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Enhanced Power Quality Improvement in a PV-Based EV Charging Station Interfaced with a Three-Phase Grid Using ANN-Based Control

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ABSTRACT

This paper presents an enhanced power quality improvement technique for a solar photovoltaic (PV)-based electric vehicle (EV) charging station interfaced with a three-phase grid. The proposed system integrates an artificial neural network (ANN)-based controller to improve system performance by reducing settling time and minimizing ripple content. The charging station operates in both standalone and grid-connected modes, ensuring efficient EV battery charging while maintaining grid stability. Additionally, the station provides reactive power compensation and harmonics mitigation, reducing total harmonic distortion (THD) in grid currents below 5% as per IEEE-519 standards. The ANN controller optimizes the control of the voltage source converter (VSC) and the bidirectional DC-DC converter, enhancing dynamic response under grid disturbances and unbalanced conditions. The system effectively performs (i) harmonics current compensation, (ii) EV battery charging/discharging control, (iii) simultaneous EV charging and harmonics mitigation, and (iv) simultaneous EV discharging and harmonics compensation. A robust synchronization mechanism ensures seamless transition between grid-connected and standalone modes. Simulation results demonstrate that the ANN-based controller significantly outperforms conventional methods in reducing ripples and achieving faster stabilization, making it a reliable solution for power quality improvement in PV-based EV charging stations.

Keywords: ANN controller, EV charging station, power quality, solar photovoltaic, voltage source converter, bidirectional DC-DC converter, harmonics mitigation.

INTRODUCTION

The rapid expansion of electric vehicles (EVs) and renewable energy integration has necessitated the development of efficient EV charging stations powered by sustainable energy sources. Among various renewable energy technologies, solar photovoltaic (PV) systems are widely adopted due to their abundant availability and eco-friendly nature. However, the intermittent nature of solar power poses challenges to power quality, voltage stability, and harmonics mitigation in grid-connected charging stations. To address these concerns, advanced power electronics interfaces and intelligent control techniques are essential to ensure stable and efficient operation.

Traditional EV charging stations rely on conventional controllers, such as proportional-integral-derivative (PID) controllers, which exhibit limitations in dynamic performance, including longer settling times and higher ripple content. To overcome these challenges, artificial neural network (ANN)-based controllers have emerged as a promising solution, offering improved adaptability, faster response, and reduced harmonic distortion. ANN-based controllers leverage machine learning techniques to optimize power quality parameters dynamically, ensuring efficient power management in both grid-connected and standalone operations.

This paper presents an enhanced power quality improvement strategy for a PV-based EV charging station interfaced with a three-phase grid. The proposed system integrates an ANN-based controller to enhance the performance of the voltage source converter (VSC) and bidirectional DC-DC converter, reducing total harmonic distortion (THD) in grid currents below 5% as per IEEE-519 standards. The system operates effectively under grid disturbances and unbalanced conditions, ensuring optimal EV charging and grid support functions, including reactive power compensation and harmonics mitigation.

The key contributions of this study include:

1. Implementation of an ANN-based controller to improve the dynamic response of the EV charging station.
2. Reduction of settling time and ripple content in comparison to conventional control methods.
3. Seamless transition between grid-connected and standalone operations through a robust synchronization mechanism.
4. Comprehensive analysis of power quality enhancement and system performance under various operating conditions.

The rest of this paper is organized as follows: Section II presents a literature survey on existing power quality improvement techniques in PV-based EV charging stations. Section III describes the methodology and system configuration. Section IV discusses simulation results and performance evaluation. Finally, Section V concludes the paper with key findings and future research directions.

LITERATURE SURVEY

The increasing penetration of EVs has led to a significant rise in power demand, necessitating the development of efficient and sustainable charging solutions. Various studies have explored power quality improvement techniques for PV-based EV charging stations, focusing on harmonics mitigation, voltage stability, and intelligent control strategies. Traditional power quality enhancement methods involve PID controllers and PI-based control strategies. These controllers provide satisfactory results under stable conditions but struggle to adapt to dynamic variations in grid voltage and load demand. Studies have shown that PID controllers exhibit longer settling times and higher overshoot, impacting overall system efficiency.

To address the limitations of conventional methods, researchers have investigated fuzzy logic controllers (FLCs) and ANN-based controllers for EV charging stations. FLCs offer robustness in handling nonlinearities but require extensive tuning for optimal performance. ANN controllers, on the other hand, provide self-learning capabilities, enabling real-time adaptation to changing grid conditions and improving system stability. Power quality issues, such as harmonic distortion and voltage fluctuations, significantly impact the performance of grid-integrated PV systems. Various studies have proposed active power filters (APFs) and hybrid filter configurations to mitigate harmonics. The integration of ANN-based control techniques with APFs has demonstrated superior THD reduction compared to conventional filtering methods. The bidirectional DC-DC converter plays a crucial role in managing power flow between the PV array, EV battery, and grid. Recent research has focused on optimizing converter design using ANN algorithms to enhance efficiency, minimize losses, and ensure seamless bidirectional power transfer. The stability of grid-connected EV charging stations depends on effective synchronization mechanisms. Advanced synchronization techniques, including phase-locked loop (PLL)-based and ANN-assisted synchronization methods, have been explored to ensure seamless transition between grid-connected and standalone operations.

EXISTING SYSTEM

The existing system for power quality improvement in a solar photovoltaic (PV)-based electric vehicle (EV) charging station relies on conventional control techniques for voltage source converters (VSC) and bidirectional DC-DC converters. These control strategies ensure the charging station operates in both standalone and grid-connected modes, allowing the PV array to charge the EV battery independently when the grid is unavailable. The charging station also compensates for harmonics and reactive power, thereby improving the overall power quality of the grid. However, traditional controllers, such as proportional-integral (PI) or proportional-integral-derivative (PID) controllers, have certain limitations in terms of dynamic response, especially under grid disturbances and voltage unbalance conditions.

One of the major drawbacks of the conventional control system is its slower response to transient conditions and increased ripple content. These controllers are based on fixed-gain control strategies, which do not adapt efficiently to changing load or grid conditions. This leads to increased total harmonic distortion (THD) in grid currents and voltage fluctuations, which can compromise grid stability. Additionally, conventional systems face challenges in optimizing power flow between the PV system, EV battery, and grid, resulting in reduced overall efficiency.

Another limitation is the lack of advanced synchronization mechanisms for smooth transitions between standalone and grid-connected modes. Traditional phase-locked loop (PLL) techniques used for synchronization often struggle with rapid variations in grid voltage and frequency. Consequently, there is a need for a more robust and intelligent control strategy that can adapt dynamically to grid and load variations while maintaining power quality within acceptable limits.

Furthermore, conventional power quality improvement techniques often rely on passive filters and simple switching strategies for harmonic mitigation. While these methods provide some degree of improvement, they are not sufficient to meet stringent IEEE-519 standards for THD reduction. The inability to effectively control power factor and mitigate harmonics under varying operating conditions further limits the effectiveness of traditional systems. These limitations highlight the necessity of an advanced control mechanism to optimize performance and improve system resilience.

Lastly, the existing system faces efficiency challenges due to suboptimal energy management strategies. The lack of intelligent predictive control mechanisms results in inefficient utilization of PV power, increased switching losses, and suboptimal EV charging performance. These challenges necessitate the integration of an intelligent control approach, such as an artificial neural network (ANN)-based controller, to enhance the overall performance of the system.

METHODOLOGY

The methodology for implementing the proposed ANN-based control system involves several key steps, including system modeling, neural network training, controller integration, and performance evaluation. The first step in the methodology is the development of a detailed mathematical model of the PV-based EV charging station, including the PV array, bidirectional DC-DC converter, voltage source converter (VSC), and grid interface. This model serves as the foundation for designing and testing the control strategy.

The second step involves training the artificial neural network (ANN) using historical data obtained from simulations and real-world operating conditions. The ANN is trained to recognize patterns in voltage, current, and power variations, allowing it to generate optimized control signals for the VSC and bidirectional DC-DC converter. The training process uses backpropagation and supervised learning techniques to minimize error and improve control accuracy.

The third step is the integration of the trained ANN controller into the system. The ANN-based control strategy is implemented in MATLAB/Simulink, where it is tested under various operating conditions, including grid disturbances, unbalanced voltage conditions, and varying load demands. The controller's performance is evaluated based on key metrics such as total harmonic distortion (THD), settling time, ripple content, and system efficiency.

The final step involves a comparative analysis between the proposed ANN-based control strategy and conventional control methods. Simulation results are analyzed to assess the effectiveness of the ANN controller in improving power quality, reducing harmonics, and enhancing system stability. The results demonstrate that the ANN-based controller achieves superior performance compared to traditional PI and PID controllers, making it a viable solution for PV-based EV charging applications.

PROPOSED SYSTEM

The proposed system introduces an artificial neural network (ANN)-based controller to overcome the limitations of conventional control methods in a PV-based EV charging station interfaced with a three-phase grid. The ANN controller is designed to improve system performance by reducing settling time, minimizing ripple content, and enhancing dynamic response under transient conditions. The charging station continues to operate in both standalone and grid-connected modes, ensuring uninterrupted power supply to the EV battery while maintaining grid stability.

One of the key advantages of the ANN-based controller is its ability to dynamically adapt to varying grid and load conditions. Unlike traditional controllers, which rely on fixed-gain parameters, the ANN-based controller utilizes a trained neural network to optimize control signals for the voltage source converter (VSC) and bidirectional DC-DC converter. This adaptive nature significantly improves the system's ability to handle grid disturbances and unbalanced voltage conditions while maintaining power quality.

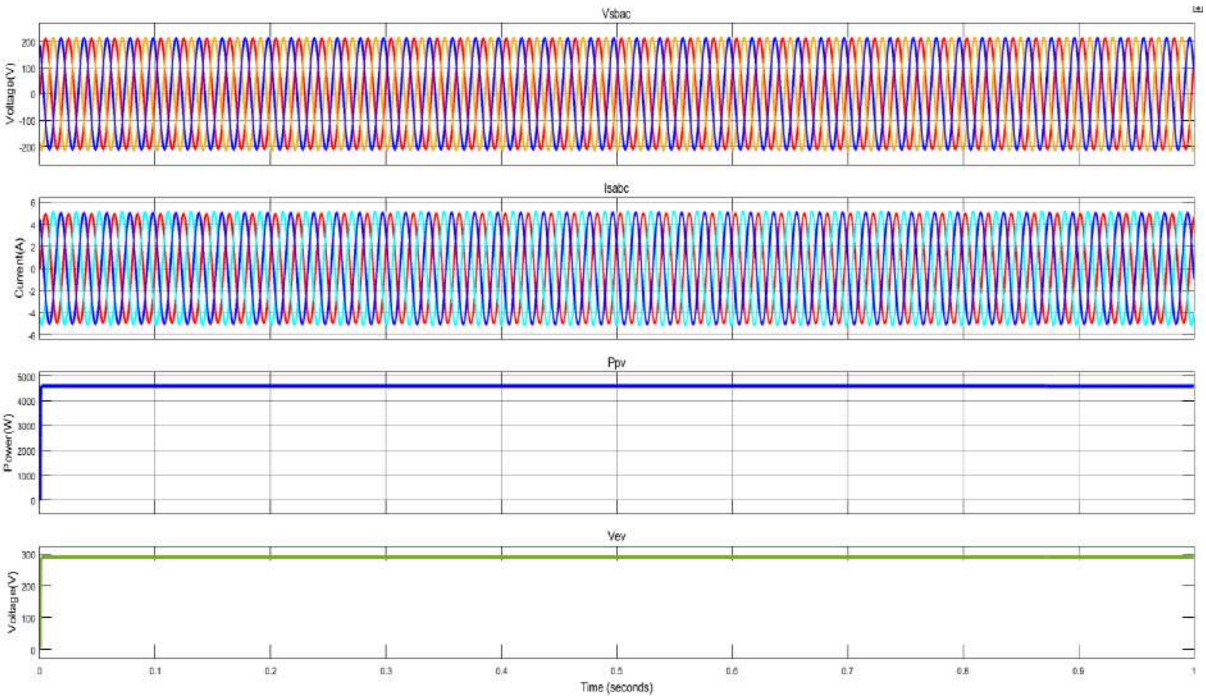
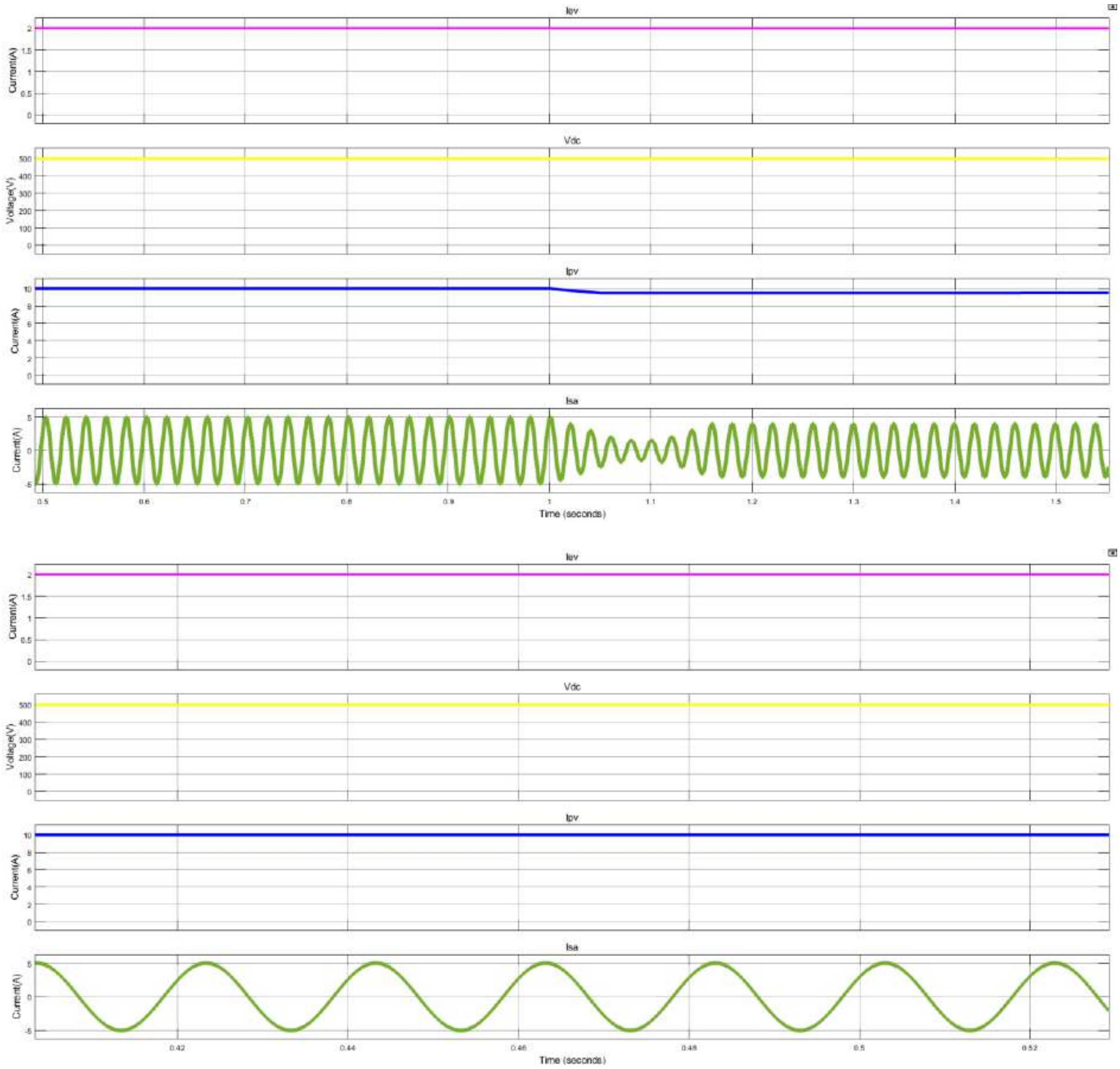


Fig 1 Simulation results of Charging Station at Steady State

The proposed system enhances the synchronization mechanism to ensure a seamless transition between grid-connected and standalone modes. The ANN controller is integrated with an advanced PLL-based synchronization unit, which improves accuracy and response time in detecting grid voltage and frequency variations. This enhancement ensures the system remains synchronized with the grid under all operating conditions, reducing the risk of disconnection and improving reliability.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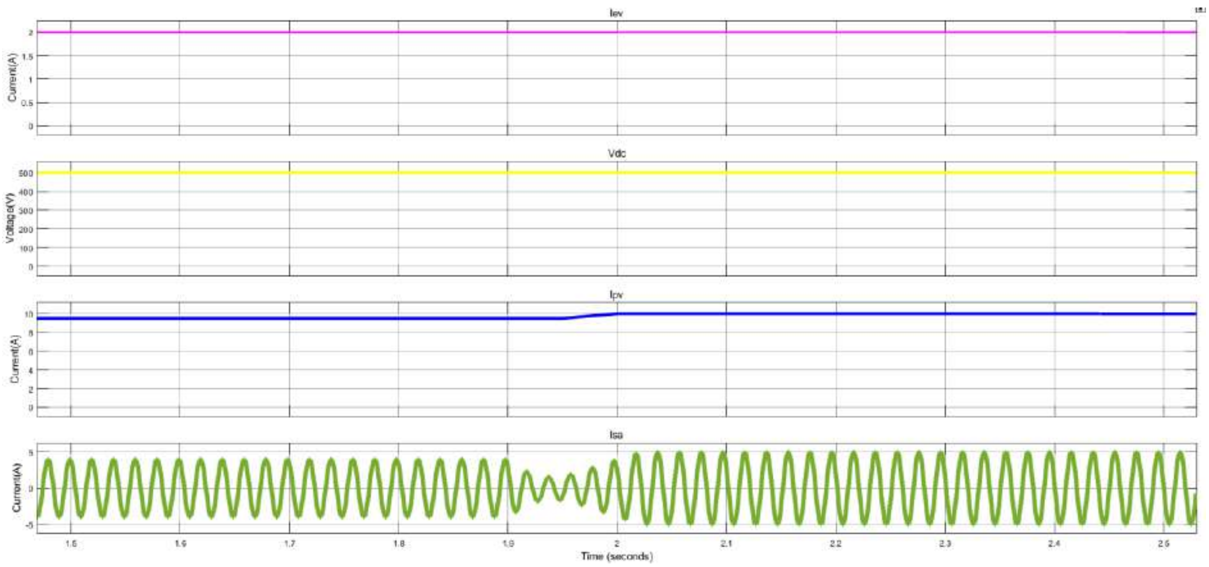
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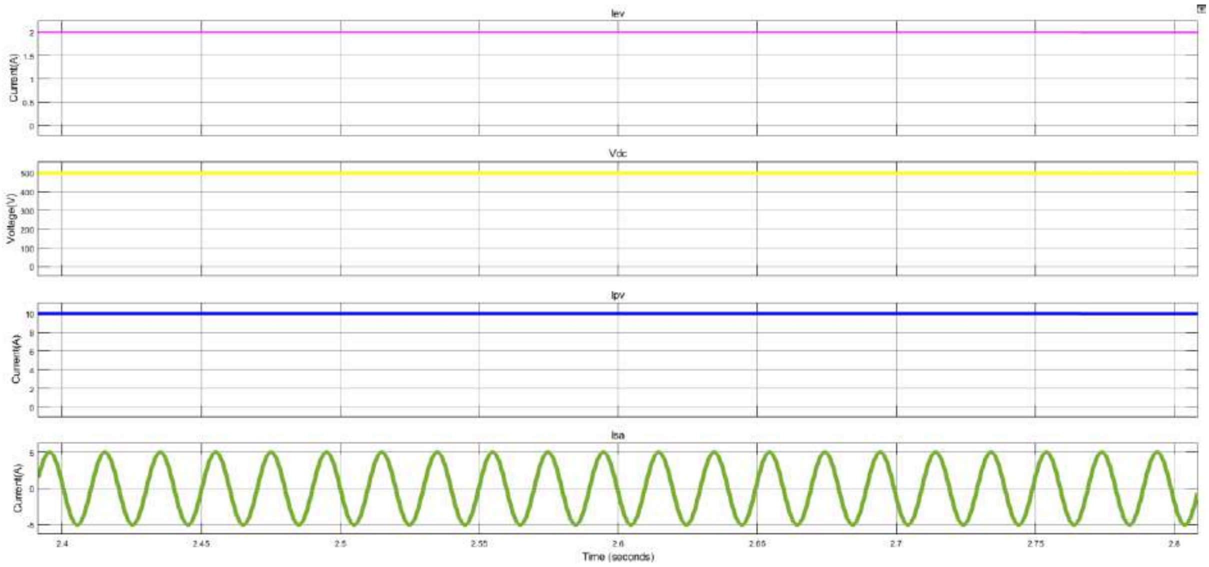
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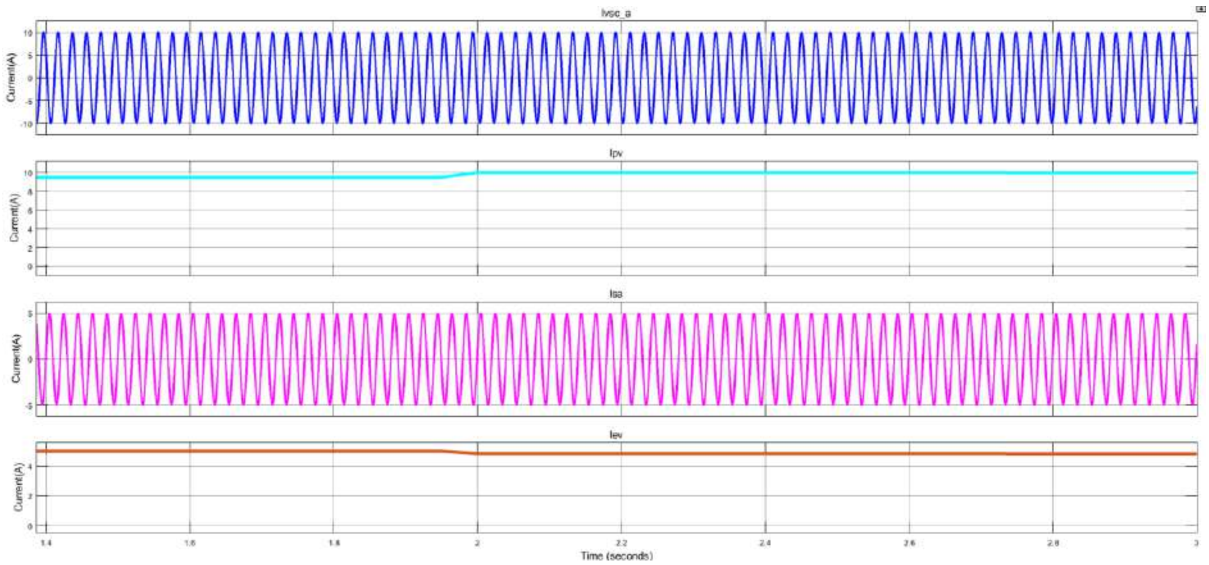
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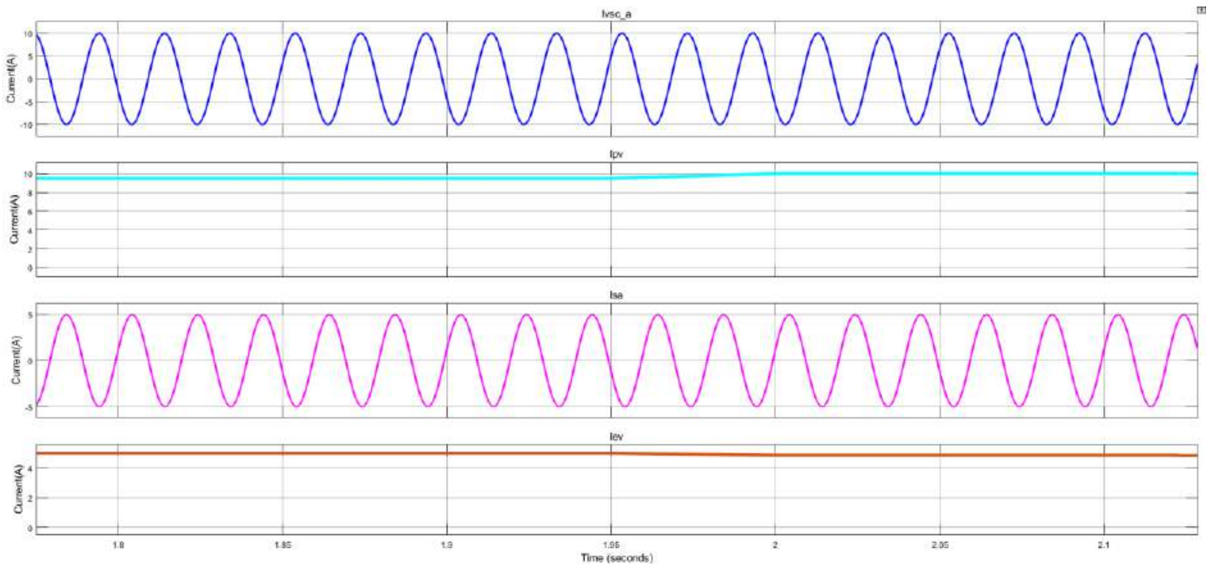
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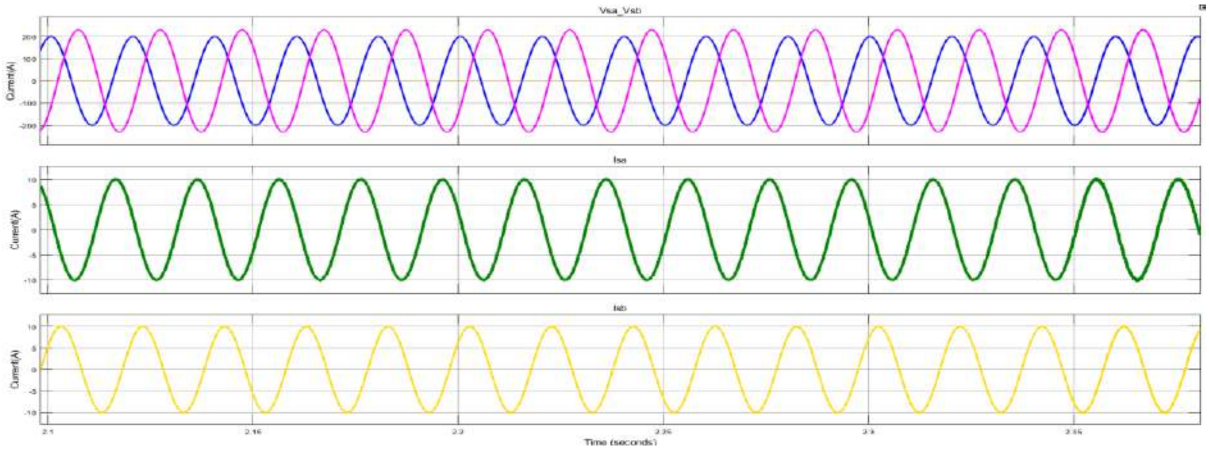


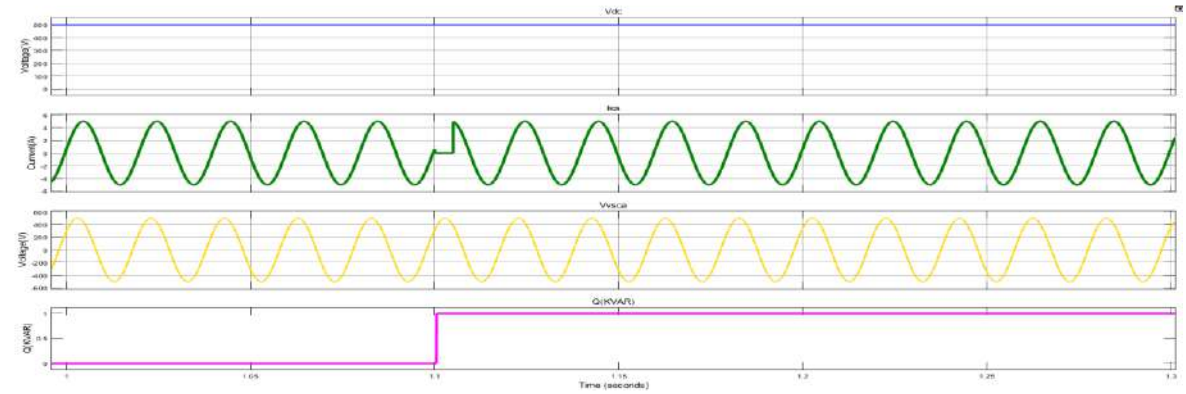
(d)

Fig 2 Dynamic response of grid connected system at (a) Increase in solar insolation (b) Fall in PV insolation (c) and (d) voltage unbalance and rise in PV insolation

Another significant improvement is in harmonic mitigation and reactive power compensation. The ANN-based controller optimizes switching strategies for the VSC, thereby achieving better harmonic filtering and reducing total harmonic distortion (THD) in grid currents below 5%, as per IEEE-519 standards. This improvement leads to enhanced power quality and increased system efficiency. Additionally, the ANN controller enables better power factor correction, ensuring efficient power utilization and reducing stress on the grid.

Moreover, the proposed system incorporates an intelligent energy management strategy to optimize power flow between the PV system, EV battery, and grid. The ANN-based predictive control mechanism ensures optimal utilization of solar power by dynamically adjusting charging and discharging profiles based on real-time grid and load conditions. This results in reduced switching losses, improved efficiency, and extended battery life for EVs.

Lastly, simulation results demonstrate that the ANN-based controller significantly outperforms conventional methods in reducing ripple content and achieving faster stabilization. The improved control mechanism leads to better voltage regulation, reduced overshoot, and enhanced overall performance of the PV-based EV charging station. These advantages make the proposed system a reliable and efficient solution for power quality improvement in grid-integrated EV charging applications.



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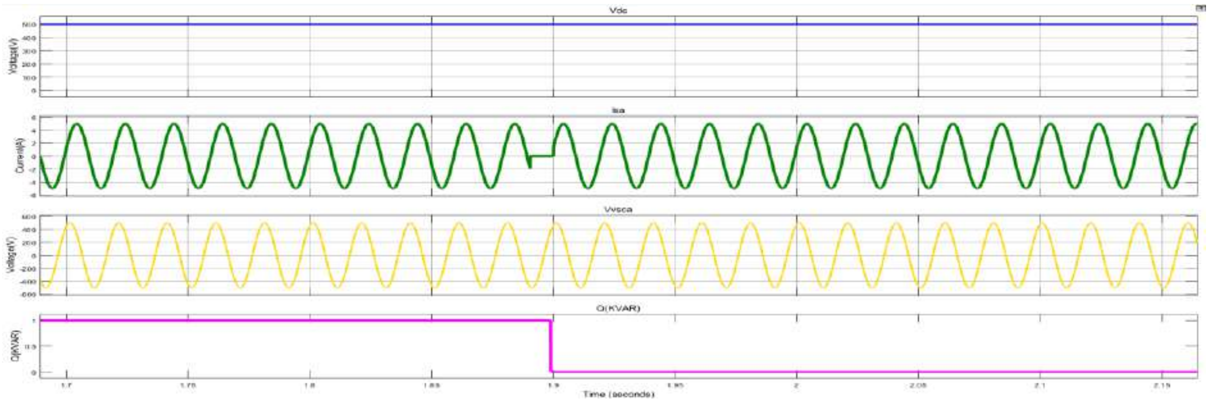
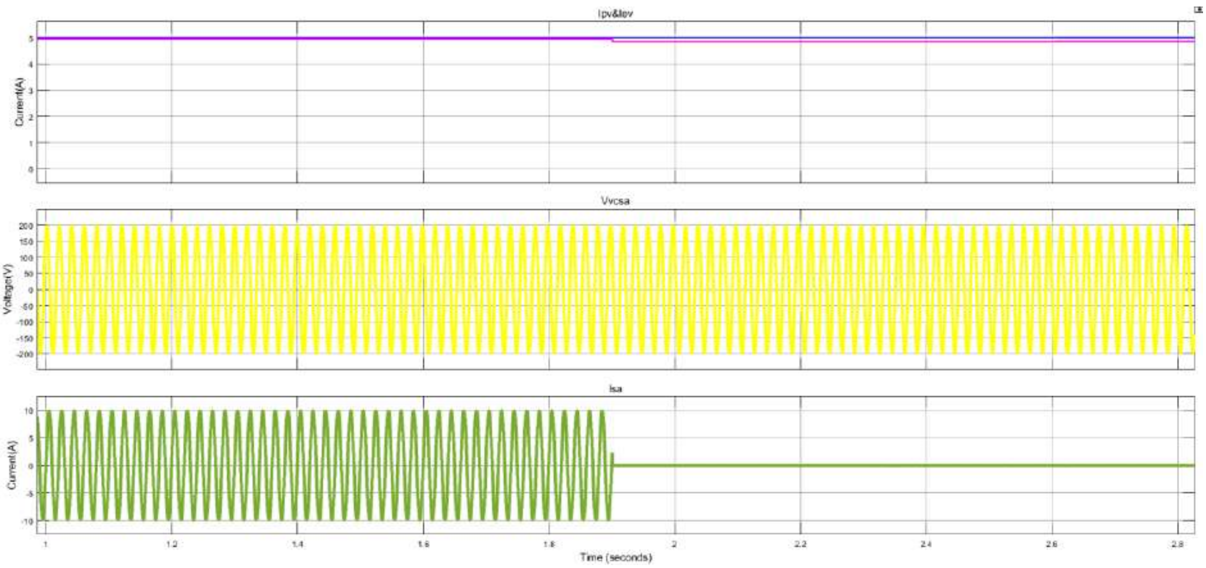
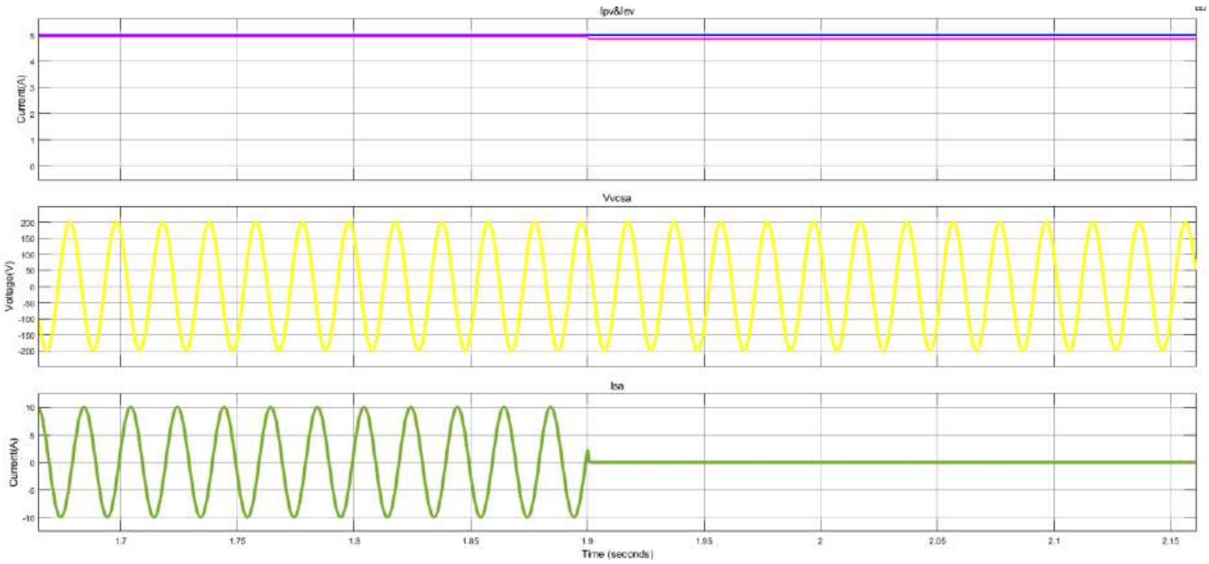


(b)

Fig 3 Charging station providing reactive power compensation to the grid

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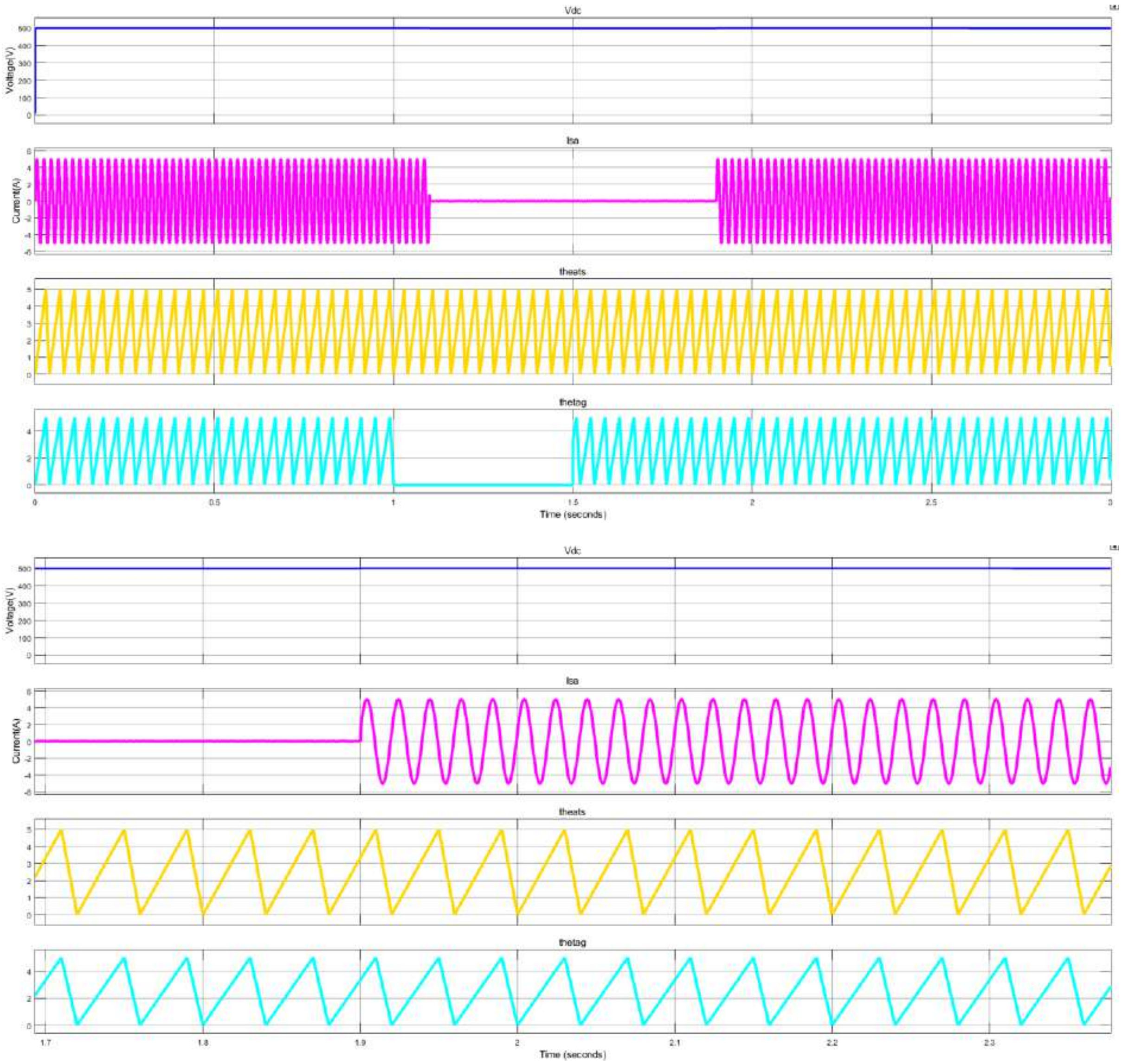
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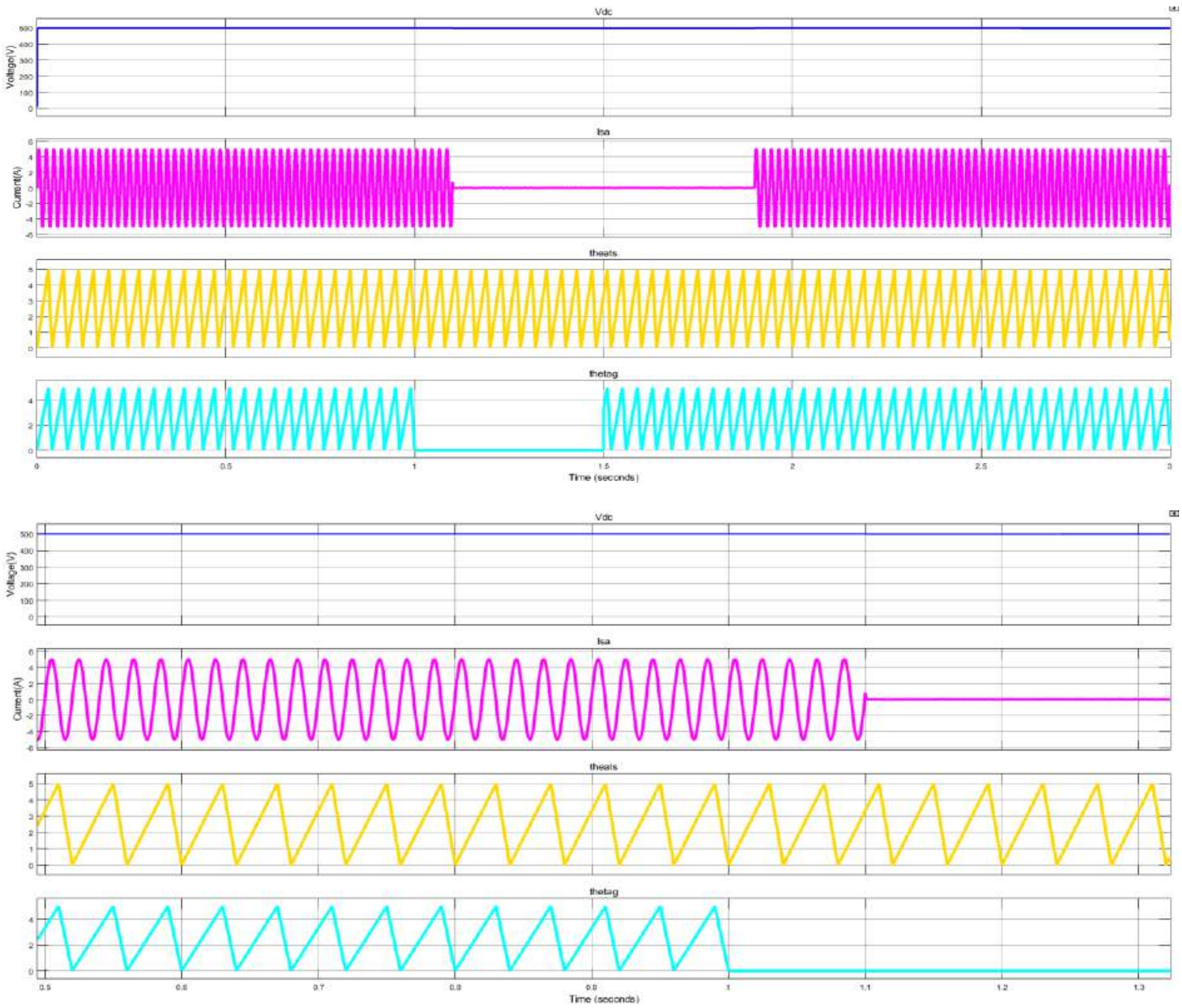

(c)

Fig 4 Performance during synchronization

CONCLUSION

This paper presents an enhanced ANN-based control strategy for power quality improvement in a PV-based EV charging station interfaced with a three-phase grid. By integrating an ANN controller, the system achieves reduced settling time, minimized ripple content, and improved harmonics mitigation. The proposed method ensures optimal performance in both standalone and grid-connected modes, addressing key challenges associated with power quality and grid stability. Simulation results validate the effectiveness of the ANN-based approach, demonstrating superior performance compared to conventional control techniques. Future research will focus on real-time implementation and further optimization of ANN algorithms for large-scale EV charging infrastructures.

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