. While the battery discharges (positive battery current), the grid power is negative, which ensures that the power is fed to the grid. The charging system is under the EV2G mode of operation. Moreover, when the battery is charging, the grid power is positive and the battery power is negative. It illustrates that the battery is charged via the grid, and depicts the G2V performance of the system. Moreover, accordingly, the battery SOC is also perturbed.

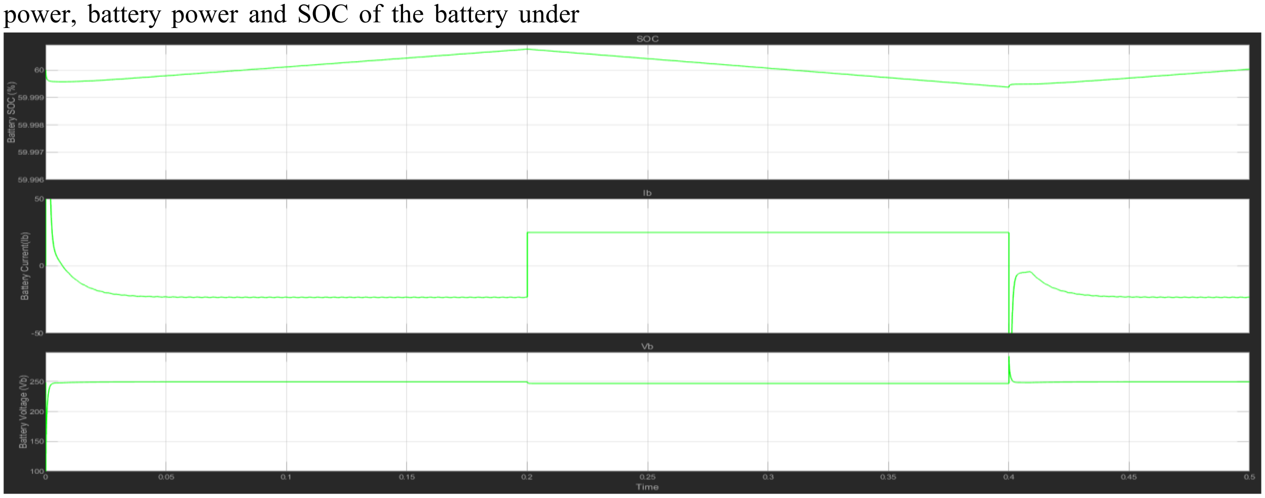

Figure 5.9 Battery SOC , Ibat and Vbat

In discharging period t=0.2s to t=0.4s the grid voltage syncronzies with the inverter voltage means both waveforms are in phase. The amplitude of the inverterd wave form magnitude also equal to grid voltage which is better perfomanace to the the load without overloaded. In charging mode of battery the sign of battery is negitive where as in discharging mode it is thaken as positive sign. But the DC link voltage is mainatained constant irrespective of state of charge of battery. This can be achived by the useage of DC-DC converter as operated as BUCK and BOOST operation mode dependes upon the percentage of SOC.

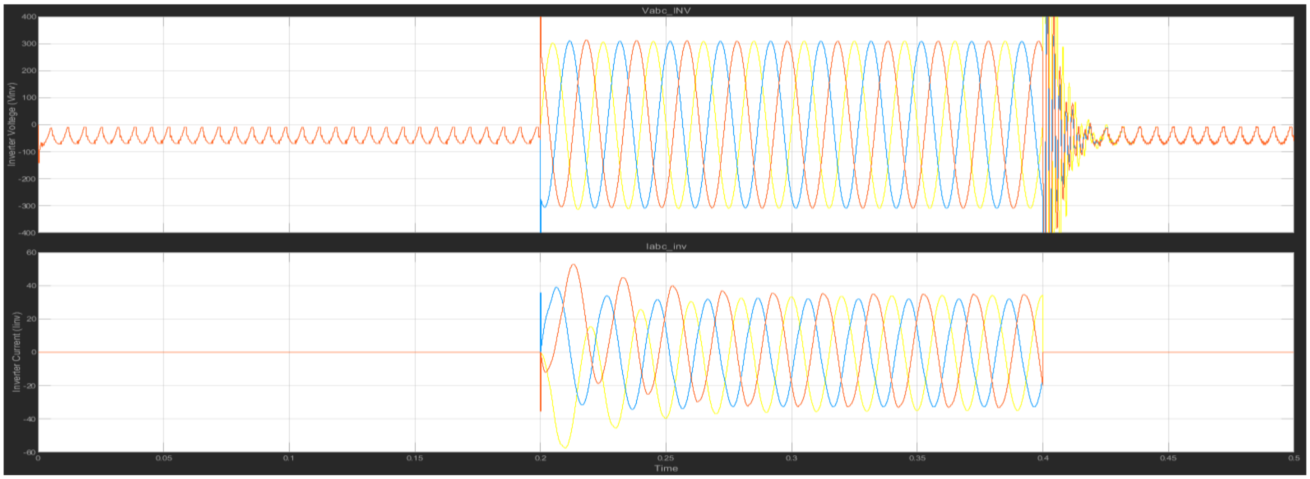

Figure 5.10 Inverter Voltage and current during G2EV and EV2G

Figure 5.10 illustrates the Voltage and current during G2EV and EV2G.The three phase voltage sourse inverter is On state when the charging system is in EV2G mode operation which is indicated on the waveforms of transistion time of t=0.2s to t=0.4s.
Further system is desigend that Inverter Voltage magnitude is as the grid voltage but the inverter current changes depending upon the type and maginitude of the load. However, a small DC voltage is generated in Inverter voltage which is considered as ripples further it will reduced based on the design of filters. Here the transition time t=0 to t=0.2s as taken as G2EV mode in this period the is no generation of inverter voltage next period t=0.2s to t=0.4s as EV2G mode , in this state the SOC of battery will discharges and DC-DC converter acts as Buck mode of operation.

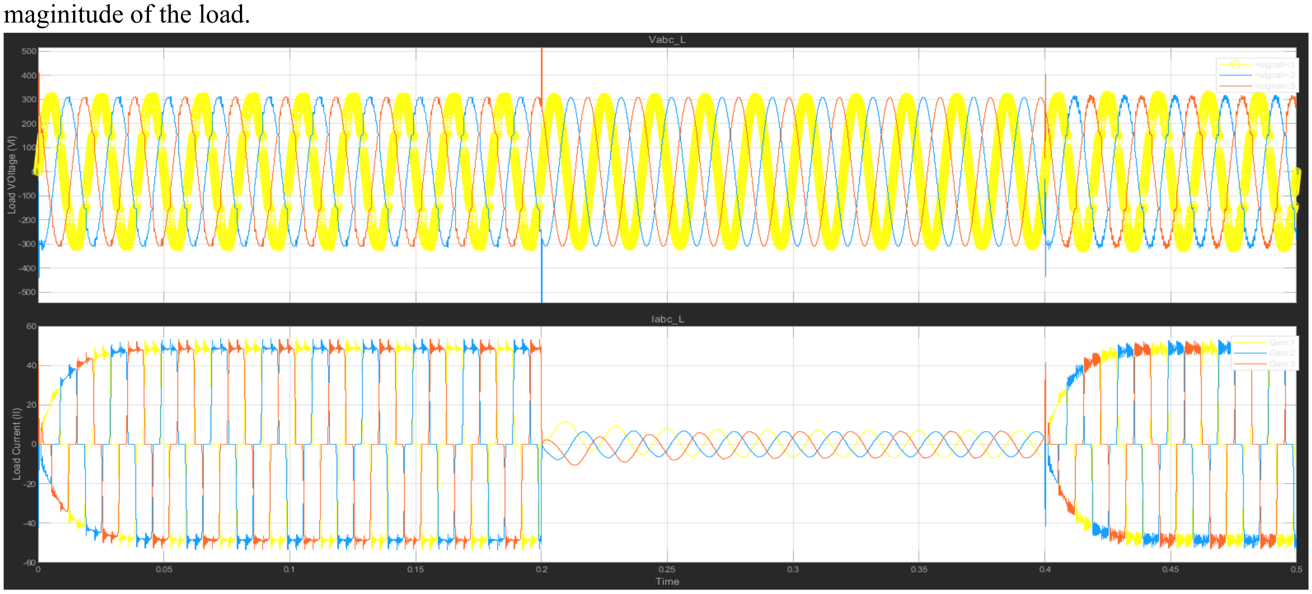

Figure 5.11 Dynamic performance of Load Voltage Vs Load Current (V_L Vs I_L)

Figure 5.11 illustrates the Load Voltage and current during G2EV and EV2G. the three phase voltage sourse inverter is On state when the charging system is in EV2G mode operation which is indicated on the waveforms of transistion time of t=0.2s to t=0.4s.

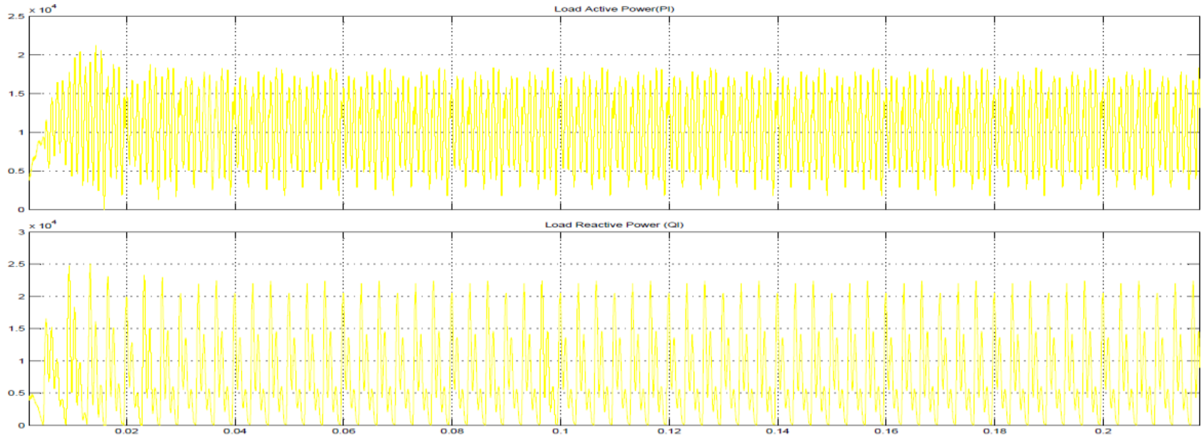

Figure 5.12 Load Active and reactive power.

Figure 5.12 illustrates the operation active and reactive powers of the non-liner load connected to grid and EV battery. This charging system which feeds the power from grid to load or EV to load depending on the SOC of the charging system. The entire system enable to transfer the power to load and multifunctional possible. To reduce the ac harmonic content filters are added which will improve the load current THD value.

Figure 5.13 illustrates the operation of the charging system under the sudden load disconnection and reconnection. It is observed that the grid voltage and grid current are out of phase and the battery current is positive, which ensures that the battery is giving energy to the grid. The sudden load disconnection is realized at 0.2 s and reconnection at 0.3 s. The VSC currents are non-sinusoidal and unbalanced to compensate for the load current. Therefore, the grid parameters are balanced and sinusoidal under the load transient . The behaviour of the internal parameters of the ANFIS controller, such as mean square error, fundamental load component, are also shown. The mean square error and fundamental active weight signal are reached as the load of a particular phase is removed.

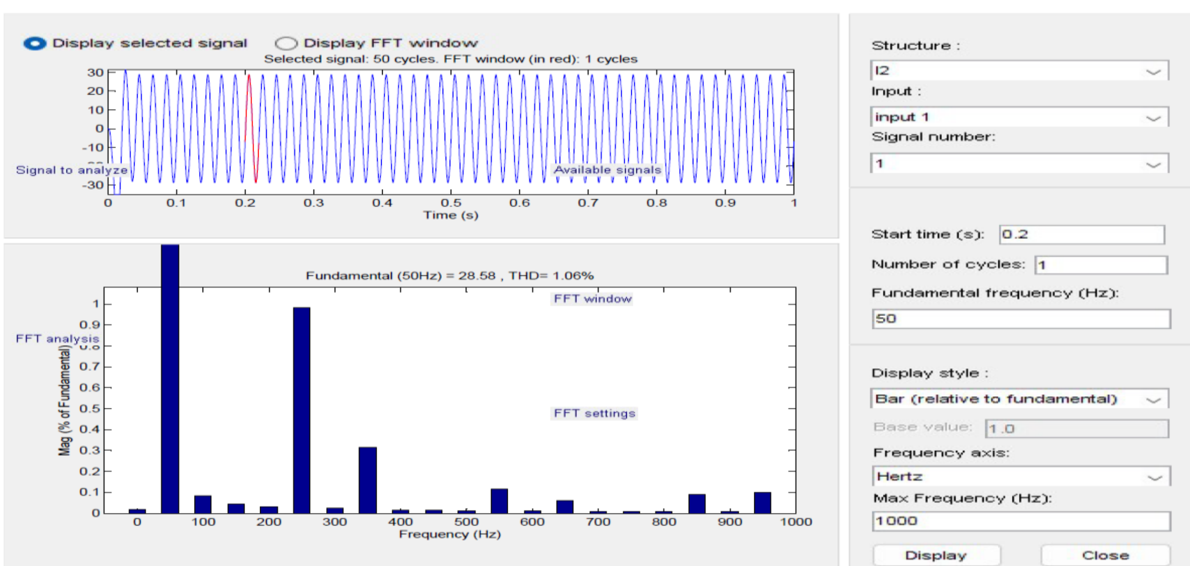

Figure 5.13 THD analysis of load current of the charging system

Figure 5.14 shows the total harmonics distortion (THD) analysis of the grid and load current of the charging system. The THD and ripples are maintained as per the prescribed IEEE standard. The source current THD is found to be 1.06%, which is less than 5% .

Comparative Analysis for THD Values of Proposed Control with Existing Control.

System Particulars	Controller	THD (%)
Bi- Directional Charging system with non-linear load	Existing Controller: sparse constrained proportionate normalized least mean fourth (SCP-NLMF)	3.73
	Proposed Controller: Adaptive Neuro Fuzzy inference System (ANFIS)	1.06

VII. CONCLUSIONS

7.1 Conclusions

The literature highlights the importance of integrating advanced control strategies, renewable energy sources, and bidirectional power flow to develop efficient and intelligent EV charging systems. The proposed ANFIS-based controller combines the advantages of fuzzy logic and neural network learning to adaptively tune control parameters in real time. This intelligent control structure provides faster convergence, enhanced stability, and superior harmonic suppression. Simulation and analytical results demonstrate a significant improvement in power quality, achieving a THD reduction to 1.06% where as Existing of SCP-NLMF controller is exhibited a THD of 3.73%.

7.2 Future Scope

Future research should focus on optimizing economic viability, addressing interoperability challenges, and incorporating AI-driven predictive control to further enhance EV charging infrastructure. Despite significant advancements, challenges remain in implementing scalable and cost-effective EV charging solutions. Communication protocols, interoperability issues, and cyber security concerns are major areas of ongoing research. Additionally, the development of next-generation energy management systems that leverage artificial intelligence (AI) and machine learning (ML) for predictive analytics is a promising future direction.

- Integration with Renewable Energy Sources
- Hardware Optimization and Real-time Implementation
- Scalability to Smart Grid and Micro grid Environments
- Enhanced Power Quality and Energy Management
- Battery Health and Lifecycle Management
- Vehicle-to-Everything (V2X) Capabilities
- AI-based Predictive Control

REFERENCES

[1] X. S.Zhou, L. Zou, Y. J. Ma, Z. Q. Gao, Y. J. Wu, J. L. Yin, and X. N. Xu, “The current research on electric vehicle,” in Proceedings of 2016 Chinese Control and Decision Conference (CCDC), 2016, pp. 5190–5194.

[2] Y. M. Zhang, P. C. You, and L. Cai, “Optimal charging scheduling by pricing for EV charging station with dual charging modes,” IEEE Transactions on Intelligent Transportation Systems, vol. 20, no. 9, pp. 3386–3396, Sep. 2019.

[3] B. L. Zhang, Y. T. Sun, B. Q. Li, and J. X. Li, “A modeling method for the power demand of electric vehicles based on monte carlo simulation,” in Proceedings of 2012 Asia-Pacific Power and Energy Engineering Conference, 2012, pp. 1–5.

[4] S. D. Feng and C. L. Magee, “Technological development of key domains in electric vehicles: Improvement rates, technology trajectories and key assignees,” Applied Energy, vol. 260, pp. 114264, Feb. 2020.

[5] J. H. Teng, S. H. Liao, and C. K. Wen, “Design of a fully decentralized controlled electric vehicle charger for mitigating charging impact on power grids,” IEEE Transactions on Industry Applications, vol. 53, no. 2, pp. 1497–1505, Mar./Apr. 2017.

[6] IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems - Redline, IEEE Standard 519–2014, 2014.
[7] K. Dartawan and A. M. Najafabadi, "Case study: Applying IEEE Std. 519–2014 for harmonic distortion analysis of a 180 MW solar farm," in Proceedings of 2017 IEEE Power & Energy Society General Meeting, 2017, pp. 1–5.
[8] A. J. Moradewicz, "On/Off - board chargers for electric vehicles," Przegla d Elektrotechniczny, vol. 1, no. 2, pp. 138–141. Feb. 2019.
[9] A. Verma, B. Singh, A. Chandra, and K. Al-Haddad, "An implementation of solar PV array based multifunctional EV charger," IEEE Transactions on Industry Applications, vol. 56, no. 4, pp. 4166–4178, Jul./Aug. 2020.
[10] S. Kim and F. S. Kang, "Multifunctional onboard battery charger for plug-in electric vehicles," IEEE Transactions on Industrial Electronics, vol. 62, no. 6, pp. 3460–3472, Jun. 2015.
[11] S. D. Wang, H. R. Li, Z. L. Zhang, M. R. Li, J. F. Zhang, X. Y. Ren, and Q. H. Chen, "Multifunction capability of SiC bidirectional portable chargers for electric vehicles," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 9, no. 5, pp. 6184–6195, Oct. 2021.
[12] Y. C. Hsu, S. C. Kao, C. Y. Ho, P. H. Jhou, M. Z. Lu, and C. M. Liaw, "On an electric scooter with G2V/V2H/V2G and energy harvesting functions," IEEE Transactions on Power Electronics, vol. 33, no. 8, pp. 6910–6925, Aug. 2018.
[13] H. Kikusato, K. Mori, S. Yoshizawa, Y. Fujimoto, H. Asano, Y. Hayashi, A. Kawashima, S. Inagaki, and T. Suzuki, "Electric vehicle charge– discharge management for utilization of photovoltaic by coordination between home and grid energy management systems," IEEE Transactions on Smart Grid, vol. 10, no. 3, pp. 3186–3197, May 2019.
[14] M. Yilmaz and P. T. Krein, "Review of battery charger topologies, charging power levels, and infrastructure for plug-in electric and hybrid vehicles," IEEE Transactions on Power Electronics, vol. 28, no. 5, pp. 2151–2169, May 2013.
[15] H. Liu, Z. C. Hu, Y. H. Song, and J. Lin, "Decentralized vehicle-to-grid control for primary frequency regulation considering charging demands," IEEE Transactions on Power Systems, vol. 28, no. 3, pp. 3480–3489, Aug. 2013.
[16] V. Monteiro, B. Exposto, J. C. Ferreira, and J. L. Afonso, "Improved vehicle-to-home (iV2H) operation mode: Experimental analysis of the electric vehicle as off-line UPS," IEEE Transactions on Smart Grid, vol. 8, no. 6, pp. 2702–2711, Nov. 2017.
[17] S. Taghizadeh, M. J. Hossain, N. Poursafar, J. W. Lu, and G. Konstantinou, "A multifunctional single-phase EV on-board charger with a new V2V charging assistance capability," IEEE Access, vol. 8, pp. 116812– 116823, Jun. 2020.
[18] J. W. Shim, G. Verbiˇc, and K. Hur, "Multi-functional EV charging methodology maximizing capability for coordinated grid frequency control," in Proceedings of the 9th International Conference on Power and Energy Systems (ICPES), 2019, pp. 1–6.
[19] G. Buja, M. Bertoluzzo, and C. Fontana, "Reactive power compensation capabilities of V2G-enabled electric vehicles," IEEE Transactions on Power Electronics, vol. 32, no. 12, pp. 9447–9459, Dec. 2017.
[20] Y. H. Shan, J. F. Hu, K. W. Chan, Q. Fu, and J. M. Guerrero, "Model predictive control of bidirectional DC–DC converters and AC/DC interlinking converters—A new control method for PV-wind-battery microgrids," IEEE Transactions on Sustainable Energy, vol. 10, no. 4, pp. 1823–1833, Oct. 2019.
[21] A. T. Al-Awami, E. Sortomme, G. M. A. Akhtar, and S. Faddel, "A voltage-based controller for an electric-vehicle charger," IEEE Transactions on Vehicular Technology, vol. 65, no. 6, pp. 4185–4196, Jun. 2016.
[22] A. Zahedmanesh, K. M. Muttaqi, and D. Sutanto, "Coordinated charging control of electric vehicles while improving power quality in power grids using a hierarchical decision-making approach," IEEE Transactions on Vehicular Technology, vol. 69, no. 11, pp. 12585–12596, Nov. 2020.
[23] S. Kumar and B. Singh, "Self-normalized-estimator-based control for power management in residential grid synchronized PV-BES microgrid," IEEE Transactions on Industrial Informatics, vol. 15, no. 8, pp. 4764– 4774, Aug. 2019.

[24] S. Kumar, B. Singh, U. Kalla, S. Singh, and A. Mittal, "Power quality control of small hydro-PV array and battery storage based microgrid for rural areas," in Proceedings of 2021 International Conference on Sustainable Energy and Future Electric Transportation (SEFET), 2021, pp. 1–6.
[25] M. A. Khan, I. Husain, and Y. Sozer, "Integrated electric motor drive and power electronics for bidirectional power flow between the electric vehicle and DC or AC grid," IEEE Transactions on Power Electronics, vol. 28, no. 12, pp. 5774–5783, Dec. 2013.
[26] A. K. Singh, S. Kumar, and B. Singh, "Solar PV energy generation system interfaced to three phase grid with improved power quality," IEEE Transactions on Industrial Electronics, vol. 67, no. 5, pp. 3798– 3808, May 2020.
[27] A. Hoke, A. Brissette, K. Smith, A. Pratt, and D. Maksimovic, "Accounting for lithium-ion battery degradation in electric vehicle charging optimization," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 2, no. 3, pp. 691–700, Sep. 2014.
[28] S. Pranith, S. Kumar, B. Singh, and T. S. Bhatti, "Finite state machine control and power quality enhancement using Goertzel filter for multifunctional battery energy storage system," IET Generation, Transmission & Distribution, vol. 13, no. 11, pp. 2145–2153, Jun. 2019.
[29] Y. Y. Wang, Y. S. Li, J. C. M. Bermudez, and X. Han, "An adaptive combination constrained proportionate normalized maximum correntropy criterion algorithm for sparse channel estimations," EURASIP Journal on Advances in Signal Processing, vol. 2018, no. 1, pp. 58, Sep. 2018.
[30] G. Gui and F. Adachi, "Adaptive sparse system identification using normalized least mean fourth algorithm," International Journal of Communication Systems, vol. 28, no. 1, pp. 38–48, Jan. 2015.