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Sustainable Electric Vehicle Fast Charging System with Integrated Solar PV, Battery Energy Storage for Renewable Energy Utilization and Grid Support

Dr.J.Srinu Naick, M. Sailaja, A. Suneel Kumar, B. Ashok Kumar Naik, N. Mounika, R. Hema Gangadhar

Department of Electrical and Electronics Engineering, Chadalawada Ramanamma Engineering College, Andhra Pradesh, India.

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Battery, centralized control, DC charging station, solar PV,P&O MPPT, electric vehicle, real-time simulator, state-of-charge, vehicle-to-grid.

ABSTRACT

The proposed study presents an integrated approach for the development of an electric vehicle (EV) charging station system that includes solar photovoltaic (PV) power generation and both grid and Battery Energy Storage Systems (BESS) connections. Solar power will be the primary source of power used for EV charging, with grid power acting as a supplemental source to charge the vehicles when there is less than adequate solar power available. The proposed system will also include a BESS to provide backup power to allow uninterrupted EV charging during periods when solar power is insufficient or during grid failures. The proposed system will have four different operational modes: (i) Grid to EV (G2V) - this mode allows the grid to directly supply power for EV charging; (ii) EV to Grid (V2G) - this mode allows excess energy generated by the EV batteries to be returned to the grid; (iii) BESS to Grid - this mode allows the energy stored in the BESS to assist in stabilizing the grid; and (iv) Renewable Energy to Grid - this mode allows any surplus solar power to be supplied directly into the grid. The use of these modes enhances energy flexibility and reliability, and provides additional stability to the grid. In addition, it optimizes the utilization of renewable energy sources. The fuzzy logic controller will manage the flow of power between the grid, the EV's, the solar PV, and the BESS to ensure efficient energy distribution and high quality power. The simulation results of the study demonstrate the ability of the proposed system to function effectively in maintaining stable operations under changing conditions of energy availability and, therefore, contributes to smart grid applications and renewable energy integration.

1. INTRODUCTION

The push towards the world-wide switch to electric vehicles (EVs) is gaining momentum as governments and other stakeholders continue their efforts to make sustainable transportation a reality and to mitigate greenhouse gases (GHGs) produced by fossil fuel use. As governments and other organizations seek to implement policies and programs to increase EV adoption, the need to take action against climate change and to reduce reliance on fossil fuels continues to grow [1]. With expectations that there will be over 350 million EVs on the road by 2030, according to the International Energy Agency (IEA), there will likely be an enormous amount of money invested in the development of EV charging infrastructure to meet the demands of the growing number of EVs [2]. However, the addition of EVs to power grids creates many problems including increased peak power demand, voltage instability, harmonic distortion and grid congestion during high demand time frames [3]. The high power demanded by EV chargers, especially when they are charged at a high rate, can cause strain to be put on the distribution network which could result in changes to the voltage profile and negatively affect the overall stability of the power grid [4]. One potential solution to these problems is the use of renewable energy resources (RES) - specifically solar photovoltaic (PV) systems - in conjunction with EV charging infrastructure. Solar powered EV charging stations allow for less dependency on traditional power grid, lower operating costs and enhanced environmental sustainability [5]. However, because solar generated electricity is intermittent, it is necessary to include energy storage systems (such as batteries or super-capacitors) to provide uninterrupted and steady state operation of EV charging, regardless of the level of solar radiation [6]. One of the major concerns regarding EV charging infrastructure connected to the grid is related to the effects of EV charging on power quality and grid stability. Increased load demand during peak hours, due to the increased penetration of EVs, results in voltage sags, power fluctuations, and increases in total harmonic distortion (THD) in grid-connected systems [7]. Furthermore, the lack of coordination between the charging of multiple EVs connected to the same grid can result in uneven loading of the grid and lead to issues of grid congestion and transformer overloading [8]. To mitigate these problems, advanced power management strategies, such as demand side management (DSM), real-time load balancing, and vehicle-to-grid (V2G) technology, are currently being researched [9]. In V2G systems, EV batteries can act as both consumers and producers of electrical energy to the grid; when the grid is experiencing high demand for electrical energy, the EV batteries can supply energy to the grid, which can help to stabilize the grid and increase the flexibility of the grid [10]. Smart controllers, such as fuzzy logic based and artificial intelligence (AI) based controllers, also play a key role in optimizing EV charging processes, minimizing power losses, and maximizing overall system efficiency [11]. Technologically, there are several types of power electronic converters used in EV charging stations to manage power flow and maximize efficiency. For example, boost converters using maximum power point tracking (MPPT) techniques are commonly used in solar integrated EV charging systems to optimize power extraction from PV panels under variable irradiance conditions [12]. For grid-side control, bidirectional AC-DC converters, such as three-level voltage source converters, can efficiently correct the power factor, and therefore minimize harmonic distortion in grid connected charging configurations [13]. Furthermore, the use of multi-port converters to integrate PV, battery storage, and grid power provides additional flexibility to utilize available power sources optimally [14]. Recently, the use of wireless power transfer (WPT) technology to charge EVs has become popular due to its convenience and ability to eliminate physical connections to the EV, thereby providing a better user experience and improved system reliability [15]. Improved compensation networks are being developed for high frequency resonant converters to minimize power loss and enable efficient wireless charging [16]. Intelligent control algorithms are another important component of EV integration to provide smooth and reliable power flow, while maintaining grid stability. PI controllers are commonly used in power converters to provide robust voltage and current regulation. However, they may not be able to handle dynamic variations in power demand and renewable energy [17]. Fuzzy logic controllers (FLCs) have been used to develop adaptive and intelligent control methods to improve the performance of EV charging systems under different grid conditions [18]. FLCs can adjust the charging process in real-time, which can shorten system response times and minimize voltage deviations due to changing loads [19]. In addition, solar PV-based EV charging systems that integrate battery storage systems provide added resiliency and reduced dependency on the traditional power grid, thus ensuring continued availability of power to EV users [20]. Overall, the rapid expansion of EVs requires new, innovative solutions to provide reliable and efficient charging services, as well as to ensure the long-term sustainability of the power grid. Integration of solar PV, energy storage systems, advanced power electronic converters, and intelligent controllers provides a viable pathway to address the challenges posed by large scale EV deployment. Future research should focus on developing optimized energy management strategies, expanding grid-friendly charging technologies, and increasing the efficiency of renewable-energy-based charging systems to create a more sustainable and resilient transportation ecosystem.

2. SYSTEM CONFIGURATION

The proposed system has a photovoltaic (PV) array that will be the primary source of renewable energy; a battery energy storage system (BESS); power electronic converters; and a grid interface that will enable the EV to be charged at fast rates with minimal impact on grid stability as illustrated in Figure 1. The battery energy storage system will provide continuous power when there is low solar generation from the PV array. The maximum power point tracking (mppt) capability of the boost converter maximizes the power generated by the solar PV array and the bidirectional dc-dc converter enables the efficient transfer of energy from the battery to the fast charger or vice versa. The bi-directional ac-dc voltage source converter (vsc) will allow for enhanced power quality and power factor correction (pfc) to reduce total harmonic distortion (thd) to integrate with the grid. The fast charger in this system will support high power ev charging and will have very little effect on grid stability. A fuzzy logic based control strategy is used for real time power management for optimal energy distribution, voltage regulation, and overall efficiency of the system.

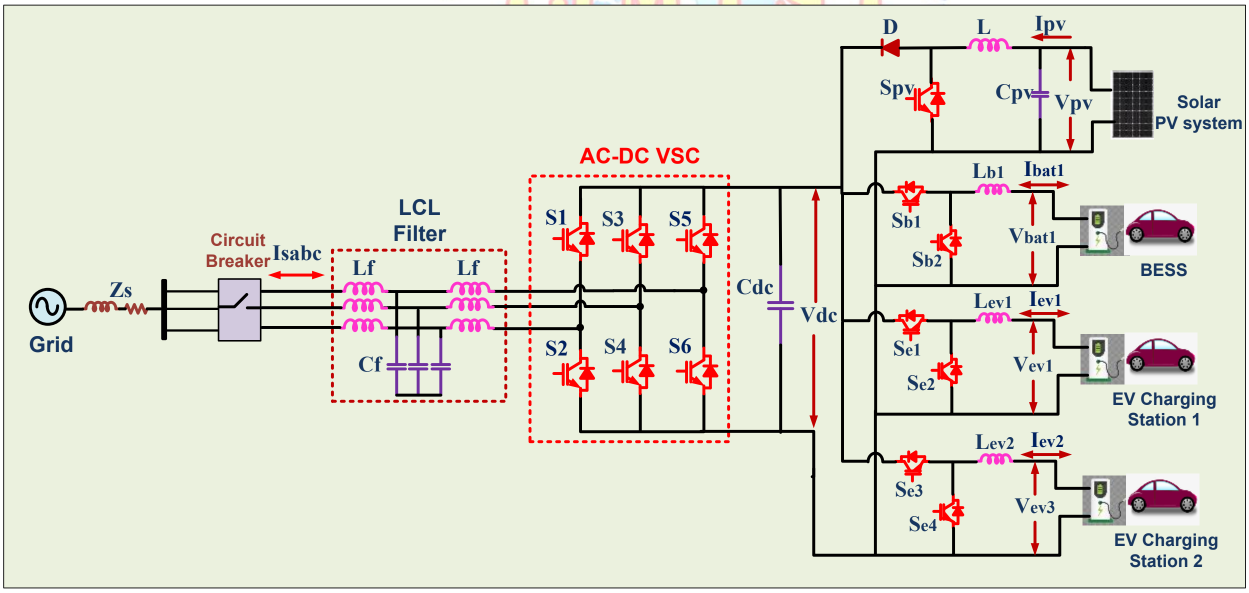


Fig. 1. V2G-enabled DC charging station model

3. MODELING AND DESIGNING OF PROPOSED SYSTEM CONFIGURATION.

A. Solar PV system

A system designed for solar powered Electric Vehicle (EV) rapid charging will include an electrical energy generation unit, a DC-DC boost converter and Maximum Power Point Tracking (MPPT), a DC-DC bidirectional converter, and an energy management system (EMS) that manages energy transfer from an electrical energy storage device (battery bank) to the EV charging station and vice versa. The electrical energy generation unit (photovoltaic array) provides the primary source of renewable energy, while the DC-DC boost converter boosts the PV array output to ensure maximum energy extraction using a P&O MPPT algorithm. The DC-DC bidirectional converter allows for energy to be transferred in both directions between the energy storage device and the EV charging station, to maximize the use of stored energy, and provide grid support when required. A Fuzzy Logic EMS is used to manage the flow of energy in the system by controlling the amount of energy drawn from the energy storage device and sent to the EV charging station; and to maintain a stable voltage within the system under varying loads and other dynamic conditions. The described system allows for the reliable and environmentally friendly rapid charging of EV's and minimizes the dependence on the existing grid and associated potential power quality issues.

a. Solar PV boost converter system configuration

A system designed for solar powered Electric Vehicle (EV) rapid charging will include an electrical energy generation unit, a DC-DC boost converter and Maximum Power Point Tracking (MPPT), a DC-DC bidirectional converter, and an energy management system (EMS) that manages energy transfer from an electrical energy storage device (battery bank) to the EV charging station and vice versa. The electrical energy generation unit (photovoltaic array) provides the primary source of renewable energy, while the DC-DC boost converter boosts the PV array output to ensure maximum energy extraction using a P&O MPPT algorithm. The DC-DC bidirectional converter allows for energy to be transferred in both directions between the energy storage device and the EV charging station, to maximize the use of stored energy, and provide grid support when required. A Fuzzy Logic EMS is used to manage the flow of energy in the system by controlling the amount of energy drawn from the energy storage device and sent to the EV charging station; and to maintain a stable voltage within the system under varying loads and other dynamic conditions. The described system allows for the reliable and environmentally friendly rapid charging of EV's and minimizes the dependence on the existing grid and associated potential power quality issues.

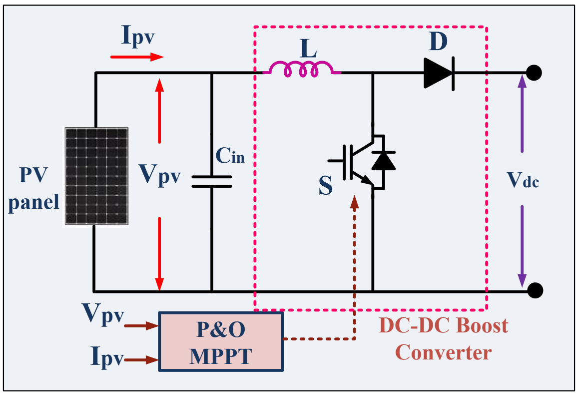


Fig. 2 solar PV P&O MPPT DC-DC boost converter

1. Single-Diode Solar PV Model: Designing a single-diode solar PV model involves analyzing the electrical characteristics of a photovoltaic (PV) cell. The single-diode model is one of the most commonly used to simulate the behavior of a PV cell. This model includes one diode, a current source, and series and shunt resistances to represent losses as shown in fig.3.
2. Basic Equation of the Single-Diode Model: The equation that governs the behavior of the single-diode PV model is derived from Kirchhoff's current law (KCL):

$$I = I_{Ph} - I_D - I_{sh} \quad (1)$$

Where: I = output current of the PV module (A), Iph = photocurrent, the current generated by light (A), ID = diode current (A), Ish = shunt current (A)

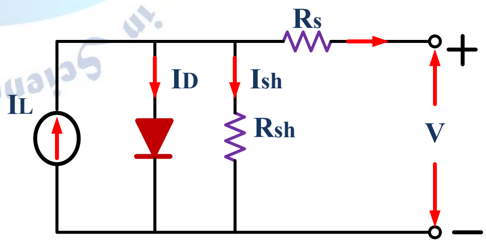


Fig. 3 equivalent model of PV solar.

3. Diode Current (ID): The current through the diode is described by the Shockley diode equation:

$$I_D = I_0\left(e^{\frac{V+IR_S}{nV_t}} - 1\right) \quad (2)$$

Where: I_0 = reverse saturation current of the diode (A), V = voltage across the PV cell (V), R_s = series resistance (Ω), n = diode ideality factor (typically between 1 and 2), V_t = thermal voltage (V), given by V_t=qkT

Here:

k = Boltzmann constant (1.38×10^{-23} J/K), T = temperature in Kelvin (K), q = electron charge (1.6×10^{-19} C)

4. Shunt Current (Ish): The current through the shunt resistance Rsh is modeled as:

$$I_{sh} = \frac{V+IR_s}{R_{sh}} \quad (3)$$

5. Equation of the Single-Diode PV Model: By substituting the expressions for ID and Ish into the main current equation, we get the complete form of the single-diode model:

$$I = I_{Ph} - I_0\left(e^{\frac{V+IR_s}{nV_t}} - 1\right) - \frac{V+IR_s}{R_{sh}} \quad (4)$$

6. Photocurrent I_{Ph}: The current generated by the cell due to light is proportional to the incident light and is affected by temperature. It can be modeled as:

$$I_{ph} = \left[I_{ph,ref} + \mu I_{Ph} \cdot (T - T_{ref})\right] \cdot \frac{G}{G_{ref}} \quad (5)$$

Where: $I_{ph,ref}$ = reference photocurrent at standard test conditions (STC), I_{Ph} = temperature coefficient of photocurrent (A/°C), T = cell temperature (°C), T_{ref} = reference temperature (usually 25°C), G = irradiance (W/m²), G_{ref} = reference irradiance at STC (1000 W/m²)

7. Saturation Current I_0: The reverse saturation current varies exponentially with temperature:

$$I_0 = I_{0,ref}\left(\frac{T}{T_{ref}}\right)^3 e^{\frac{Eg}{nV_t}\left(\frac{1}{T_{ref}}-\frac{1}{T}\right)} \quad (6)$$

Where:, $I_{0,ref}$ = reverse saturation current at reference temperature, Eg = bandgap energy of the semiconductor (typically 1.1 eV for silicon)

B. P&O MPPT algorithm designing

The P&O MPPT algorithm is a widely used method to extract the maximum amount of energy from a solar photovoltaic (PV) system. As shown in Fig.4 the P&O MPPT algorithm creates a periodic perturbation in the PV voltage and observes the corresponding change in power to determine the location of the MPP. The P&O MPPT algorithm makes small incremental or decremental changes in the PV voltage (Vpv) and measures the resultant change in power (Ppv), then uses this information to adjust the duty cycle of the DC-DC boost converter to reach the MPP.

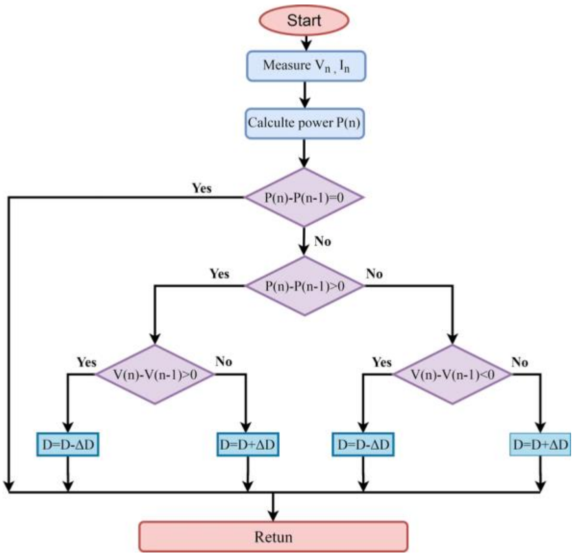


Fig.4 flow chart of P&O MPPT algorithm

1. Calculate Power Output:

$$P_{Pv} = V_{Pv} \times I_{Pv} \quad (7)$$

Where: Vpv = PV panel output voltage, Ipv = PV panel output current, Ppv = PV panel output power

2. Compare Current and Previous Power:

$$\text{change in Power}: \Delta P = P_{Pv}(t) - P_{Pv}(t-1) \quad (8)$$

$$\text{change in Voltage}: \Delta V = V_{Pv}(t) - V_{Pv}(t-1) \quad (9)$$

3. Decision Conditions:

$$if\ \Delta P > 0\ and\ \Delta V > 0 \rightarrow increase\ Voltage \quad (10)$$

$$if\ \Delta P > 0\ and\ \Delta V < 0 \rightarrow decrease\ Voltage \quad (11)$$

$$if\ \Delta P < 0\ and\ \Delta V > 0 \rightarrow decrease\ Voltage \quad (12)$$

$$if\ \Delta P < 0\ and\ \Delta V < 0 \rightarrow increase\ Voltage \quad (13)$$

4. Duty Cycle (D) of Boost Converter:

- The new duty cycle is adjusted based on the voltage perturbation decision.
- The boost converter duty cycle is given by:

$$D = 1 - \frac{V_{pv}}{V_{dc}} \quad (14)$$

Where: Vdc= Output voltage of the boost converter

C. Bidirectional Buck-Boost Converter for EV Charging in DC Microgrid

The Bidirectional Buck-Boost Converter is an important component for controlling energy transfer between the Battery Energy Storage System (BESS) and the DC Bus within a Microgrid; this will allow for both Charging and Discharging of the BESS with the purpose of maintaining consistent Power Delivery to Electric Vehicle (EV) Charging. As depicted in Fig. 5, the Converter functions as a Step Down Buck Converter when the Converter charges the BESS and reduces the Voltage of the DC Bus and functions as a Step Up Boost Converter when the

Converter supplies the Microgrid or EV Load by increasing the Voltage of the BESS. The Control Strategy of the Converter regulates the Power Flow through dynamic adjustments of the Duty Cycle of the Converter. Additionally, the Converter stabilizes the Voltage on the DC Bus by reducing the Fluctuations caused by the Intermittent Renewable Energy Sources (such as Solar and Wind). The Energy Management Strategy ensures that the Optimal Charge and Discharge Cycles are used for the BESS which allows for the extension of the Lifetime of the Battery and enhances the Efficiency of the Overall System.

1. Buck Mode (Battery Charging)

Output Voltage in Buck Mode:

$$V_b = D \cdot V_{dc} \quad (15)$$

Where: Vb = Battery voltage, Vdc = DC bus voltage, D = Duty cycle (0<D<1)

Inductor Current Ripple in Buck Mode:

$$\Delta I_L = \frac{(1-D)V_{dc}}{Lf_S} \quad (16)$$

Where: ΔIL = Inductor current ripple, L = Inductor value, fs = Switching frequency

2. Boost Mode (Battery Discharging)

Output Voltage in Boost Mode:

$$V_{dc} = \frac{V_b}{1-D} \quad (17)$$

Inductor Current Ripple in Boost Mode:

$$\Delta I_L = \frac{DV_b}{Lf_S} \quad (18)$$

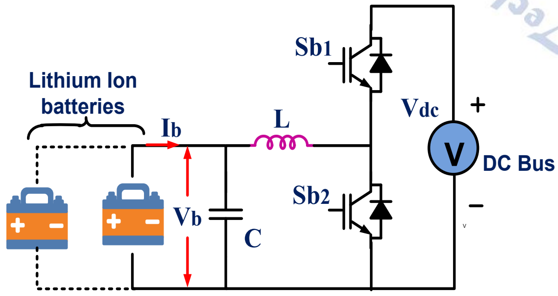


Fig.5 principle operation bidirectional dc-dc buck boost converter

D. Double-Loop Controller for EV Charging System

The control strategy for electric vehicle (EV) charging involves a double-loop control system to ensure efficient, stable, and safe charging as shown in Fig.6. The outer voltage loop maintains a constant DC bus voltage, while the inner current loop regulates the battery charging current. A Proportional-Integral (PI) controller is used in both loops to minimize steady-state error and improve dynamic performance.

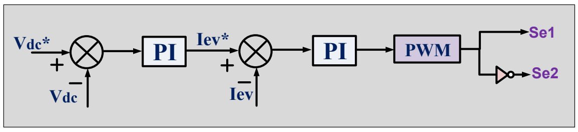


Fig. 6 double loop ev charging controller

1. Outer Voltage Loop: DC Bus Voltage Control

The outer voltage loop ensures the DC bus voltage (Vdc) remains stable and within the desired range. Since variations in EV charging loads and grid fluctuations affect the DC bus voltage, this loop provides a reference current (Iev∗) for the inner current loop.

Error Signal Calculation:

$$e_v(t) = V_{dc}^* - V_{dc} \quad (19)$$

PI Controller Output (Reference EV Charging Current Iev∗)

$$I_{ev}^*(t) = K_{Pv} e_v(t) + k_{iv} \int e_v(t)\, dt \quad (20)$$

Where: Iev∗= Reference charging current for the inner loop, Kpv= Proportional gain of voltage controller, Kiv= Integral gain of voltage controller

This reference current is then passed to the inner current loop for precise battery charging control.

2. Inner Current Loop: Battery Current Control

The inner current loop ensures the EV battery is charged with a smooth and regulated current to prevent over current issues and battery degradation. The PI controller in this loop generates the duty cycle for the DC-DC converter (buck or boost).

Error Signal Calculation:

$$e_i(t) = I_{ev}^* - I_{ev} \quad (21)$$

PI Controller Output (Duty Cycle Control)

$$D(t) = K_{Pi} e_i(t) + k_{ii} \int e_i(t)\, dt \quad (22)$$

Where: D = Duty cycle of the DC-DC converter, Kpi= Proportional gain of current controller, Kii= Integral gain of current controller

This duty cycle (D) is applied to the DC-DC converter, adjusting the output voltage and current to regulate battery charging.

IV. GRID-SIDE CONVERTER CONTROL USING FUZZY CONTROLLER

The Grid Side Converter (GSC), in a DC Microgrid, is responsible for both Bidirectional Power Flow between the Grid and the DC Bus, as well as for maintaining DC Bus Voltage Stability with Power Factor Correction (PFC). An application for an efficient and reliable DC to AC power conversion is a Three Level Bidirectional AC-DC Voltage Source Converter (VSC). By utilizing the Three Level VSC, harmonic reduction and grid stability are enhanced. In order to implement control on the GSC, the synchronous dq reference frame is used. As such, the DC link voltage is regulated via the d-axis of the dq frame; whereas, the q-axis of the dq frame is used to regulate the reactive power. To improve the systems ability to adapt to varying grid conditions, a Fuzzy Logic Controller (FLC) was chosen over a traditional PI controller. The dc-link voltage control loop and the grid current control loop are contained within the overall control structure of the GSC as illustrated in Fig. 7. The dq reference currents (Idref and Iqref) are produced by the fuzzy based dc-link voltage controller that produces the minimum possible steady state errors and total harmonic distortion (THD) of the grid current. The d-axis control enables the stable transfer of active power by maintaining the dc-link voltage, whereas the q-axis control either minimizes or regulates the reactive power as necessary. Using the park transformation, the voltage and current control equations for the three level VSC are developed allowing for efficient power flow control and an improvement in overall grid performance.

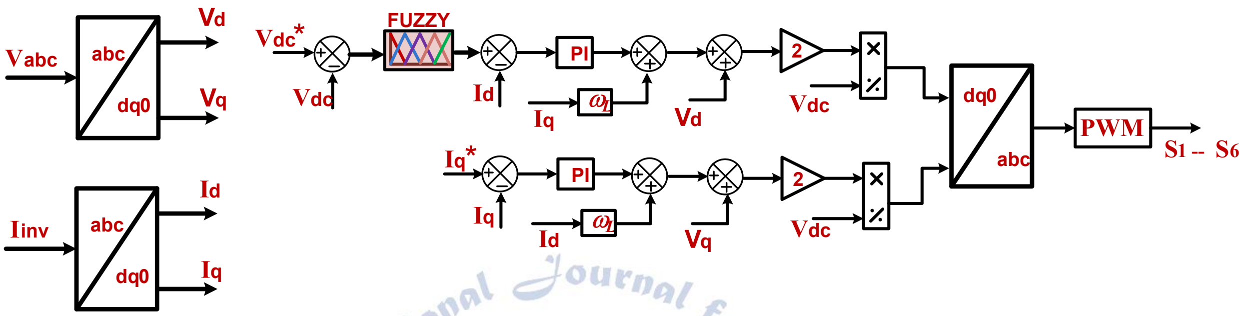


Fig. 7 Grid conversion controller

1. d-q Axis Voltage Equations

$$V_d = R_S I_d + L_s \frac{dI_d}{dt} - \omega L_s Iq + V_{gd} \quad (23)$$

$$V_q = R_S I_q + L_s \frac{dI_q}{dt} - \omega L_s I_d + V_{gq} \quad (24)$$

2. Active and Reactive Power Equations

$$P = \frac{3}{2}(V_d I_d + V_q I_q) \quad (25)$$

$$Q = \frac{3}{2}(V_q I_d - V_d I_q) \quad (26)$$

Where: P = Active power (W), Q = Reactive power (VAR)

3. PI Controller for d-q Current Control

$$V_d^{ref} = K_p(I_d^{ref} - I_d) + K_i \int (I_d^{ref} - I_d)\, dt \quad (27)$$

$$V_q^{ref} = K_p(I_q^{ref} - I_q) + K_i \int (I_q^{ref} - I_q)\, dt \quad (28)$$

Where: Kp,Ki = PI controller gains, Vdref,Vqref = Reference d-q axis voltages

The PI controller ensures accurate current regulation by adjusting the error between reference and actual d-q currents. The grid-side converter uses these control strategies to maintain power quality, regulate the DC-link voltage, and manage bidirectional power flow between the grid and the DC microgrid efficiently.

5. PI Controller for DC-Link Voltage Regulation

The DC-link voltage PI controller generates the reference d-axis current:

$$I_d^{ref} = K_{P_{dc}}(V_{dc}^{ref} - V_{dc}) + K_{I_{dc}} \int (V_{dc}^{ref} - V_{dc})\, dt \quad (29)$$

Where: Idref = Reference d-axis current (A), Vdcref = Reference DC-link voltage (V), Vdc = Actual DC-link voltage (V), Kpdc,Kidc = PI controller gains for DC voltage regulation

This control strategy ensures that the DC-link voltage remains stable under varying grid conditions, enabling efficient energy exchange between the grid and the DC microgrid.

5. DESIGN OF FUZZY LOGIC CONTROLLER

A fuzzy logic controller (FLC) is an advanced control system that uses fuzzy logic to handle uncertainties and manage complex systems as shown in fig.8. Unlike traditional binary logic, which operates with crisp values (true or false), fuzzy logic allows for a range of values between 0 and 1, representing degrees of truth. This makes FLCs particularly effective for systems where precise mathematical models are difficult to develop or where input data is uncertain or imprecise.

Components of a Fuzzy Logic Controller

a. **Fuzzification**: Converts crisp input values into fuzzy values using membership functions. Membership functions define how much a particular input belongs to a fuzzy set. For instance, instead of a precise temperature value, fuzzification might categorize it as "high," "medium," or "low."

b. **Rule Base**: Contains a set of fuzzy rules that represent the knowledge or control strategy of the system. These rules are typically in the form of "IF-THEN" statements. For example, "IF temperature is high THEN reduce fan speed."

c. **Inference Engine**: Processes the fuzzy rules based on the fuzzified inputs. It applies logical operations to combine the rules and determine the fuzzy output. The inference engine evaluates how well each rule applies to the current situation and aggregates the results.

d. **Defuzzification**: Converts the fuzzy output from the inference engine into a crisp value that can be used by the system. This step translates the fuzzy control decisions into actionable commands, such as adjusting a motor speed or setting a temperature.

e. **Output**: The defuzzified output is used to adjust the system's variables, such as controlling a motor's speed or regulating the temperature.

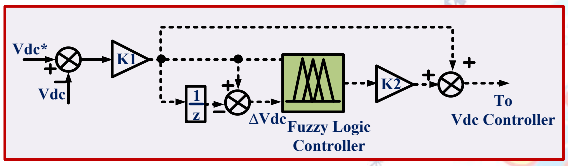
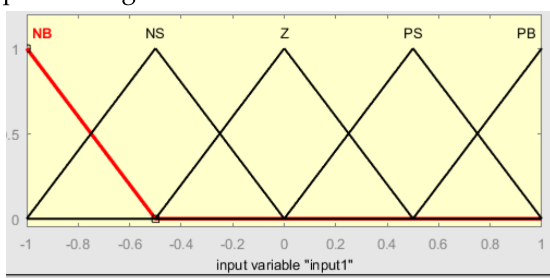


Fig. 8. Schematic diagram of Vdc controller.

Fuzzy controls are straightforward. Input, processing, and output. The input stage maps sensors, switches, thumbwheels, etc. to membership functions and truth values. The processing stage invokes each rule, generates a result for each, and combines the results. The output stage translates the combined result into a control output. Most membership functions are triangular, but trapezoidal and bell curves are also employed. The shape is less significant than the quantity and positioning of curves.



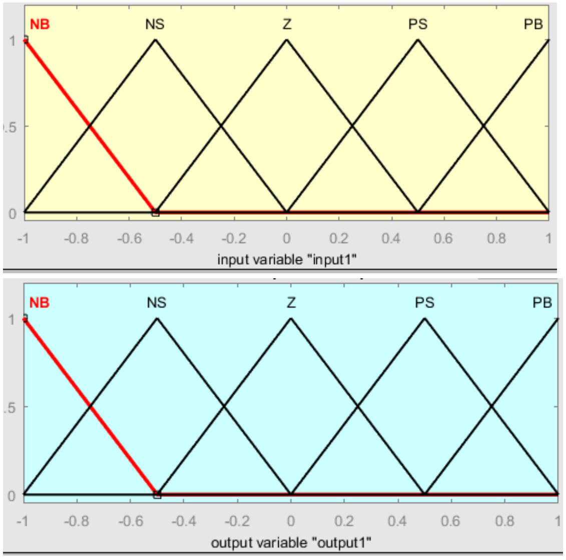


Fig.9 Example figures of input and output membership functions

Fuzzy control system design is based on empirical methods, basically A methodical approach to trial and-error. The general process is as follows:

- Document the system's operational specifications and inputs and outputs.
- Document the fuzzy sets for the inputs.
- Document the rule set.
- Determine the defuzzification method.
- Run through test suite to validate system, adjust details as required.
- Complete document and release to production.

This mechanism is divided into three parts. First, using input membership functions the inputs are fuzzified and then based on rule bases and inference system, outputs are produced and finally the fuzzy outputs are defuzzified and applied to the system. Error and the error change rate are selected as inputs. The block diagram of fuzzy control is represented as follows:

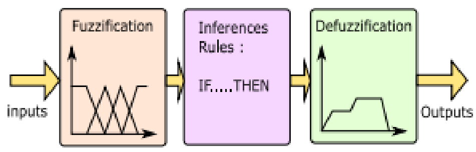


Table 1 :Inference matrix

e|ê	NB	NS	Z	PS	PB
NB	NB	NB	NB	NS	Z
NS	NB	NB	NS	Z	PS
Z	NB	NS	Z	PS	PB
PS	NS	Z	PS	PB	PB
PB	Z	PS	PB	PB	PB

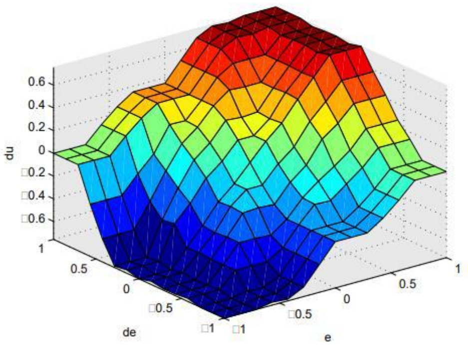


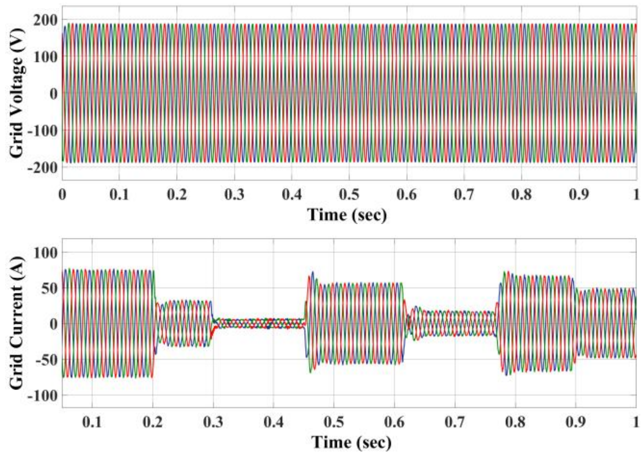
Fig 10 Surface generated by the fuzzy system

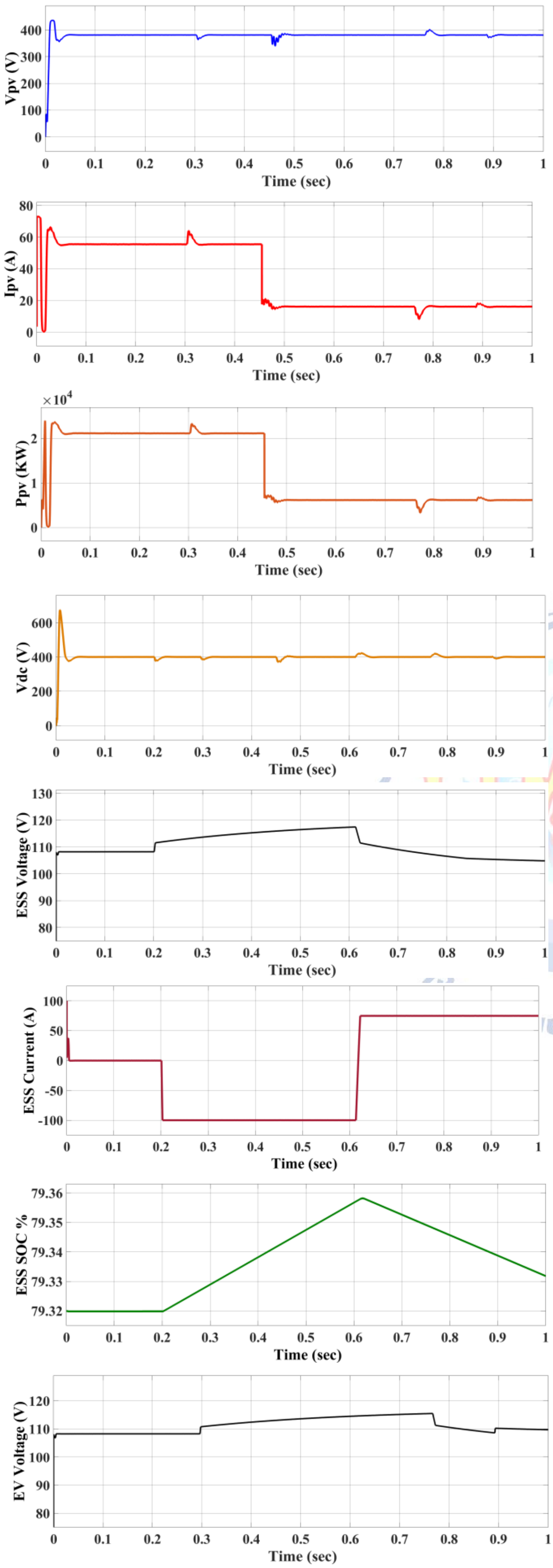
The general process to develop a fuzzy controller for control of electric drives involves the development of fuzzy controller parameters which include, linguistic variables, membership functions, methods of inference and defuzzification strategies. The fuzzy controller inputs are the error and the derivation of the error and the output of the controller is the command. A triangular and trapezoidal membership function has been applied to the universe of discourse normalized between -1 and 1 for each variable as illustrated in Fig. 8 for inputs (the error and the variation of the error) and output (the input process). The fuzzy membership of the subsets have been denoted as follows: NB - Negative-Big; NS - Negative-Small; Z - Zero; PS - Positive-Small; PB - Positive-Big. The fuzzy rules that define the output of the controller based on the input variables are listed in table 1. This section presents the simulation results for Enhancing Power Quality and System Stability in Grid-Connected Electric Vehicle Charging Systems Using Fuzzy Logic Control Integrated with Renewable Energy Sources. In the single-phase configuration, both configurations described in Section II are examined in the context of the single-phase case: A single-phase BESS grid-connected utilizing the buck-boost characteristics of the EV; and a hybrid single-phase grid connected PV-EV systems providing stable power to the grid while using the battery as an energy buffer. The three-phase configuration examines a hybrid system with two DC sources and one AC load.

6. RESULTS AND DISCUSSION

A. Simulation Results and Performance Evaluation of proposed system configuration

The simulation results demonstrate that the three-level bidirectional voltage source converter (VSC) with fuzzy logic control effectively maintains the DC-link voltage at 400V, ensuring stable power flow across the system. The solar PV system, controlled via a boost converter with P&O MPPT, efficiently operates at 350V and 50A, delivering 20 kW of power with an MPPT efficiency of 98.5%. The energy storage system (ESS) plays a crucial role in stabilizing power, dynamically charging at 10 kW with 96% efficiency to balance fluctuations in solar generation and load demand. Meanwhile, the EV charging system draws 5 kW, ensuring smooth and efficient energy transfer without affecting grid stability. The grid-side converter, operating in a synchronous dq reference frame, provides seamless bidirectional power exchange while ensuring power factor correction (PFC). The grid power factor is maintained at 0.99, and the Total Harmonic Distortion (THD) of the grid current is reduced to 1.80% using a fuzzy logic controller (FLC), significantly improving performance over a conventional PI controller as shown in Fig.11. The system responds swiftly to dynamic load variations, with voltage fluctuations remaining within ±1.5%, ensuring smooth operation of the PV, ESS, and EV charging infrastructure.





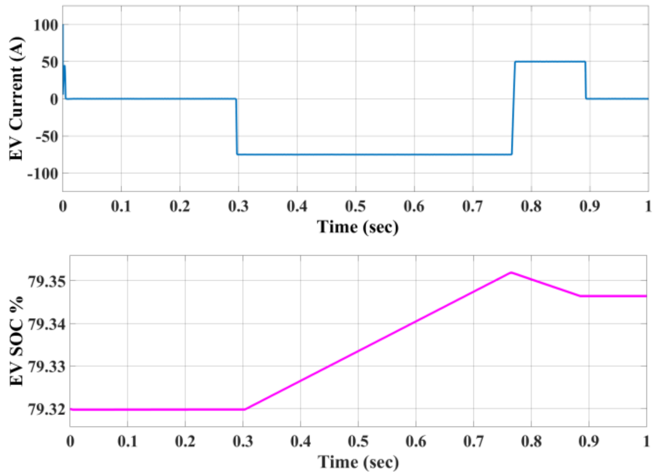


Fig.11 simulation result and performance of proposed microgrid system

B. Dynamic Power Management in a Grid-Connected Solar PV, ESS, and EV Charging System with Fuzzy Logic Control

A sophisticated Dynamic Power Management (DPM) strategy integrates Solar Photovoltaics (PV), an Energy Storage System (ESS), Electric Vehicle (EV) Charging, and a Three-Level Bidirectional Voltage Source Converter (VSC) to provide Grid Stability while utilizing Fuzzy Logic Control (FLC). DPM adjusts Energy Use based on Real-Time Solar Output, Load Demand, and Grid Interaction, thus optimizing the Energy Use in various operational conditions. For the first time frame, from 0 s to 0.2 s, the Solar PV System produces 20 kW at maximum capacity at 1000 W/m² Irradiance, however no Local Load is present during this interval; therefore all generated electricity is fed into the Grid to maximize the utilization of Solar Energy. High Grid Interaction Efficiency is achieved by maintaining 400 V DC-Link Voltage and Power Factor close to Unity. The next interval, from 0.2 s to 0.7 s, represents a transition towards favoring local Energy Storage and EV Charging. The ESS is charged with 10 kW to store additional Solar Electricity during periods of Low Generation. The EV Battery Charging consumes 5 kW from 0.3 s to 0.75 s. Coordinated Power Management allows for the reduction of the potential for overloading of the overall system while maximizing Renewable Energy Utilization. The primary challenge is the slow decrease in the Solar Power Output upon irradiance dropping from 1000 W/m² to 300 W/m² in a short span of 0.45 s. The FLC regulates the Power Flow between the ESS, EV, and Grid, thus compensating for the dynamic adjustments of the MPPT-Controlled Boost Converter to Maximize PV

System Power. This helps maintain stable system operation despite the fluctuations in the Solar Generation. During the interval from 0.6 s to 1 s the system transitions into Discharge Mode to Support both Grid Stability and Local Load. The ESS provides 7.5 kW of Electricity back to the System, thereby counteracting the decreased Solar Power Output. In the interval from 0.75 s to 0.9 s, the EV Battery Discharges 5 kW to Provide Energy Transmission to the Microgrid without Inducing Voltage Fluctuations. The Fuzzy Logic-Based Control Minimizes Power Imbalance, and Improves Overall System Efficiency by Seamlessly Transitioning Between Charging/Discharging Modes. The results of the simulation illustrate the effective Handling of Bidirectional Power Flow by the Three-Level Bidirectional VSC while Maintaining a Stable 400 V DC-Link Voltage and Correcting the Power Factor. Fuzzy Logic Controllers Outperform PI-Based Control Approaches by Reducing the Total Harmonic Distortion (THD) of the Grid Current to 1.80%. The results of the Simulation Illustrate the Potential of the DPM Strategy in Preserving System Stability and Optimizing Energy Distribution Under Different Operating Conditions, as Shown in Fig. 12. Furthermore, the Intelligent Coordination among Solar PV, ESS, EV Charging, and the Grid enables the Optimal Utilization of Renewable Energies and the Reduction of the Dependence of the Grid on Non-Renewable Sources. Finally, the Results of the Simulation Show that the Proposed FLC-Controlled Three-Level Bidirectional VSC Improves the Integration of Renewable Energies, the Grid Stability and the Rapid-Charging Efficiency of EVs in Modern Power Systems.

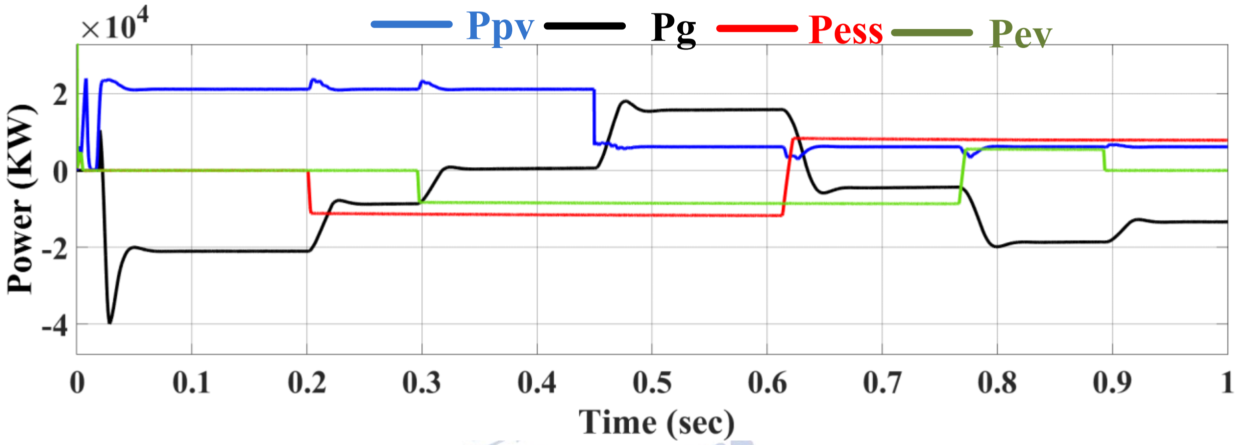


Fig.12 simulation results of dynamic power management in proposed system

C. Modes of Operation in a Grid-Connected Solar PV, ESS, and EV Charging System

a. Grid to EV and ESS Mode

When power flows from the grid to charge the EV and ESS, the grid voltage and current remain in phase, ensuring efficient power transfer and maintaining power factor correction (PFC) as shown in fig.13 (a). In this mode, the grid supplies energy to support EV charging and ESS storage, stabilizing the system under varying load conditions.

b. Solar, EV, and ESS to Grid Mode

When power flows from the solar PV, ESS, or EV back to the grid, the grid voltage and current are out of phase, indicating power export as shown in fig.13 (b). This mode ensures surplus energy from renewable and storage sources are efficiently fed into the grid, reducing dependency on conventional power sources while maintaining overall system balance.

c. Total Harmonic Distortion (THD) Comparison

With a conventional PI controller, the system exhibits a THD of 3.27%, affecting power quality and increasing harmonic distortion in the grid current. However, by implementing a fuzzy logic controller (FLC), the THD is significantly reduced to 1.80%, leading to improved power quality, enhanced system efficiency, and smoother grid integration as shown in fig.13 (b),(c).

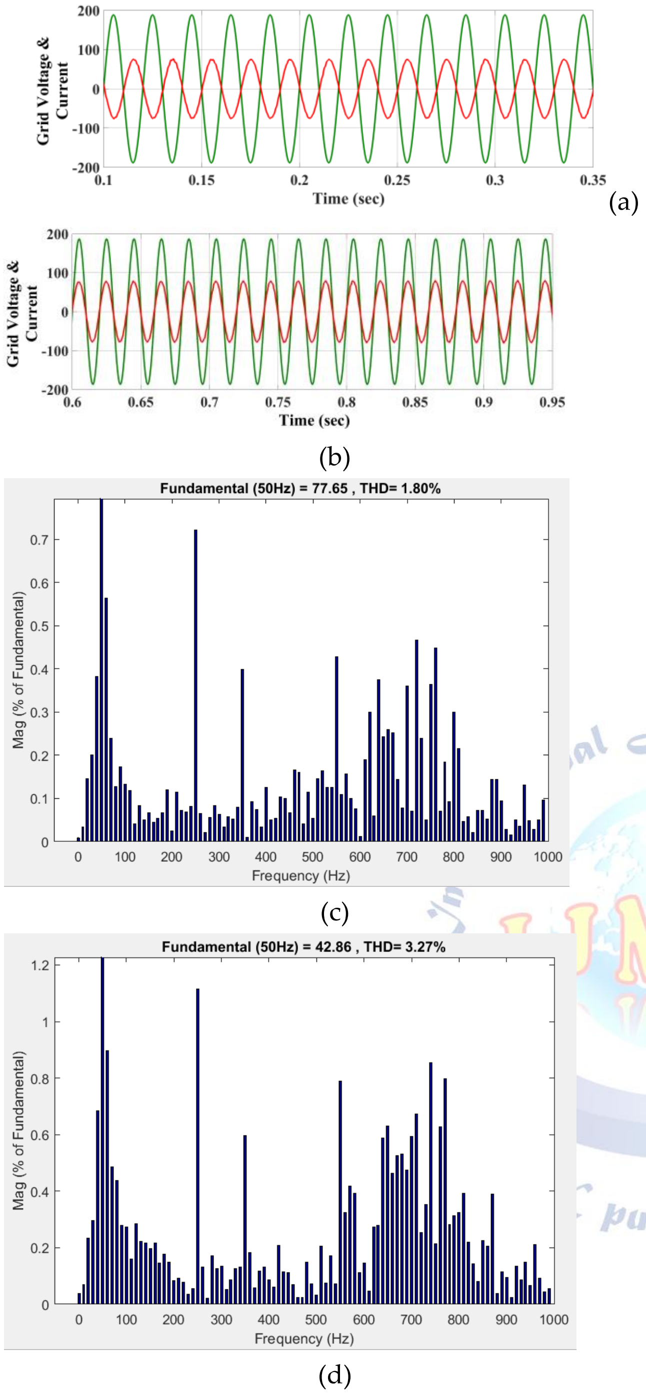


Fig. 13 (a) represents grid to load mode (b) solar or energy storage system to grid mode (c) grid current THD value of fuzzy logic controller (d) THD value of PI controller

7. CONCLUSION

The proposed grid-connected system enables efficient control of power-flow among solar PV, Energy Storage System (ESS), Electric Vehicle (EV) Charging Station and Grid during real-time varying conditions of operation. As well, it can smoothly transition through multiple operational modes that enable optimal energy usage while maintaining Grid Stability. Conversely, when power flows from the Grid to both the EV and ESS, the Grid Voltage and Current will always be in Phase as this is the most efficient way for power to be transferred. However, when power is sent back from Solar PV, ESS or EV to the Grid, the Voltage and Current become Out-of-Phase with each other, denoting Reverse Power Flow. Implementing Fuzzy Logic Controller (FLC) has greatly enhanced the performance of the entire system by improving Power Quality and by reducing Harmonic Distortion; in comparison to a Conventional Proportional Integral (PI) controller which demonstrates Higher Harmonic Distortion. As such, the FLC demonstrated lower Total Harmonic Distortion (THD) and therefore more Smoother Operation and also Improved Power Factor Correction (PFC). Moreover, the system is able to adapt to Fluctuations in Solar Irradiance, Load Variations and EV charging/discharge Conditions while maintaining Stable Operating Conditions. Therefore, the Intelligent Control Strategy used in this system has Enhanced Renewable Energy Integration, Reduced Grid Disturbances and Ensured Reliable and Efficient EV Charging Infrastructure.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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