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Development and Analysis of a NN-Based Controller for Enhancing Power Quality in EV Charging Station

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Abstract*: This paper presents development and analysis of a Neural Network (NN) controller for a PV-based Electric Vehicle charging station aimed at improving power quality. The charging station (CS) operates in grid-connected and standalone modes, incorporating bidirectional power flow to support both G2V and V2G operations. Replacing the conventional PI controller with an NN controller enhances system adaptability and dynamic response under varying grid and PV conditions. The NN controller is trained to optimize voltage regulation, reactive power compensation, and harmonic current mitigation, ensuring compliance with IEEE-519 standards for Total Harmonic Distortion (THD). Simulation results validate the proposed control strategy, demonstrating reduced THD, faster response to transient events, and improved charging/discharging efficiency. This innovative approach advances an integration of electric vehicle charging infrastructure with renewable energy systems, promoting sustainable energy solutions while maintaining robust grid interaction*

Keywords: Photovoltaic System, Grid, Power Quality, Electric Vehicle Charging Station, Battery, Voltage Source Converter, Neural Network Controller

I. INTRODUCTION

The growing implementation of EVs has led to a growing demand for sustainable and efficient charging infrastructure. Traditionally, EV batteries are charged using grid power, which often results in challenges like increased load on the grid and limited reactive power support [1-3]. Integrating RES such as solar PV systems with EV charging stations addresses these challenges by reducing grid dependency and promoting the utilization of clean energy. A PV-based EV charging station offers dual advantages: charging EVs with renewable energy and supporting the grid during peak demand through vehicle-to-grid (V2G) operations [4-6].

Power quality plays a crucial role in ensuring reliability and efficiency of these systems. Factors such as voltage imbalance, harmonic distortion, and fluctuating PV generation can degrade system performance and grid interaction [7, 8]. The existing control strategies for PV-based charging stations, like the Proportional-Integral (PI) controller, offer satisfactory operation under steady-state conditions. However, their performance often deteriorates under dynamic grid and PV conditions due to their limited adaptability to non-linearities [9-11]. This creates a need for advanced control techniques that can handle such complexities while ensuring compliance with standards like IEEE-519 for Total Harmonic Distortion (THD).

In recent years, artificial intelligence techniques, particularly NN, have gained significant attention for their ability to model and control non-linear systems. NN controllers are data-driven and can adapt to varying system conditions, making them ideal for PV-based EV charging stations [13-15]. By replacing the traditional PI controller with an NN controller, the system's adaptability to dynamic operating conditions can be enhanced, leading to better voltage regulation, reduced harmonics, and improved reactive power compensation. Moreover, NN controllers can optimize the

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charging and discharging operations of EV batteries, ensuring efficient energy utilization while maintaining grid stability [16-18].

This paper proposes a novel control strategy for a PV-based electric vehicle charging station by introducing an NN controller in place of the conventional PI controller. The charging station functions in both standalone and grid-connected modes, enabling smooth power transfer between photovoltaic system, electric vehicle battery, and grid. The proposed NN controller is designed to regulate a voltage, mitigate harmonic distortion, and provide reactive power support under various operating conditions, including grid voltage fluctuations and PV insolation variations.

Simulation studies are conducted to validate performance of proposed NN-based control strategy. The results demonstrate the NN controller outperforms the PI controller by achieving lower THD, faster transient response, and improved power quality. The charging station is also capable of bidirectional power flow, supporting G2V and V2G operations, which further enhances its functionality and flexibility.

The organization of the following paper contains: Section II provides a comprehensive system description. Section III introduces the proposed method, focusing on the implementation of the ANN controller for enhanced voltage regulation. In Section IV, the simulation results and discussions are presented, demonstrating a performance of proposed method under several operational conditions. Finally, Section V concludes the paper with key findings and suggests avenues for future research.

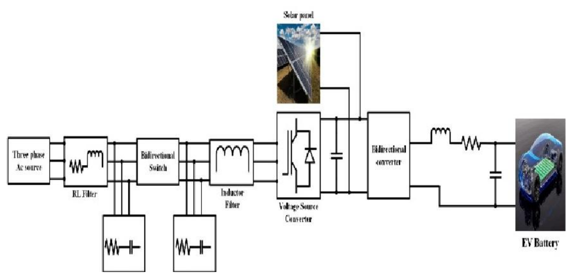

Fig.1 Block diagram

II. SYSTEM DESCRIPTION

The configuration comprises a solar PV array, a DC-link capacitor, a bidirectional dc-dc converter, and a VSC as shown in the figure.1. The system supports bidirectional power flow, enabling both G2V and V2G operations [19, 20]. It operates in grid-connected mode under normal conditions and seamlessly transitions to standalone mode during grid failures.

The Photovoltaic array is directly connected to DC-link, eliminating need for an additional boost converter, which simplifies the system and lowers costs. The DC-link serves as the interface between photovoltaic system, electric vehicle battery, and VSC [21-23]. A bidirectional dc to dc converter manages charging and discharging of EV battery, ensuring efficient energy flow. The VSC facilitates conversion of DC power to AC for grid integration and provides reactive power compensation to maintain grid stability.

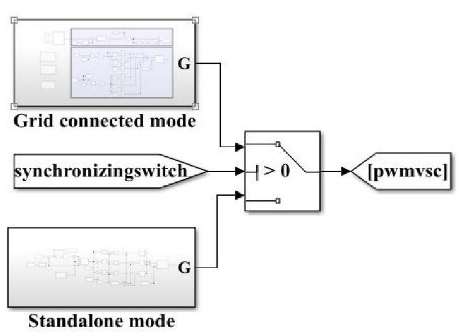

Figure.2 controlling topology

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A) Voltage Source Converter (VSC) Control

The seamless operation of photovoltaic-based EV CS in grid-connected mode. Its primary function is to regulate exchange of active and reactive power between CS and grid. The VSC operates based on two key inputs: the active power reference command (Pref) and the reactive power reference (Qref). The Pref determines whether EV battery is in charging G2V or discharging V2G mode, allowing the system to adapt to operational needs dynamically. Meanwhile, reactive power command, Qref, governs a reactive power compensation required to maintain grid stability, addressing issues such as voltage sags and phase imbalances.

To achieve precise control, the system calculates reference grid currents using unit components of terminal voltages. These templates are designed to align with the grid phase voltages, ensuring synchronized current injection. A hysteresis current controller is employed to track these reference currents. This controller dynamically adjusts the VSC's gate pulses, minimizing the error between actual and reference currents. By operating in this manner, the VSC ensures sinusoidal grid currents, reduced harmonic distortion, and a near-unity power factor, contributing significantly to overall power quality improvement and the control topology is depicted in the above fig.2.

B) Grid Synchronization

Grid synchronization is a critical component for ensuring the charging station operates effectively under varying grid conditions. The synchronization control strategy allows the system to transition seamlessly between grid-connected and standalone modes. This is particularly important during events such as grid failures or voltage fluctuations.

The synchronization process begins by estimating positive sequence components of grid voltage. This estimation helps in determining accurate phase angle of grid voltage (θg). Simultaneously, the phase angle of PCC voltage (θs) is measured. The difference between these two angles, referred to as the phase angle error, is processed through a PI controller. The controller minimizes this error by dynamically adjusting the system parameters, thereby aligning the PCC and grid voltages in terms of both magnitude and phase. This ensures a smooth reconnection to the grid when synchronization conditions are met.

$$upa = \frac{vpa}{Vt}, \quad upb = \frac{vpb}{Vt}, \quad upc = \frac{vpc}{Vt} \quad 1$$

$$uqa = -upb, \; uqb = upa - upc, \; uqc = upb \quad 2$$

Where Vtis the terminal voltage amplitude.

The active (Ip) and reactive (Iq) components are used to compute reference currents

$$i^*_{sa=Ip.upa+Iq.uqa}, \quad i^*_{sb=Ip.upb+Iq.uqb}, \quad i^*_{sc=Ip.upc+Iq.uqc} \quad 3$$

The active current Ipand reactive current Iq are derived from the reference active power (Pref) and reactive power (Qref)

$$Ip = \frac{P_{ref}}{\frac{2}{3}V_t}, \quad Iq = \frac{Q_{ref}}{\frac{2}{3}V_t} \quad 4$$

The grid connected mode simulation model is as shown in the below figure.3

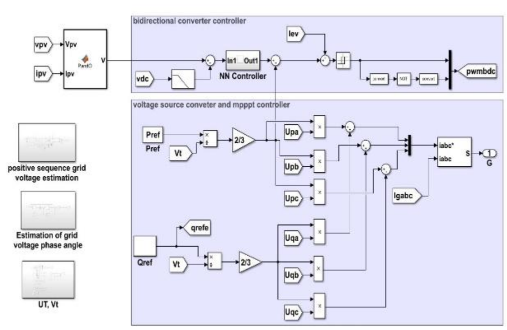

Figure.3 grid connected mode

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To generate the gate pulse from the grid connected mode, the positive sequence grid voltage estimation and the estimation of grid voltage phase angle, UT, and Vt play significant roles, as shown in the simulation models in Fig. 4, Fig. 5, and Fig. 6.

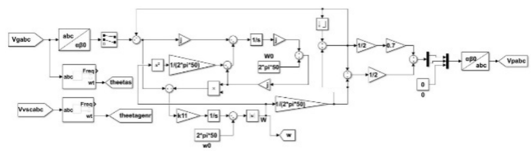


Figure.4 positive sequence grid voltage estimation

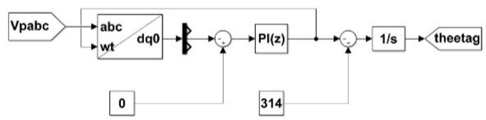


Figure.5 Estimation of grid

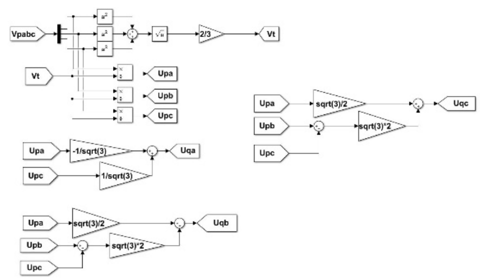


Fig.6 UT, Vt

C) Standalone Mode Control

During grid failures, the system shifts to standalone mode, ensuring uninterrupted operation. In this mode, the VSC generates sinusoidal reference voltages to maintain stable operation at the PCC. The generated reference voltages are synchronized with the grid voltage profile to avoid sudden transitions when the grid reconnects.The EV battery assumes a pivotal role in this mode by acting as an energy buffer. It is charged using the PV array's power, ensuring the DC-link voltage remains constant despite dynamic changes in PV generation. The VSC ensures that the power supplied to the EV battery and any connected loads remains stable, maintaining a reliable operation in the absence of grid support.

The error between the grid (θg) and PCC phase angle (θs) is calculated as

$$\Delta\theta = \theta g - \theta s \quad 5$$

A PI controller minimizes the phase angle error to determine the new phase angle

$$\theta n = \theta s + \Delta\theta \quad 6$$

v^*sca=$V_{ts}\sin(\theta n)$, v^*scb=$V_{ts}\sin(\theta n - 120°)$, v^*scc=$V_{ts}\sin(\theta n - 240°)$ 7

The control of the standalone mode is illustrated in Fig. 7, while the synchronizing switch control topology is shown in Fig. 8. Based on both the grid-connected and standalone modes, the voltage source converter operates by receiving gate pulses for the VSC.

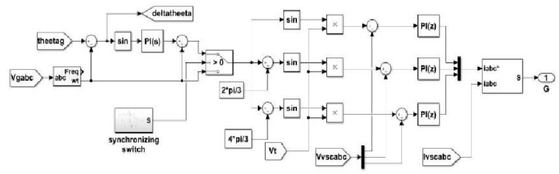


Fig.7 standalone mode

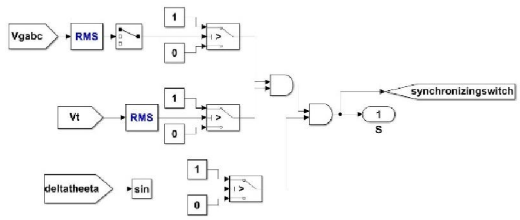


Fig.8 synchronizing switch

D) Control of a Bi-directional dc to dc Converter

The bi-directional dc to dc converter regulates discharging and charging of EV battery, facilitating bidirectional power flow between battery and DC-link to support G2V and V2G operations. It controls the battery current by regulating duty cycle of its switches based on system requirements. A proportional integral controller stabilizes DC-link voltage by processing error between reference and actual voltage. The controller's output fine-tunes the duty cycle to maintain voltage stability under varying loads or PV generation fluctuations. This ensures system reliability and extends the battery's lifespan.

III. PROPOSED METHOD

The proposed method introduces a NN-based controller to replace the conventional PI controller in a P Photovoltaic-based Electric vehicle charging station. The CS operates in both grid-connected and standalone modes, ensuring optimal power exchange between PV array, EV battery, and grid. The NN controller enhances the system's adaptability, enabling precise voltage regulation, harmonic mitigation, and reactive power compensation under varying operating conditions, including grid voltage fluctuations and PV insolation changes.

The NN controller is designed to address the limitations of traditional PI controllers, which rely on fixed gain values and struggle with non-linearities and dynamic variations. The NN is trained using system data such as grid voltages, currents, and PV generation levels to model the system's behaviour and predict control actions dynamically. By leveraging a multi-layer architecture, the NN captures complex system dynamics, ensuring faster response and greater accuracy. The controller outputs optimized signals for the VSC and bidirectional dc to dc converter, ensuring smooth power exchange while maintaining DC-link voltage stability.

The NN controller is compared against PI controller under various scenarios. The results validate that NN controller significantly improves the THD, enhances the system's transient response, and ensures. This innovative approach not only optimizes the charging and discharging of EV batteries but also promotes robust grid interaction, making it a sustainable and effective solution for modern electric vehicle charging stations integrated with renewable energy systems.

Structure of ANN:

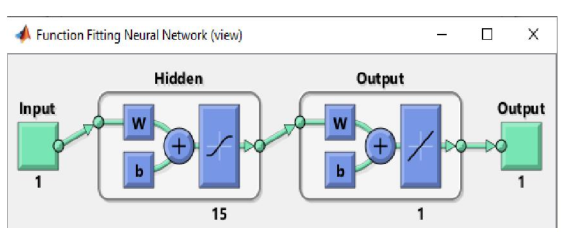


Fig. 9 Schematic diagram of NN controller

IV. SIMULATION RESULTS AND DISCUSSION

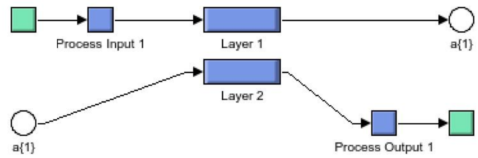


Fig.10 Internal Structure of NN Controller

The NN controller demonstrates superior performance, optimizing power flow and voltage regulation. Through intelligent learning, the NN controller adapts to dynamic system conditions, enhancing stability and efficiency. The results reveal significant improvements in grid integration, reduced harmonic distortions, and enhanced overall power quality.

Case_1

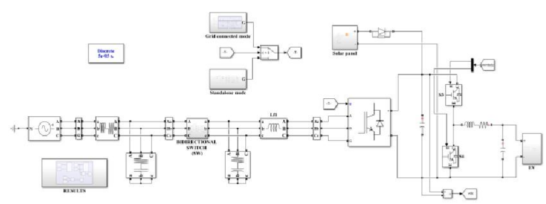
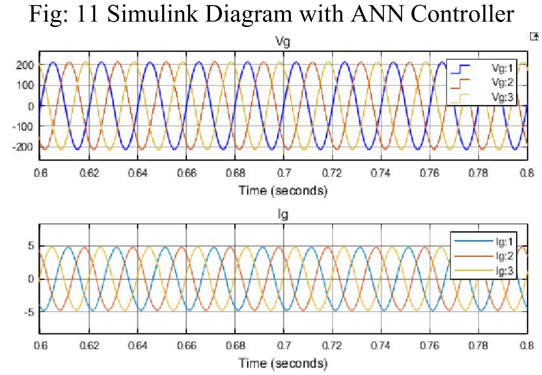
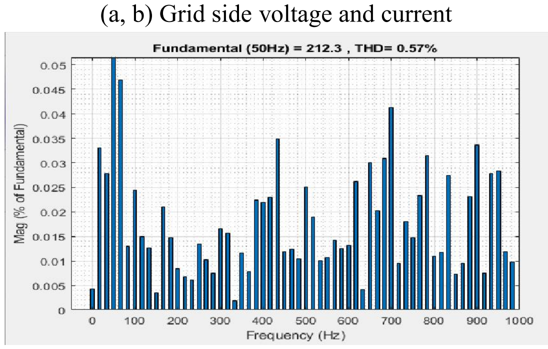


Fig: 11 Simulink Diagram with ANN Controller



(a, b) Grid side voltage and current



Vga

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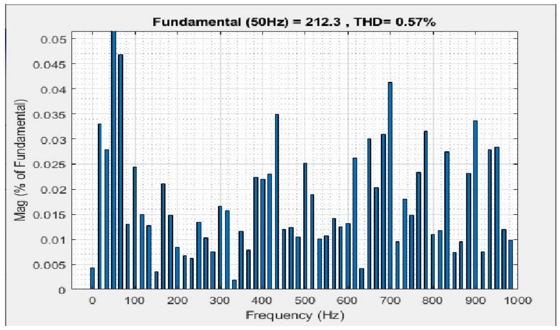
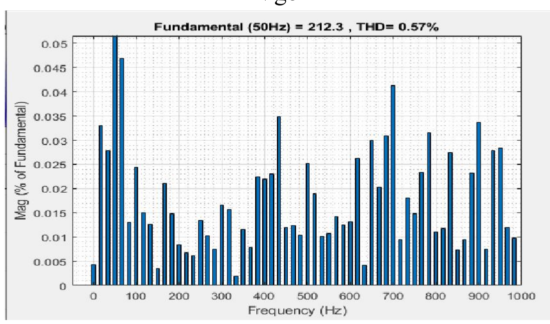
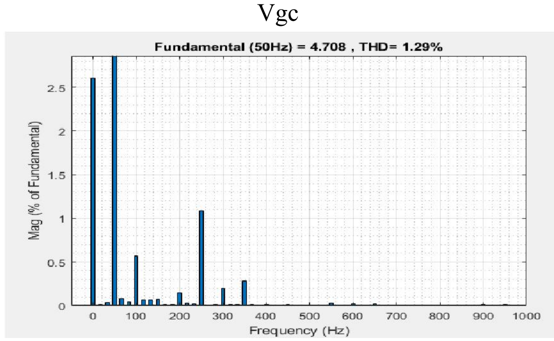


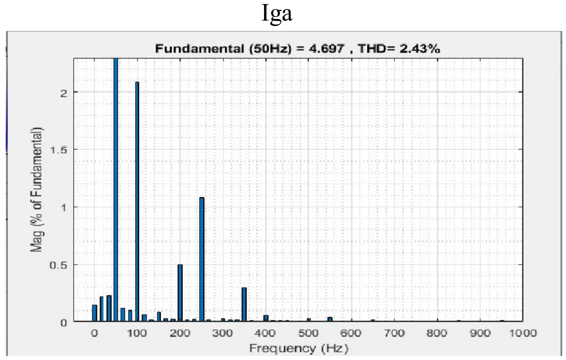
Vgb



Vgc



Iga



Igb

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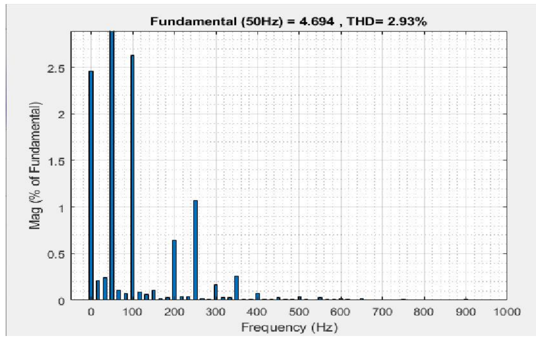

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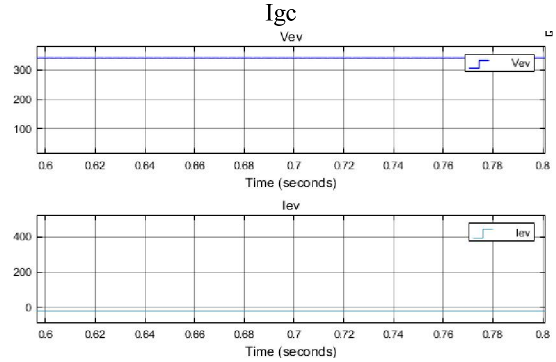
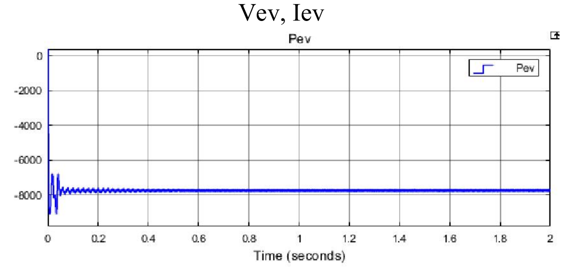
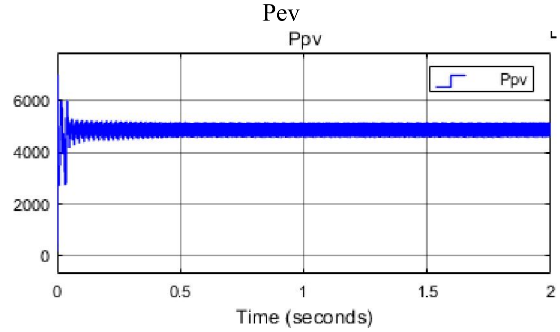


Vev, Iev



Pev



PPV

Fig. 12 Steady-State Charging Station: (a-b)

Voltage and current waveforms; (d) Harmonic spectrum of vsab; (e) Harmonic spectrum of isa; (g) PV power; (h) EV voltage (vev) and current; (i) EV power

In Fig. 12(a), the 3Ø grid voltages (213.37 V, 216.99 V, 214.70 V) and currents (4.987 A, 5.155 A, 5.072 A) exhibit balanced, sinusoidal behaviour. Fig. 12(b) shows a power factor of 0.9978 and a power contribution of 1.885 KW from the PV array to the grid. Figs. 12(c-d) reveal low total harmonic distortions (THDs) in grid voltages. Fig. 12(e) indicates minimal unbalance in grid voltages and currents. (figs. 12(f-g) present Electric vehicle voltage (289.1 V), current (5.139 A), and power consumption (1.68 kW), with negative signs for both grid and EV power indicating consumption, reinforcing the NN controller's superior performance over the PI controller.

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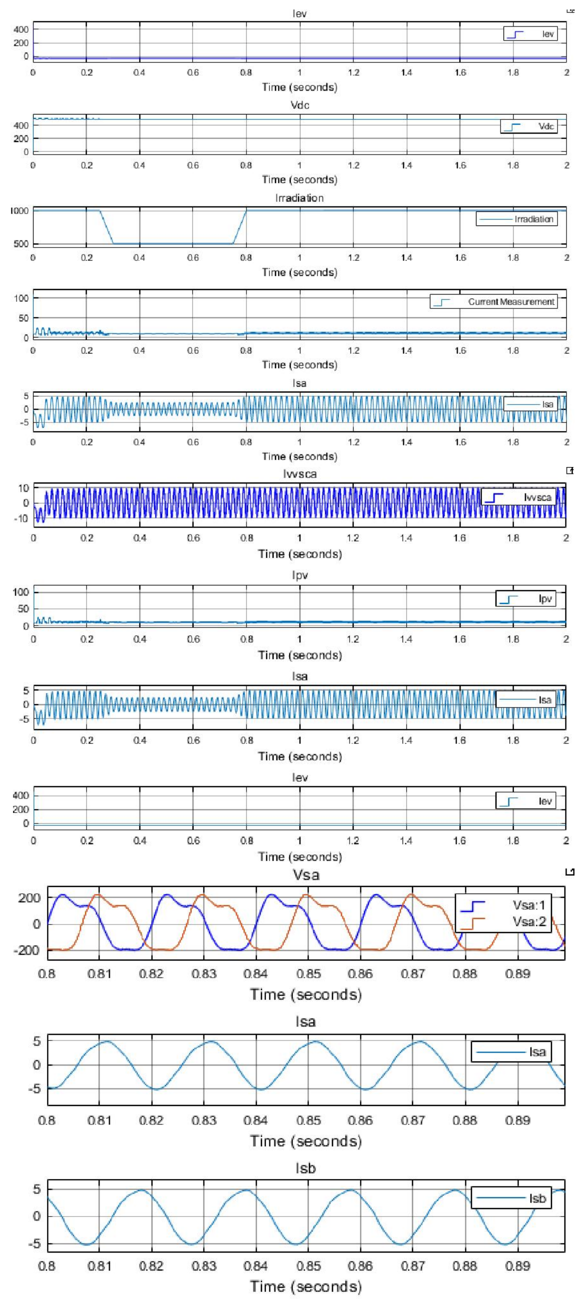
Case_2



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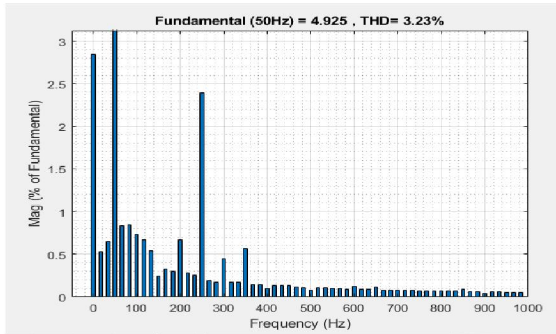
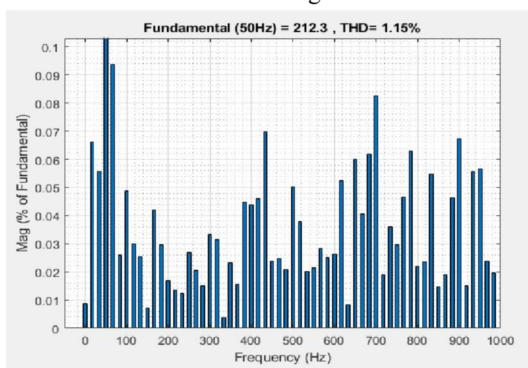


THD of Ig



THD of Vg

Fig. 13 illustrates the dynamic behaviour of the grid-connected system under: (a) an increase in solar insolation, (b) a decrease in PV insolation, (c) voltage imbalance accompanied by a rise in PV insolation, and (d) substantial fluctuations in grid voltages.

Fig. 13 illustrates charging station's performance during a decrease in Photovoltaic insolation. As PV insolation drops, power production also declines, leading to a noticeable reduction in Photovoltaic array current. However, As the EV charges at a consistent rate, the grid compensates for the reduced energy output, leading to a decrease in grid current without affecting the PV voltage, DC-link voltage, or Electric vehicle current. This indicates that the NN controller outperforms the PI controller by ensuring superior regulation and stability, even under varying insolation conditions.

Case_3

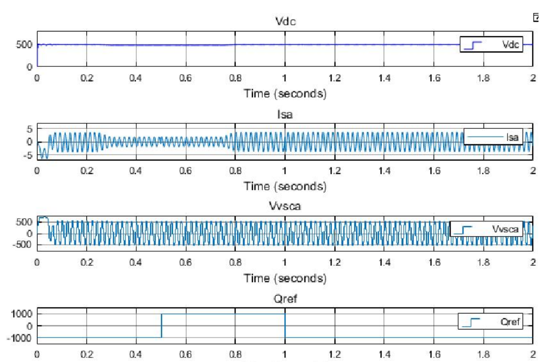


Fig. 14 CS providing reactive power assistance to grid

The CS maintains a -1 kVAR Qref while providing

Reactive power support to the grid when required. The station supplies capacitive reactive power, with grid current driving grid voltage, as seen in Fig. 14(a). Inductive reactive power, on the other hand, has a different grid current direction. The DC-link and PCC voltages don't change throughout this process. A smooth transition between 1 and -1 kVAR, where the grid current alternates between trailing and leading the grid voltage, is depicted in Fig. 14(b). This

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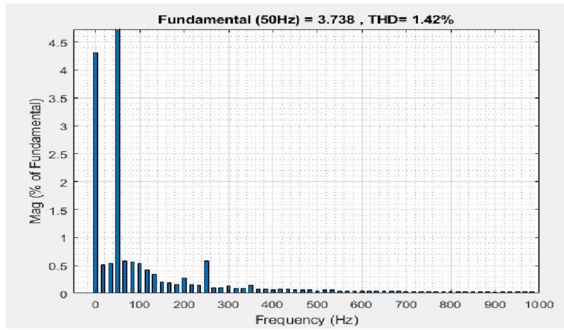
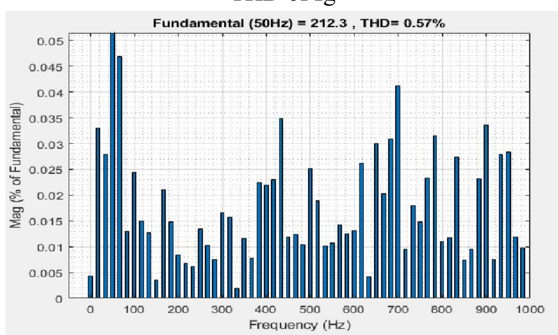
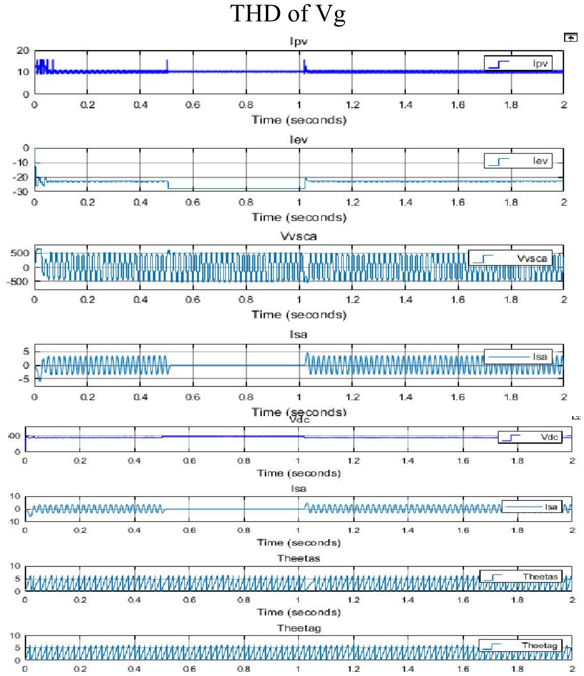
indicates that the station can effectively control both capacitive and inductive reactive power, with the NN controller outperforming the PI controller.



THD of Ig



THD of Vg



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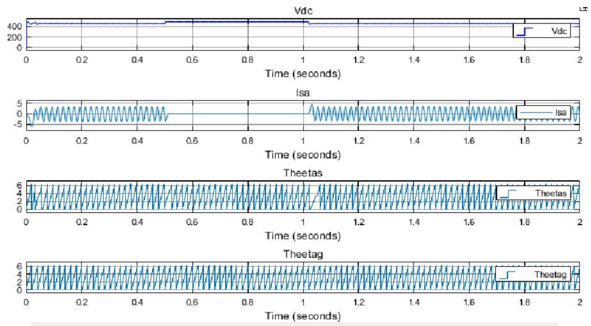
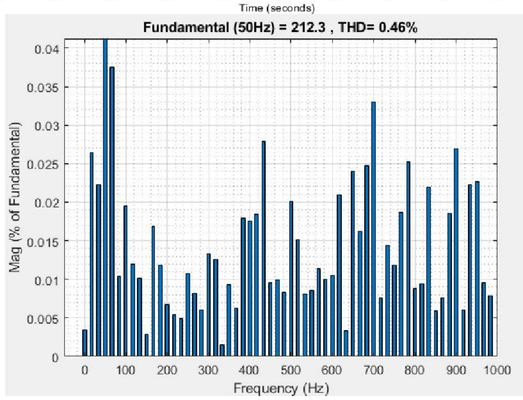
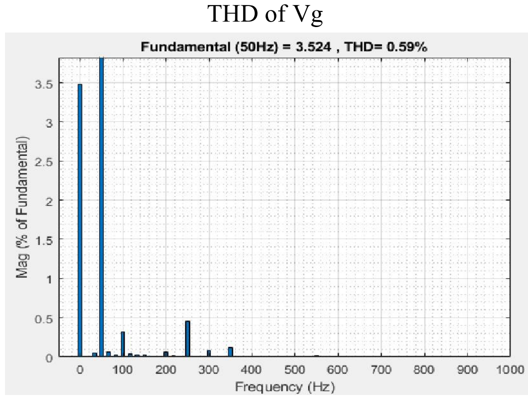




THD of Vg



THD of Ig

Fig. 15 Performance during synchronization, grid connected, islanded

Figs. 15(a-c) demonstrate charging station's operation during grid stoppage, relinking, and synchronization. When the grid disconnects abruptly, grid current and θg cease, but the PV array continues providing constant power for the EV charging. The PCC voltage remains stable in standalone mode, as shown in Figs. 15(a-b), with the VSC maintaining voltage generation at the PCC (vvsca). Once synchronization conditions are met, θg aligns with θs, enabling grid reconnection and the return of grid current (Fig. 15(c)). Throughout these transitions, the DC-link voltage remains unchanged.

V. CONCLUSION

The proposed system demonstrated enhanced performance in regulating voltage, mitigating harmonic distortion, and managing reactive power compensation. Unlike traditional PI controllers, the NN controller adapted dynamically to non-linear system behaviours and varying grid and PV conditions, ensuring seamless operation. Simulation results confirmed the NN controller's ability to significantly reduce THD, while achieving faster transient responses. The system maintained efficient power exchange between the PV array, EV battery, and grid, even during dynamic scenarios such as voltage unbalances and PV insolation fluctuations. By integrating NN control, the study highlights a

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path toward sustainable and efficient EV charging infrastructure that improves grid interaction and renewable energy utilization, advancing the scope of modern power systems.

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