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An Intelligent Fuzzy Logic Controller- Based Charging Strategy for ESS-Free DC Fast EV Charging Stations

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Abstract: ***The exponential growth of EVs has created an unexpected and severe strain on power grids, as the demand for charging stations has skyrocketed. One eco-friendly option is photovoltaic-powered direct current fast charging stations (DC-FCSs), although existing systems rely on expensive ESSs to balance power. This article presents an intelligent charging approach for DC fast charging stations that do not use ESS. It is based on field-effect transistors (FLCs) and aims to improve operating efficiency and reduce system cost. By monitoring DC bus voltage, PV production, and EV state-of-charge (SOC), the suggested Fuzzy Logic Controller (FLC) expertly controls the power flow among the PV source, grid interface converter, and EVs. Optimising PV usage, maintaining DC bus stability, and providing continuous charging in varied scenarios may be achieved by including dynamic power regulation into the charging process. The suggested method, which boosts charging efficiency, increases converter utilisation, and ensures ESS-free operating reliably, is confirmed by the simulation results.***

Keyterms: ***Grid interface converters, intelligent charging methods, electric cars, solar systems, ESS-free charging stations, direct current fast charging, power flow management***

I.INTRODUCTION

Across the globe, more and more people are opting for electric cars (EVs) and hybrid EVs as a means to lessen their impact on the environment and reliance on fossil fuels [1]-[3]. In order to increase the speed and range of electric vehicles (EVs), rapid charging stations that employ direct current (DC) are crucial. Voltage fluctuations and operational problems are major problems for utility systems caused by unexpected and excessive power use. Photovoltaic (PV) DC rapid charging stations are one potential answer that has arisen in response to these issues and the need to encourage environmentally friendly transportation [4]. For high-power charging applications, PV systems are ideal because to their cost-effectiveness, scalability, and technical maturity [5].

To stabilise charging and reduce power fluctuations, conventional DC fast charging stations that use renewable energy sources often include energy storage systems (ESSs) such as batteries, supercapacitors, or flywheels [6]-[11]. A number of research have suggested technological methods for managing energy consumption in order to enhance the efficiency of the system [6, 7]. We looked at DC fast charging topologies made feasible by ESS, and the mechanisms for adaptive droop control for multi-mode operation are detailed in references [8] and [9]. Also included in [12]-[15] were various charging strategies, such as PV, grid, ESS, and EVs. Despite the operational flexibility that these technologies provide, ESS is not practicable because to its high cost, extensive maintenance needs, and replacement costs associated with deterioration. The system is also excessively sophisticated and complicated.

Recent studies have attempted to optimise the size and functioning of ESS in order to circumvent these restrictions [16]-[19]. Evidence suggests that ESS sizing [16], degradation-aware control techniques [17], coordinated charging and discharging [18], and efficient energy management systems [19] all contribute to cost-effectiveness. There hasn't been nearly enough research on totally doing away with ESS, even though it might drastically save infrastructure expenses and maintenance duties. Additionally, most current control approaches aren't applicable to settings without ESS since they rely on it to regulate power fluctuations.

Power production, grid support, and electric vehicle charging requirements may be efficiently met by DC fast charging stations that use solar energy systems (PV) and do not rely on energy storage systems (ESS). Typical linear control methods often fall short in delivering consistent performance across a range of operating situations when dealing with electric vehicle charging loads and intermittent PV

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production, which are dynamic and nonlinear in nature. Because it does not need a precise mathematical model, Fuzzy Logic Control (FLC) is an effective method for handling system uncertainties, nonlinearities, and inaccurate input data.

Dynamic management of electric vehicle charging power is achieved via the proposed FLC-based intelligent charging system's real-time monitoring of crucial system parameters including DC bus voltage, PV output power, EV state-of-charge (SOC), and charging demand. In order to maintain DC bus stability and uninterrupted charging performance, the controller takes into account two factors: optimal utilisation of PV power and adaptive coordination of grid support. Skilful decision-making improves system efficiency and guarantees dependable operation—without the costly ESS connection, of course.

Keeping the system running well depends on making good use of the grid interface converter (GIC). Because the converter is less efficient while operating at half load, operational losses increase. The suggested FLC technique maximises GIC usage and guarantees effective power sharing under dynamic charging situations via adaptive management of grid power exchange.

This study systematically reviews the literature and then suggests a smart charging method for DC fast charging stations that avoids the need for electronic signal suppression (ESS). A summary of the key points made in the article is as follows:
1. To drastically cut down on system cost and maintenance complexity, we provide a DC fast charging station design that is not reliant on ESS. This layout would make advantage of photovoltaic (PV) technology.

2. To enhance the management of power flow among the PV source, grid interface converter, and EV charging loads, a Fuzzy Logic Controller (FLC) is created.

The proposed FLC controls the charging power dynamically according to DC bus voltage, PV availability, and EV state of charge to keep the system stable and make the most of renewable energy.

4. By using adaptive grid power regulation, we may potentially enhance the utilisation of grid interface converters and guarantee that electric vehicle charging stays uninterrupted under a variety of operational conditions.

5. Simulation results show that the suggested strategy improves charging efficiency, maintains voltage stability, and allows ESS-free dependable operation.

II. THE ARCHITECTURE OF THE PROPOSED FCS

A power storage system is not part of the fast charging station (FCS) architecture that is being considered, as shown in Figure 1. A photovoltaic (PV) producing unit connected to the utility AC grid, electric vehicles (EVs), a number of charge stations (CPs), and many grid-interlinking converters (GICs) are the primary elements of the system. A central DC bus distributes electricity to the rapid charging station and links all of its subsystems.

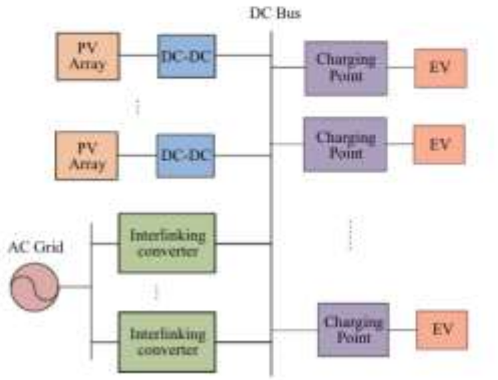

Fig. 1. The proposed FCS.

A DC-DC boost converter with MPPT control would link the solar system, which would constitute the major renewable energy source of the planned DC fast charging station, to the DC bus. This would enable the station to extract the maximum power possible regardless of changes in irradiance. The PV system may redirect power from the utility grid to EVs when the sun is really out.

A system of grid-interlinking converters (GICs) connected to the utility grid controls the DC bus voltage and maintains a steady bidirectional flow of power, allowing it to provide backup power. Enhancing efficiency, adaptability, and the potential for power sharing may be achieved by using several low-power converters.

All of the charging stations are connected to the common DC bus by DC-DC buck converters that are placed at each station. Using an enhanced CC-CV method, it allows adaptive charging control by monitoring charging voltage, current, and the charge state of EV batteries.

Through real-time data collection, an operational control unit manages and monitors the PV system, grid converters, and charge points. Without the need for long-term energy storage, smart power management achieves system stabilisation, charging power regulation, and power flow balancing. Electric vehicles are able to efficiently absorb variations in PV production as their charging needs align with solar power throughout the day. This is clearly seen by the energy profile during a 24-hour period. In addition to reducing grid stress, increasing renewable energy utilisation, and making ESS-free operation viable, this also cuts total system cost.

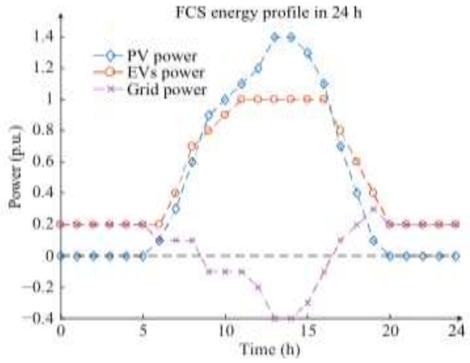

Fig. 2. The 24 h energy curves of DC FCS.

See how grid power, electric vehicle charging demand, and solar power production affect the DC fast charging station's daily energy profile in Figure 2. The charging power required is supplied by the utility grid since PV output is almost nonexistent in the early morning and late night hours. The electricity grid will have less strain to charge electric vehicles as the quantity of sunshine reaching Earth's surface grows throughout the day, leading to a rise in the production of photovoltaic (PV) cells. If there is an excess, it is returned to the grid at noon, when PV power is at its highest. This might happen if PV output is outstripped by the need for charging. As PV production drops later in the day, the grid steps in to make up for the electricity shortfall once again. By reducing grid stress and making the most of renewable energy sources, this profile demonstrates that the intended DC fast charging station can function without ESS.

III.SMART CHARGING ALGORITHM AND CONTROL STRATEGY DESIGN

Power fluctuates due to photovoltaic (PV) production interruptions and the unpredictability of electric vehicle (EV) arrival and departure. A common solution is the installation of an energy storage system (ESS) at traditional fast charging stations (FCSs). This study proposes an Intelligent Coordinated Algorithm (ICA) for electric vehicle (EV) power scheduling using grid-interlinking converters (GICs) as a means to accomplish ESS replacement without the need of an ESS. The Self-Regulated Algorithm (SRA) is the first component of the ICA, while the Grid-Regulated Algorithm (GRA) is the second component. The first metric to think about while analysing FCS power imbalance and fluctuation levels is the DC bus voltage. Inadequate management of the unique temporal behaviour and dynamic load features of charging electric cars might lead to underutilization of gas injection capacitors (GICs) caused by frequent power fluctuations.

Since it takes many hours to charge an electric car, reducing the amount of power needed to charge them might help with small power fluctuations. Hence, the SRA is used to dynamically manage the charging current for electric cars, preventing small power fluctuations. With the use of state-of-charge (SOC) input, the SRA employs a modified droop-based charging method to distribute power evenly and proportionally across all connected EVs. Without negatively impacting charging performance or battery status, this technique maintains a constant DC bus voltage.

Nevertheless, prolonged charging periods or substantial power fluctuations—both of which may reduce battery life—may result from relying only on SRA in situations when power changes are substantial. People who use electric cars can't stand these weather conditions. To keep the energy level suitable for charging electric vehicles (EVs), the Grid-Regulated Algorithm (GRA) is used when GICs either absorb or provide the necessary power. The usage rate of the GICs is also enhanced by this approach.

An upper and lower voltage limit (U_max) and a nominal DC bus voltage (U_nom) are established to provide reliable and seamless switching between SRA and GRA. To avoid control oscillations and frequent switching, the DC bus voltage must restore to its nominal value before the transition from grid-regulated to self-regulated mode may occur. There is always only one active regulatory mechanism, whether it SRA or GRA. The decision-making process of the proposed ICA is shown in Figure 3, which is a detailed flow diagram. While it regulates operations, the self-regulating algorithm (SRA) keeps the utility grid current flowing to the fast charging station (FCS). Thus, so long as SRAs remain operational, the grid will not attempt to compensate for brief power losses. Rather, regulating power variations brought on by photovoltaic (PV) intermittency and unexpected charging needs is the job of electric vehicles (EVs). Keeping an eye on the DC bus voltage deviation from its nominal value allows the real-time control

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centre to precisely determine the FCS's instantaneous power fluctuation.
In real time, the SRA responds to power changes by adjusting the charging power of linked EVs. Charging times for electric cars are typically measured in hours, thus small changes in charging power won't affect the battery life or the user experience. Consequently, EVs could be able to absorb or release power fluctuations by making good use of their flexibility as loads. The SRA is a tweaked version of the droop-based charging system that monitors the SOC of each electric car to determine the maximum amount of power that may be utilised to charge them.
Implementing this technique may be done in a few different ways. One is to charge more electric vehicles with lower state-of-charge (SOC) and fewer with higher SOC. Maintaining system stability and equitably distributing power to all EVs is achieved by this SOC-based droop control. To increase charging efficiency and avoid the needless reduction of overall charging capacity, the SRA redistributes charging power instead of evenly dropping. The power adjustment for charging electric cars will be maintained as long as the DC bus voltage fluctuation remains within an acceptable range. Keeping grid-interlinking converters (GICs) inactive when voltage changes are within the operational constraints of the SRA is one technique to enhance converter utilisation and minimise grid power exchange frequency. Without grid backup or long-term energy storage, the FCS can autonomously remove tiny power oscillations using this local control mechanism.
The SRA is an effective and easy way to smooth out small power ripples in a fast charging station that doesn't employ ESS. The SRA keeps the DC bus voltage constant, charges all EVs fairly, and reduces utility grid contact by taking use of the inherent flexibility of electric vehicle charging loads and integrating state-of-charge data into the management strategy.

$$\Delta P_{\text{CS}} = P_{\text{EV}} - P_{\text{PV}} - P_{\text{G}}$$

Meanwhile,

$$\Delta P_{\text{CS}} = \sum \Delta P_{\text{EV}i}$$

The values of the grid voltage (PG), the PV system's output power (PPV), the current overall demand power (PEV), and the fluctuation power (ΔPCS) are inputs to the calculation. The overall regulatory variation of electric vehicle charging power as a function of SRA is represented by PΔPEVi.

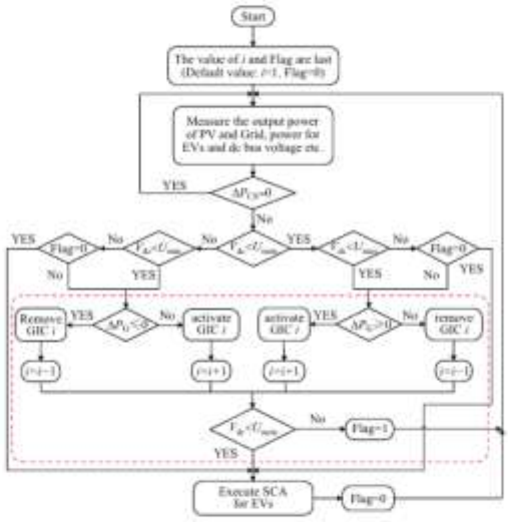

Fig. 3. The proposed ICA.

By coordinating grid interaction via GICs (GRA) and electric vehicle charging control (SRA), the suggested Intelligent Coordinated Algorithm (ICA) might function as a stationary energy storage device, as shown in Figure 3. This procedure continues after initialisation, which sets a control flag and the index of active grid-interlinking converters to their default settings. The DC bus voltage, grid power, PV output power, and power for electric car charging are some of the most critical system variables that the control centre monitors.
Determine whether the charging station's net power fluctuation is zero. This is the first stage of the technique. Without any changes, the system will continue to function as it does now. To detect a power imbalance, one compares the DC bus voltage to three specified limits: U_nom, the nominal voltage; U_max, the upper limit; and U_min, the lower limit. Grid regulation (GRA) and self-regulation (SRA) are used depending on the voltage thresholds.

If the DC bus voltage dispersion is modest and stays within the acceptable range around U standard, then the Self-Regulated Algorithm (SRA) will be prioritised. To eliminate tiny power fluctuations, SOC-based droop control is used to adjust the power supplied to the EV chargers in this case. Higher states of charge (SOC) electric cars get less power when charging, whereas lower SOC EVs receive more. This DC bus stabilisation occurs by proportionate redistribution, independent of the grid.

The Grid-Regulated Algorithm (GRA) activates when the DC bus voltage is deemed excessive, which occurs when it exceeds U_max or falls below U_min. As part of the GRA process, the grid-interlinking converters are individually switched on and off. Adding additional GICs to the grid is a solution to the growing power shortfall. To mitigate the effects of grid contact during times of surplus electricity, GICs are slowly depleted. You may change the amount of active GICs by adding or deleting values from the index.

IV. DESIGN OF THE CONTROL STRATEGY

A) Controller for the PV System

For the planned quick charging station's DC bus and photovoltaic (PV) system to function at peak performance, an efficient management strategy is required. With the help of the maximum power point tracking (MPPT) algorithm, which was created using perturbation and observation (P&O), the PV array can collect the highest amount of power that is possible regardless of the circumstances. Thanks to its straightforward design, short learning curve, and consistent performance even when irradiance changes slowly, the P&O method has found widespread use.

In Figure 4, the control system schematic for the PV system is shown. One way to determine the PV array's instantaneous output power is to continually measure its output voltage U_pvand current I_pv. The PV controller receives this data. By changing the operating voltage and subsequently measuring the power change, the P&O approach takes the power-voltage relationship into consideration. If the power goes up, the direction of the disturbance stays the same; if it goes down, it turns around. Over time, this recurring method brings the PV operating point closer to the MPP.

The reference PV voltage U_pv^*, which is the result of the maximum power point tracking (MPPT) approach, is attained at the voltage where the greatest power is produced. The difference between the actual PV voltage and this reference voltage is handled by the proportional-integral (PI) controller. The PI regulator makes adjustments to the duty cycle of the DC-DC boost converter so that the PV voltage remains in step with the reference value produced by the MPPT algorithm.

With the use of a PI controller, this PV control loop's transfer function is

$$G_{PI}(s) = k_{p\text{-}pv} + \frac{k_{i\text{-}pv}}{s} \tag{1}$$

You may think of the integral gain of the PV voltage controller as k_(i"-" pv), and the proportional gain as k_(p"-" pv). The integral term gets rid of the inaccurate steady-state voltage monitoring, while the proportional term makes the system more responsive in the short term. If these settings are fine-tuned, the PV system will run continuously and reach maximum power point rapidly.

Regardless of variations in temperature and solar irradiation, the PV system can stay functioning at its maximum power point with the aid of a PI-based voltage control loop and the P&O MPPT algorithm. This management method maximises the use of renewable energy sources while decreasing dependence on the utility grid. The quick charging station's main power source might perhaps be the PV system due to this. Maintaining DC bus stability with consistent photovoltaic voltage regulation is helpful for controlling grid-interlinking converters and electric vehicle charging.

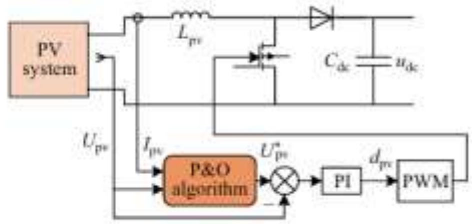

Fig.4 The control block of the PV system.

B) Controller for the Charge Point (CP)

Each charge point (CP) controller in the proposed fast charging station uses a modified droop control method to dynamically regulate the power used to charge electric automobiles (EVs) while maintaining consistent charging performance. A DC-DC buck converter connects each control point (CP) to the shared DC bus. The amount of current or voltage sent to charge a battery in an electric vehicle is determined by the controller of each CP. In Figure 8.7, you can see the schematic representation of the charging stages with a constant voltage (CV) and current (CC). Depending on the battery's state of charge (SOC), electric cars may be charged using continuous voltage (CV) or continuous current (CC) methods. In the first stage of charging, when the battery is low, the electric car runs in CC mode to quickly increase the charge. When the state of charge (SOC) gets close to its maximum, the charging mode switches to constant current (CV) mode to ensure the safety of the battery and avoid overcharging it.

The regulatory power allocated to each electric vehicle (EV) is continuously calculated by the Self-Regulated Algorithm (SRA) using the DC bus voltage fluctuation and the EV battery state of charge (SOC). Whenever the current charging mode is changed, the SRA generates a new reference value. It generates a reference voltage in CV mode and a reference current in CC mode. In order to keep power fluctuations to a minimum at the fast charging station, these standard values provide the ideal charging power adjustment.

The reference values of the SRA are precisely tracked by proportional-integral (PI) controllers in both charging modes. The PI regulator, while operating in CV mode, adjusts the charging voltage according to the newly referenced voltage. The transfer function of the PI controller in CV mode is

$$G_{PI\_v}(s) = k_{p\text{-}v} + \frac{k_{i\text{-}v}}{s}, \quad (2)$$

k_(i"-" v) represents the integral gain, while k_(p"-" v) represents the proportional gain for voltage control.
A PI controller also controls the charging current when in CC mode. This is equivalent to the transfer function.

$$G_{PI\_c}(s) = k_{p\text{-}c} + \frac{k_{i\text{-}c}}{s}, \quad (3)$$

The rule defines the integral gain (k_(i"-" c)) and the proportional gain (k_(p"-" c)). The charging system's smooth mode transitions, dynamic responses with minimal steady-state error, and optimal operation are all guaranteed by these regulators.
To reduce power fluctuations, the CP controller efficiently manages the power supplied to the EV charger utilising a combination of superior droop control and mode-dependent PI regulation. Because of this layout, EVs may act as variable loads, enabling DC buses to operate continuously without endangering charging efficiency or battery life. Consequently, the suggested CP controller is critical for the fast charging station's constant operation without ESS.

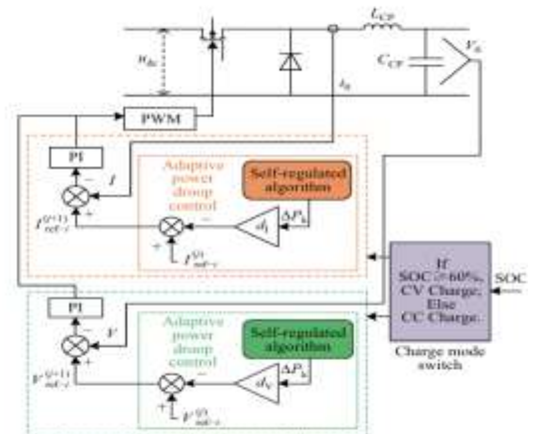

Fig.5 Charging modes for CC and CV are controlled by this block.

Figure 5 shows the charge point's (CP) internal control architecture for CC and CV charging, which incorporates improved droop-based self-regulation. Connecting the CP to the common DC bus is a DC-DC buck converter that includes a freewheeling diode, an inductor L_CP, a capacitor C_CP, and a controlled switch. Whenever an electric car is in operation, it keeps a close eye on the voltage at the output of the converter, the current flowing through the battery, and the battery's level of charge.

C) Controller for Multiple Grid-Interlinking Converters (GICs)

The grid-interlinking converters (GICs) control block diagram is depicted in Figure 8. In order to keep the DC bus voltage constant and the grid operation consistent, a GIC controller mainly regulates the power transmission from the utility grid to the fast charging station (FCS). In order to maintain stable operation, equitable allocation of power, and prevent system instability, a coordinated control mechanism is necessary when numerous GICs are operating simultaneously.
Creating the GIC controller allows for the stabilisation of both the AC grid and the DC bus at the same time. Maintaining a constant output voltage relative to the common DC bus voltage is essential for accurate voltage control and equitable power distribution across converters. Also, when using converters in conjunction, you must make sure that any circulating currents that may be created by incompatible control settings or switching activities between the converters are eliminated. Potentially impacted by these currents include losses, thermal stress, and system dependability.
Every GIC uses a dual-loop control system to accomplish these goals. An inner loop regulates the current (AC) while an outside loop controls the voltage (DC). The reference current is accurately and rapidly tracked by the inner loop, while the DC bus voltage and GIC reference current are regulated by the outside loop.

The DC bus voltage is compared to the reference DC voltage in the outer DC voltage control loop. This voltage error is handled using a proportional-integral (PI) controller. Provided by it is its transfer function.

$$G_{PI\_dc}(s) = k_{p\text{-}dc} + \frac{k_{i\text{-}dc}}{s}, \quad (4)$$

where the integral gain is denoted by k_(i"-" dc) and the proportional gain by k_(p"-" dc) of the DC voltage controller. In order to keep the DC bus

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voltage constant and avoid power imbalance, this controller produces the reference current that is required. As a component of this loop, the adaptive droop mechanism ensures that multiple GICs distribute power correctly and that converters may be smoothly switched on and off in response to changes in operating circumstances.

To guarantee that the converter's output current is in perfect sync with the reference supplied by the outer loop, the AC-side current of the GIC is regulated by the inner current control loop. The transfer function, as implemented by PI controllers, is used in this loop.

$$G_{PI\_g}(s) = k_{p\text{-}g} + \frac{k_{i\text{-}g}}{s}, \quad (5)$$

in the present controller, k_(p"-" g) represents incremental gains and k_(i"-" g) represents absolute gains. Due to its larger bandwidth, the inner loop may respond dynamically far more quickly than the outer loop, mitigating disruptions such as unexpected spikes in demand or oscillations in the grid.

In order to maintain a steady DC bus voltage, precise power distribution, and seamless interaction with the utility grid, the suggested GIC controller splits current management and voltage regulation into two interconnected loops. Optimising converter utilisation, decreasing circulating currents, and increasing system efficiency may be achieved by operating several GICs in parallel using adaptive droop control. As a result, the DC fast charging station may operate efficiently even in the absence of ESS, and the suggested controller increases system dependability while also accounting for high power fluctuations.

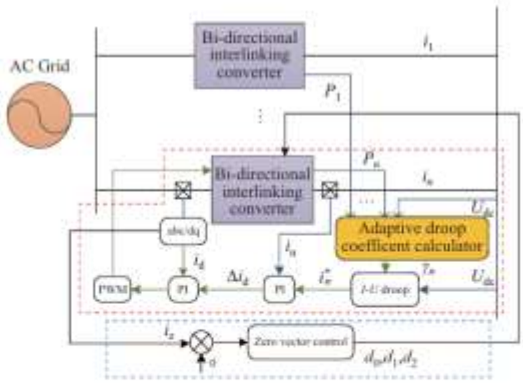

Fig.6 Multiple GICs' control blocks.

Figure 6 shows the control framework that coordinates various bidirectional grid-interlinking converters (GICs) with the AC utility grid and the common DC bus. Fast charging stations are made possible by this. Keeping the DC bus voltage constant, distributing power proportionally, and preventing circulating currents are the goals when many converters are running in parallel.

V. PROPOSED FUZZY LOGIC CONTROLLER

To use the fuzzy method, one must follow these three simple procedures.

(1) Level of input,
(2) Stage of processing,
Thirdly, the Stage of Output.

The input process of the fuzzy controller gets feedback from the error signal. In order to reduce the error signal, membership and truth values are used throughout the processing step. Here, the output volume is defuzzified, and the output stage becomes the regulated, defined output value. There are four parts to the configuration of the fuzzy-based logic controller:

(1) Not enough explanation.
2) The Groundwork of Law
Method of inference
4. Detangle.

The PI controller is now the most often used controller in industrial applications due to its low cost, simplicity of design, and simple form. Despite these benefits, the PI controller is ineffective with highly non-linear and unpredictable objects. This makes developing a fuzzy logic controller more easier while yet retaining the advantages of a PI-style control system. The outcome of the control in this case is

$$K_p \Delta u_f + k_i \int e \, dt \quad (6)$$

which are the same as the traditional PI controller and stand for the FLC output (kp and ki).

Fuzzification

The term "fuzzification" refers to the process of combining input variables with fuzzy variables. Each fuszified variable has a membership function associated with it. The inputs of a fuse controller are the error and derivative error, and the output and inputs are floated by three sets of fluids: P for positive, Z for zero, and N for negative. You may see this setup in Figure 8.9.

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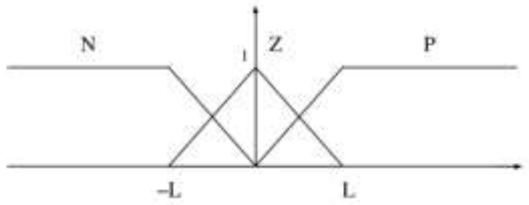


Fig.7 Fuzzy controller membership functions.

Feature of membership in the positive set

$$\mu_p(x_i) = \begin{cases} 0 & xi < 0 \\ \frac{xi}{L} & 0 \leq xi \leq L \\ 1 & xi > L \end{cases}$$

By "xi," we mean the fuzzy inputs that the controller receives. One of the member's downsides is

$$\mu_N(x_i) = \begin{cases} 1 & xi < -L \\ \frac{-xi}{L} & -L \leq xi \leq 0 \\ 0 & xi > 0 \end{cases} \quad (7)$$

Additionally, there is no membership feature set:

$$\mu_Z(x_i) = \begin{cases} 0 & xi < -L \\ \frac{xi+L}{L} & -L \leq xi \leq 0 \\ \frac{-xi+L}{L} & 0 < xi \leq L \\ 0 & x_i > L \end{cases} \quad (8)$$

Inference

The control decisions are informed by the changeable factors. Specifics act as roadmaps, informing production decisions. The controller's ruleset is shown in Table 1. The degree of membership for the output variables is determined using the min-max inference. See this here. Another suggestion was a fuzzy controller. Make an attempt.

Table 1: Fuzzy Controller Rule Base

$\dot{e}[k]$	$e[k]$ $\Delta u_f[k]$		
	N	Z	P
N	N	N	Z
Z	N	Z	P
P	Z	P	P

Defuzzification

The fuzzy inference technique requires you to alter its output variables before you can get numerical results. Fuzzy controller output is obtained by combining the universal defuzzifier with the Zadeh operating principles:

$$\Delta u_f(k) = \frac{\sum_{i=1}^{9} \mu c(\mu f)\mu f}{\sum_{i=1}^{9} \mu c\,(\mu f)} \quad (9)$$

One tool in dynamic control is fuzzy logic. A multi-rules technique is used to examine and resolve a variety of criteria. In the last ten years, fuzzy MPPT has become more popular. Tolerance for non-linearity, operation with faulty inputs, and absence of need for a correct mathematical model are a few of the many benefits of fuzzy logic controllers. Using Simulink, the graphic depicts a Fuzzy MPPT model with a single output and two inputs. An input to FLC is the error (E), and an output is the change of error (CE). An output variable might be anything like a duty cycle (D). Because of this, fuzzy control algorithms may outperform more traditional approaches to monitoring both linear and nonlinear loads. Nonlinear control is another area where fuzzy logic shines since it is not dependent on complicated mathematical formulae. The organisation of the membership functions inside the rule base is one of the several factors that impact the conduct of an FLC.

The Fuzzy Logic Tool Box in MATLAB is used to generate the rule base and membership functions. Figure 7.10 shows the membership function visually in an error-oriented way. Figures 7.11 and 7.12 show the duty cycle and change of error, respectively, of the fuzzy logic controller.

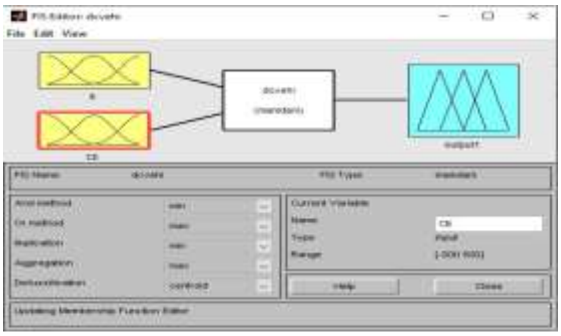


Fig.8 Applying Fuzzy Logic to Simulations

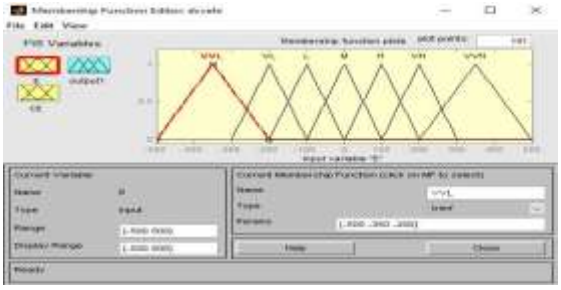


Fig.9 The input error of fuzzy logic (E)

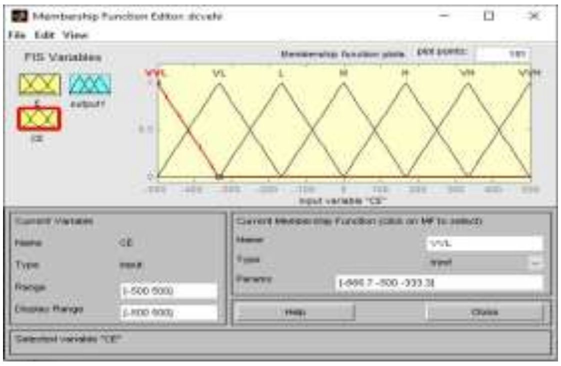


Figure 10: Fuzzy Logic Input Mistake Correction

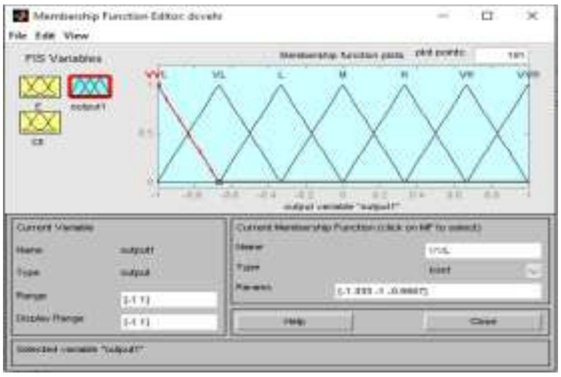
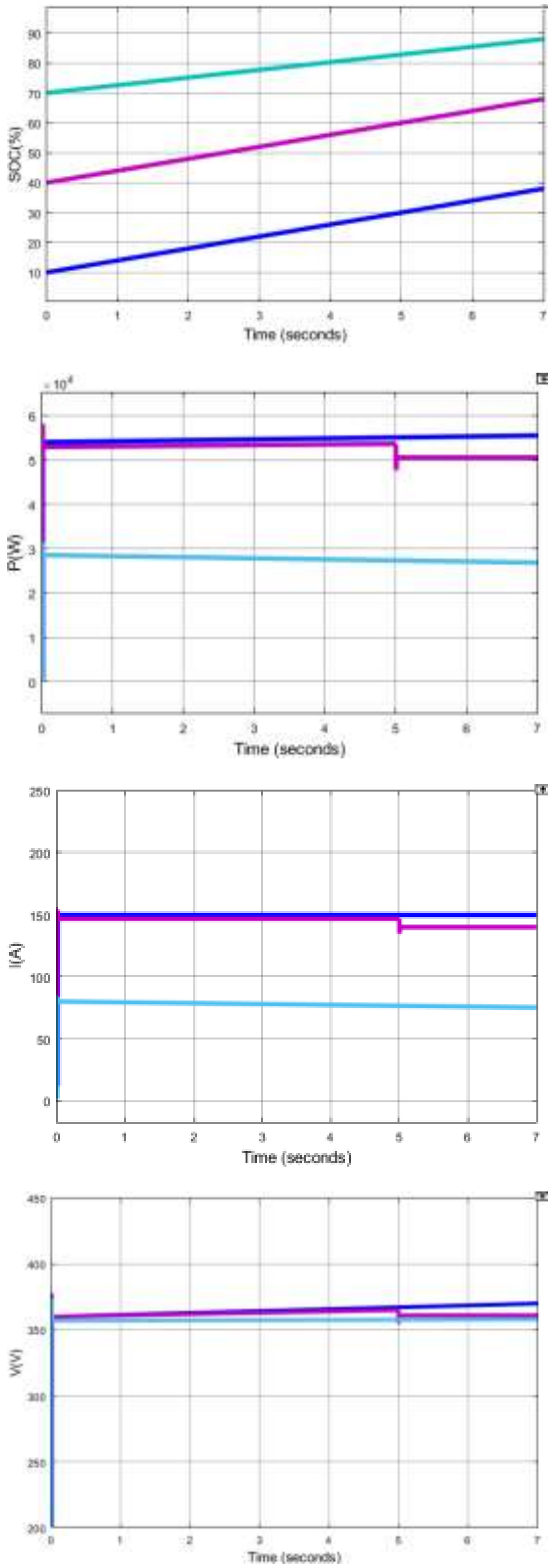


Fig.11 The output of fuzzy logic (D)

A visual depiction of the error signal, a representation of the change in the error signal, and a representation of the duty cycle are all given by the membership function. When setting up fuzzy logic controllers, we tried out a few different subset numbers. For this round, we used seven categories based on 49 factors. Tuning the 49 rules to improve responsiveness and accuracy takes effort, but the payoff is substantial.

VI. SIMULATION RESULTS

A) EXISITNG RESULTS (PI CONTROLLER)



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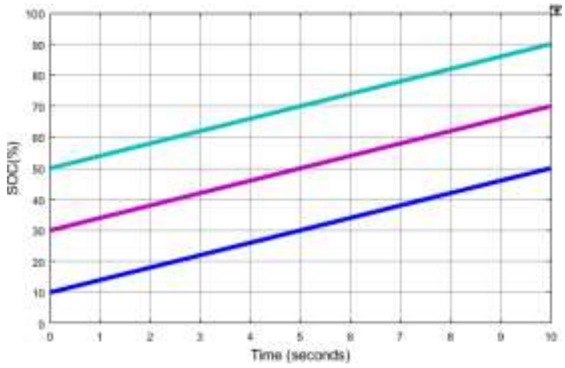
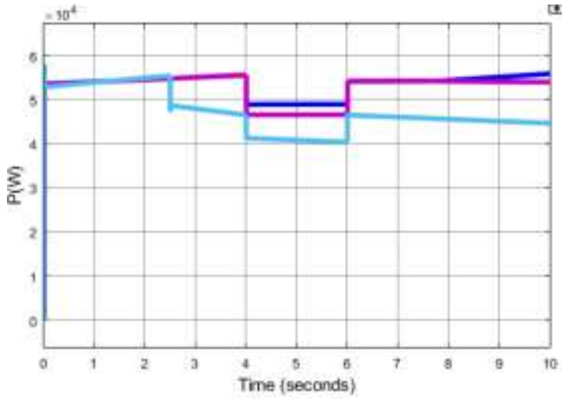
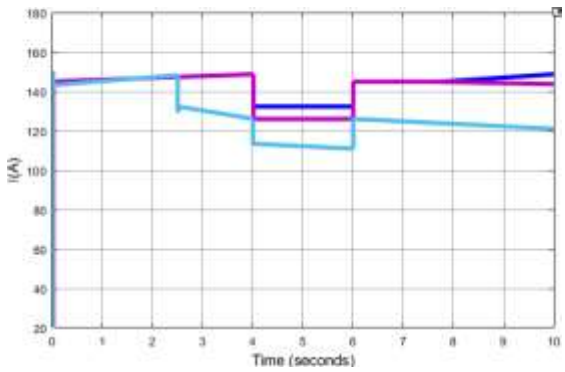
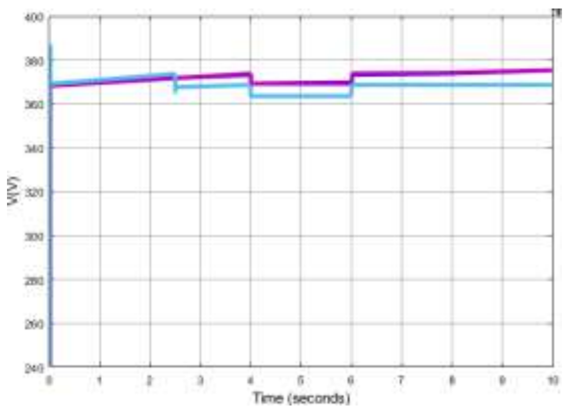


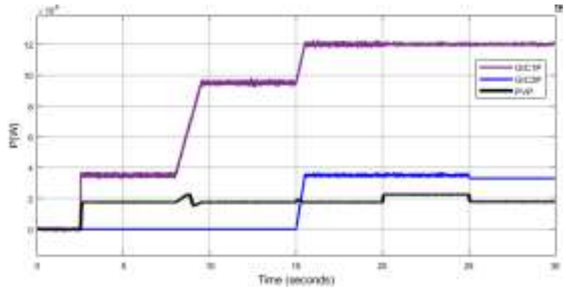






(b)

Fig.12 Charging curves for electric vehicles in a normal condition (b) Fluctuations in power in a curve situation.



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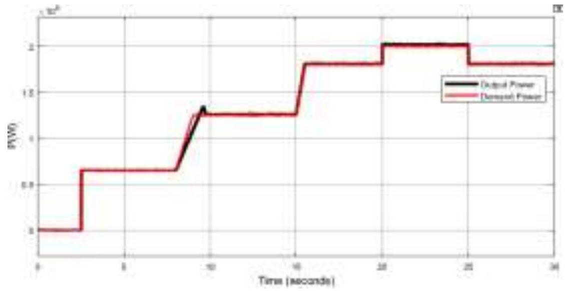

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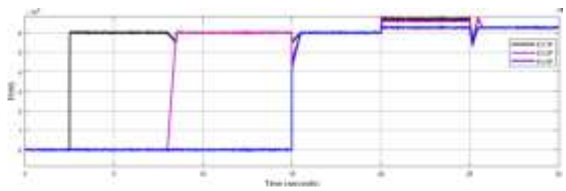
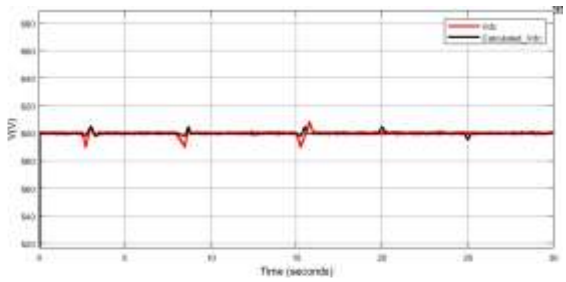


(c)



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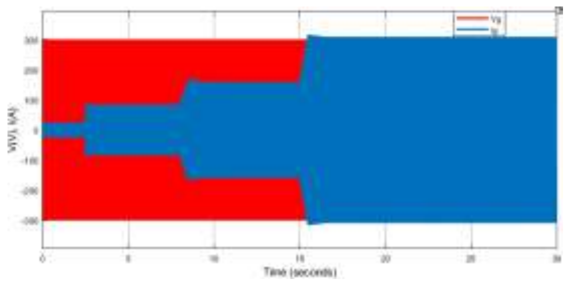

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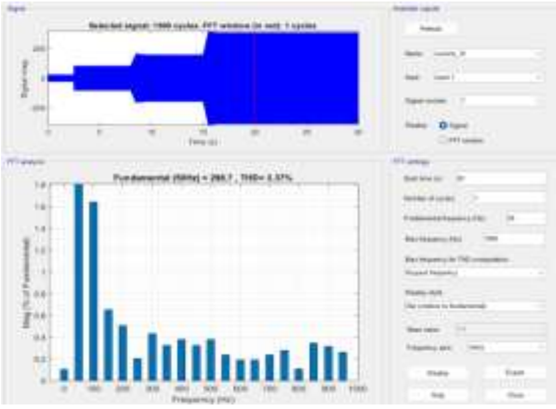
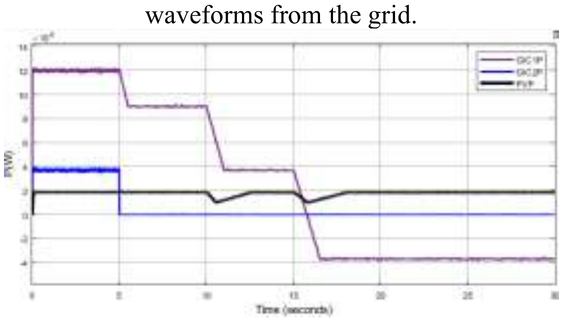


(e)

Fig.13 Photovoltaic (PV) system power profile with GICs—simulation results (b) the system's electrical output and the amount of power required by EVs. The energy consumption pattern of charging an electric car (c). (d) How the voltage on the DC bus reacts. (e) Phase-A voltage and current waveforms from the grid.



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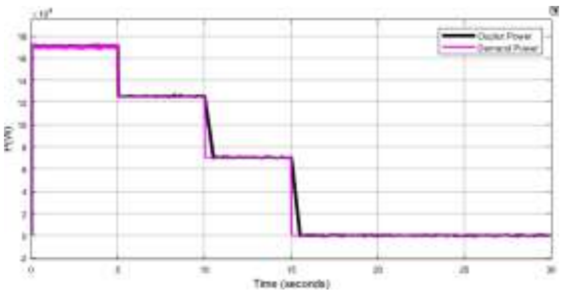

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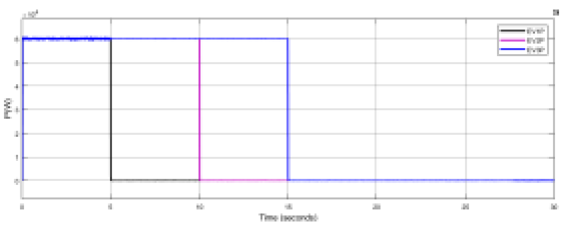

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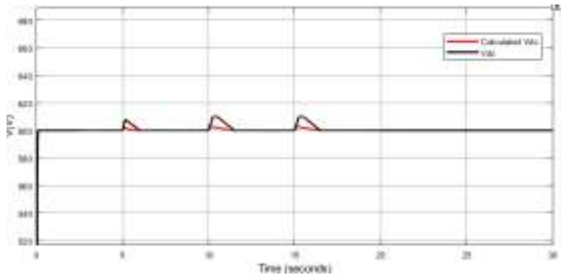

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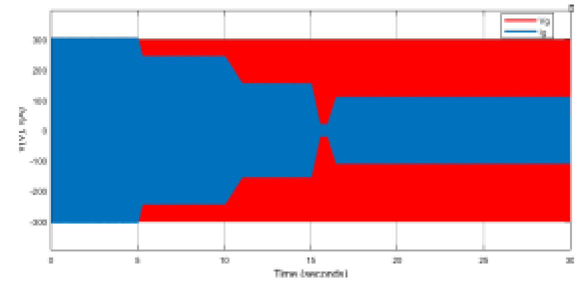

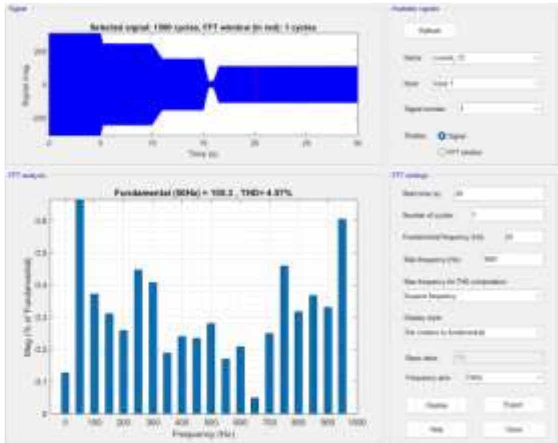

(e)

Fig.14 The results of the simulation with the GICs unplugged, which illustrates the power profile of the PV system. (b) the system's electrical output and the amount of power required by EVs. The energy consumption pattern of charging an electric car (c). (d) How the voltage on the DC bus reacts. (e) Phase-A voltage and current waveforms from the grid.

B) EXTENSION RESULTS (FLC CONTROLLER)

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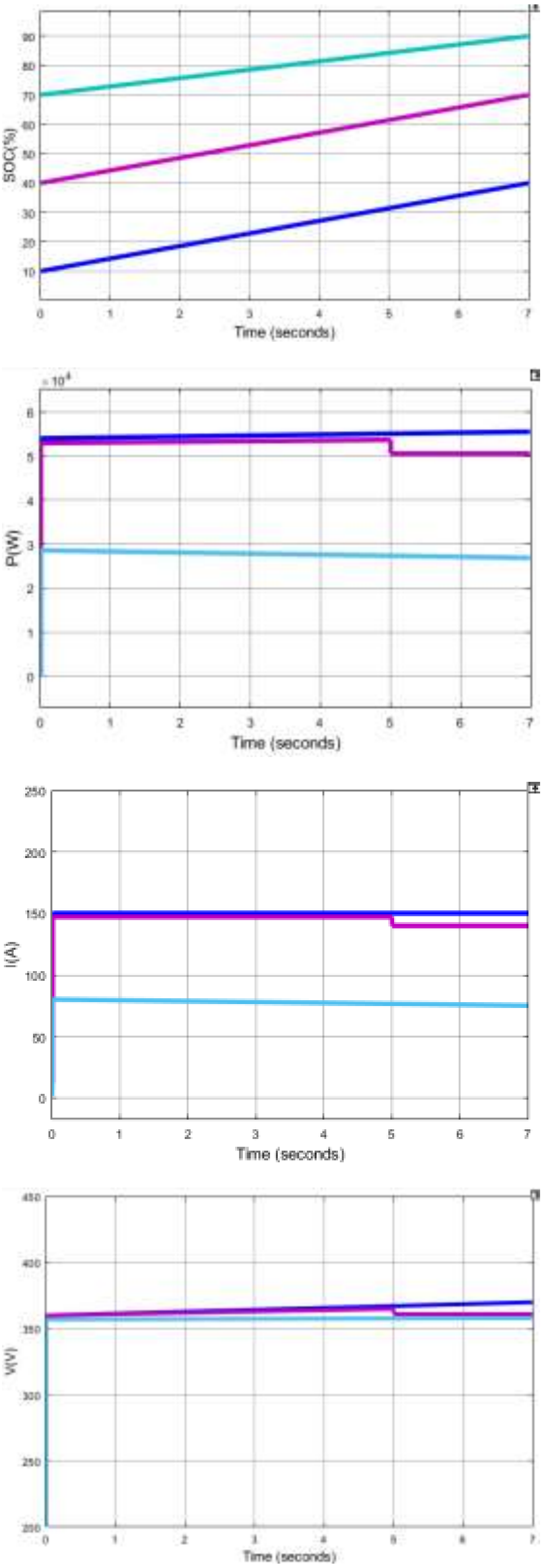

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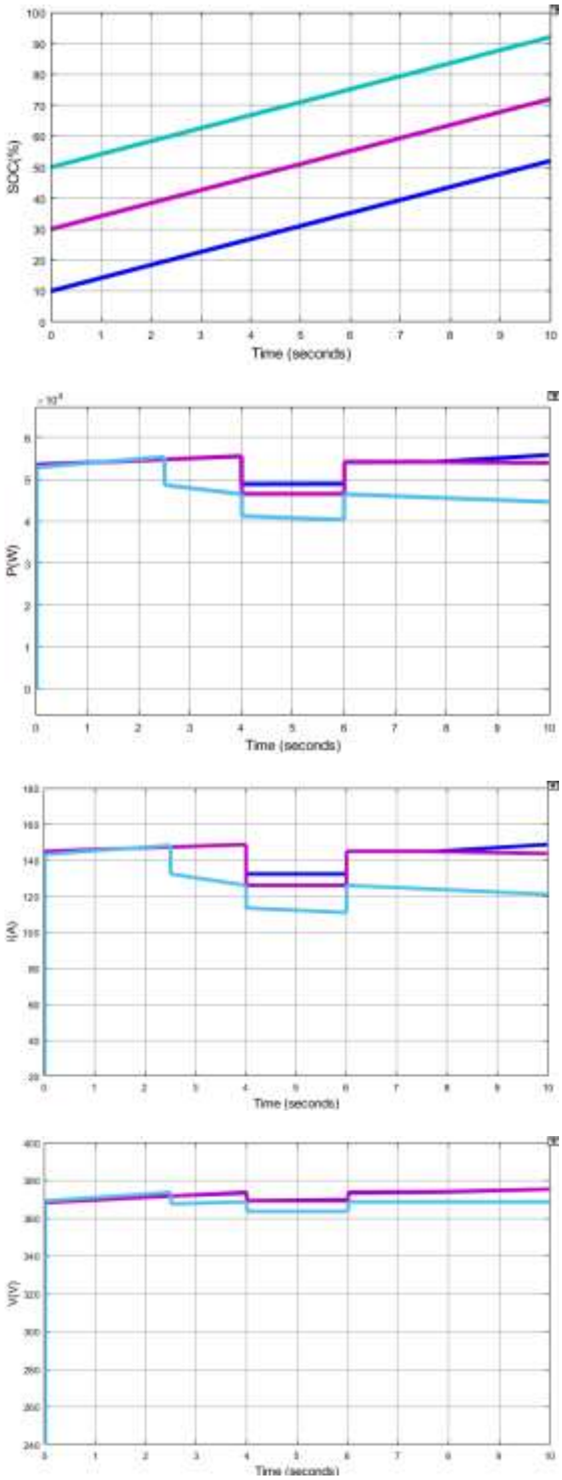

(b)

Fig. 15. Charging curves for electric vehicles in a normal condition. (b) Fluctuations in power in a curve situation.

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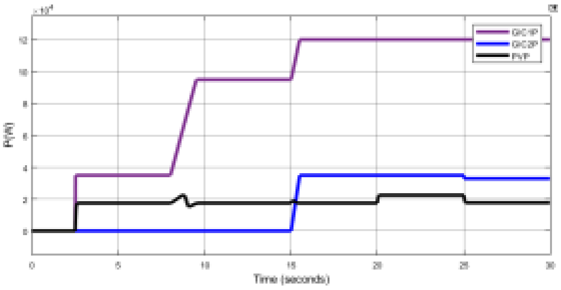

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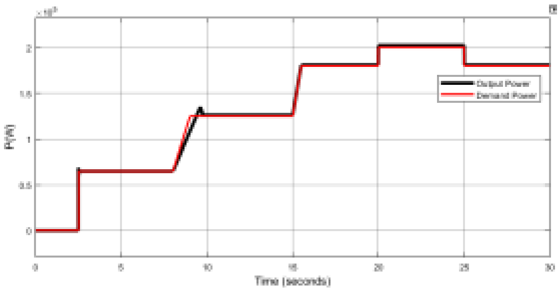

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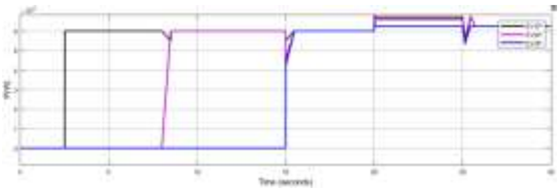

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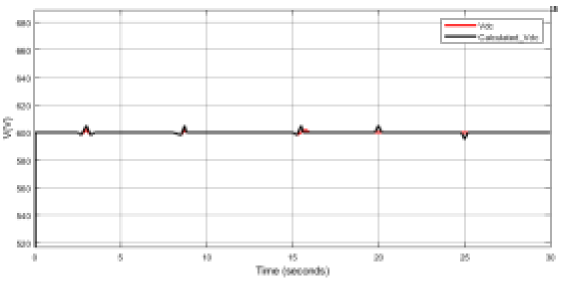

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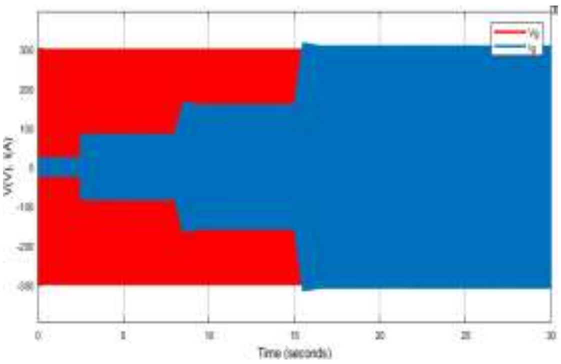
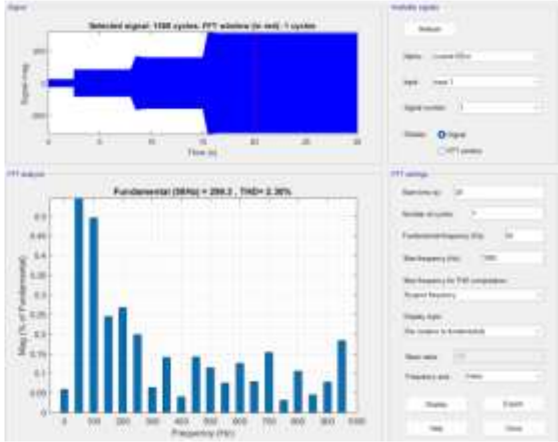
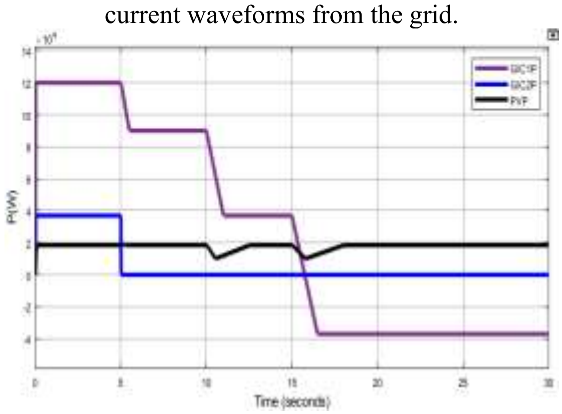




(e)

Fig.16 A result of the simulation, which shows the power profile of the PV system with GICs. (b) the system's electrical output and the amount of power required by EVs. The energy consumption pattern of charging an electric car (c). (d) How the voltage on the DC bus reacts. (e) Phase-A voltage and current waveforms from the grid.



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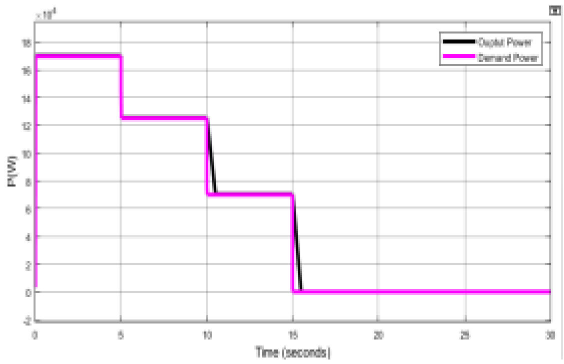

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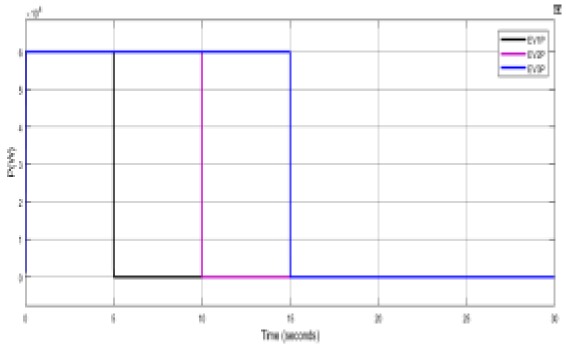

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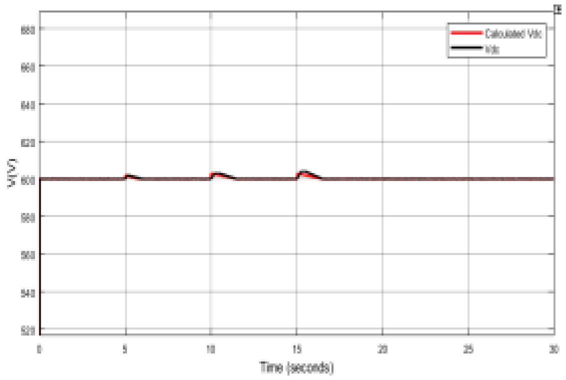

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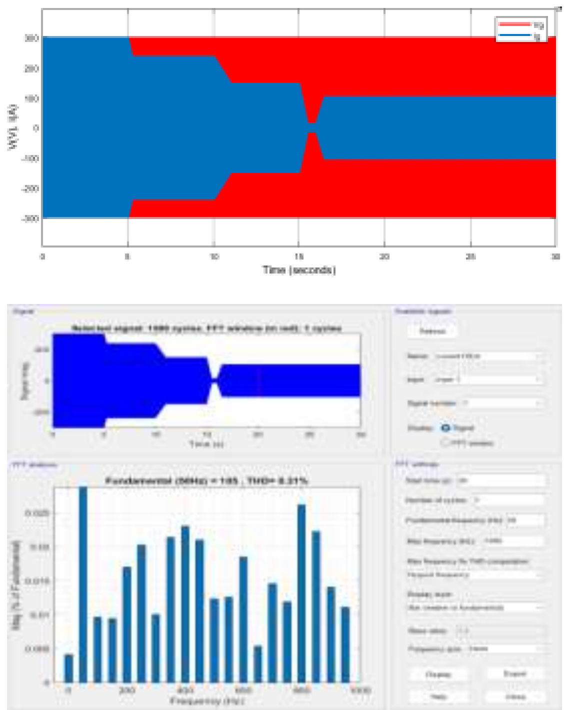

(e)

Figure 17: The simulation results illustrate the power profile of the PV system without GICs. (b) the system's electrical output and the amount of power required by EVs. The energy consumption pattern of charging an electric car (c). (d) How the voltage on the DC bus reacts. (e) Phase-A voltage and current waveforms from the grid.

CONCLUSION

The proposed ESS-free DC fast charging station uses an intelligent charging technique based on field-level coupling (FLC) to increase grid interface converter (GIC) utilisation and minimise system cost. This method effectively controls power variations caused by variable PV output and erratic EV charging demand. The Fuzzy Logic Controller dynamically changes the power utilised to charge electric cars (EVs) based on essential system variables such as DC bus voltage, PV power availability, and EV state-of-charge (SOC), ensuring stable operation and efficient power sharing. An energy storage system (ESS) is not necessary for the adaptive control capabilities of the proposed FLC, which enhance converter utilisation and enable reliable coordination of the PV source, grid support, and electric vehicle charging loads. The results of the simulation show that the proposed method effectively maintains voltage stability, maximises the utilisation of renewable energy, and guarantees uninterrupted charging performance.Even though ESS removal significantly reduces infrastructure cost and maintenance complexity, the existing FLC-based charging system still has its limitations. Models for electric vehicles (EVs) are too simplistic, they don't account for charging demand data in real-time, and they don't take vehicle-to-grid (V2G) capabilities into account.

The topics that will be the subject of future research include integrating traffic-aware and real-time electrical data for improved charging optimisation, including V2G capabilities, and taking diverse EV battery qualities into account for more realistic system analysis. These enhancements will make the system smarter, more operationally flexible, and more adaptable, which will help with the actual installation of large-scale DC fast charging stations that don't use ESS.

COMPARSIOIN TABLE

Parameter	PI (GICs Connected)	Fuzzy (GICs Connected)	PI (GICs Disconnected)	Fuzzy (GICs Disconnected)
DC Bus	±18 V	±5 V	±24 V	±8 V

Voltage Ripple				
Settling Time (s)	0.45	0.18	0.52	0.24
Overshoot (%)	8.2	2.1	10.4	3.5
Current THD (%)	3.37%	2.30%	4.57%	0.31%
Charging Efficiency (%)	90.5	96.2	88.4	94.5

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