

# Design of a Smart Solar Powered EV Charging Station with Power Quality Enhancement Using Advanced Inverter Control

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**Abstract-** The increasing adoption of electric vehicles (EVs) and renewable energy technologies has created new challenges and opportunities for modern power systems. Solar photovoltaic (PV) energy is widely considered one of the most promising renewable sources for powering EV charging infrastructure. Integrating solar power with EV charging stations enables sustainable transportation while reducing dependence on fossil fuels and lowering greenhouse gas emissions. However, the integration of EV charging loads and solar energy systems into distribution networks introduces several power quality issues such as harmonic distortion, voltage fluctuations, reactive power imbalance, and power factor degradation. These disturbances arise mainly due to nonlinear loads and power electronic converters used in EV chargers and solar inverters. Poor power quality can affect the reliability and efficiency of power systems, leading to overheating of electrical equipment, increased transmission losses, and reduced system stability. This study proposes the design of a smart solar powered EV charging station with enhanced power quality using advanced inverter control techniques. The proposed system integrates a solar photovoltaic array, energy conversion units, EV charging modules, and a grid interface with an intelligent inverter control mechanism. The smart inverter employs advanced control algorithms such as pulse width modulation, reactive power control, and harmonic compensation to regulate voltage and current waveforms. These control strategies ensure stable power delivery and minimize total harmonic distortion in the distribution system. Simulation models are developed to analyze the performance of the proposed system under varying operating conditions including solar irradiation changes and EV charging demand variations. The results demonstrate that the proposed advanced inverter control significantly improves power quality by reducing harmonic distortion, stabilizing voltage profiles, and improving system power factor. The system also ensures efficient utilization of solar energy while maintaining compliance with international power quality standards. Therefore, the implementation of advanced inverter control in solar powered EV charging stations offers a reliable and efficient solution for future smart grid infrastructure.

**Keywords:** Electric Vehicle Charging, Solar Photovoltaic System, Smart Inverter Control, Power Quality Improvement, Renewable Energy Integration

## I. INTRODUCTION

The global demand for sustainable transportation has accelerated the development of electric vehicles and renewable energy technologies [1]. Electric vehicles are increasingly adopted worldwide as an effective solution for reducing greenhouse gas emissions and minimizing dependence on fossil fuels [2]. However, the rapid growth of EV adoption has increased the demand for reliable charging infrastructure capable of supporting large numbers of vehicles without compromising power system stability [3].

Solar photovoltaic (PV) energy has emerged as one of the most attractive renewable energy sources for EV charging applications due to its abundance and environmental benefits [4]. Integrating solar PV systems with EV charging stations provides a sustainable solution for meeting transportation energy demands while reducing carbon emissions [5]. Solar powered EV charging stations allow electric vehicles to be charged using renewable energy rather than electricity generated from conventional fossil fuel sources [6].

Despite these advantages, the integration of EV charging loads and solar PV generation into distribution networks introduces significant power quality challenges [7]. Power quality refers to maintaining stable voltage, frequency, and waveform characteristics in electrical systems to ensure reliable operation of connected devices [8]. In solar-integrated EV charging stations, several disturbances such as voltage fluctuations, harmonic distortion, and reactive

power imbalance may occur due to nonlinear loads and power electronic converters [9].

Electric vehicle chargers typically use AC-DC converters that draw nonlinear current from the grid, generating harmonics and causing waveform distortion [10]. Harmonics can lead to overheating of transformers, malfunction of protection systems, and increased power losses in transmission lines [11]. Similarly, solar PV systems rely on inverters to convert DC electricity into AC power for grid connection, and these inverters may introduce switching harmonics and voltage fluctuations if not properly controlled [12].

Advanced inverter control technologies have been proposed as an effective solution to improve power quality in renewable energy systems [13]. Smart inverters can regulate voltage, control reactive power, and reduce harmonic distortion through advanced control algorithms and switching techniques [14]. These capabilities allow solar PV systems to provide additional grid support functions beyond simple power generation [15].

Recent research indicates that advanced inverter control strategies can significantly improve power quality in solar-integrated EV charging systems by maintaining voltage stability and reducing harmonic distortion [16]. Intelligent control algorithms enable real-time monitoring and adjustment of power flow between the solar PV system, the EV charging station, and the distribution grid [17].

Therefore, this research aims to design a smart solar powered EV charging station equipped with advanced inverter control techniques to enhance power quality. The proposed system focuses on improving voltage regulation, reducing harmonic distortion, and optimizing the utilization of renewable energy resources in EV charging infrastructure.

## II. LITERATURE REVIEW

The integration of renewable energy sources and electric vehicle (EV) charging infrastructure has become a major research focus in modern power systems. With the increasing adoption of EVs

worldwide, the demand for efficient and reliable charging infrastructure has significantly increased. Researchers have investigated various solutions to integrate renewable energy technologies such as solar photovoltaic (PV) systems with EV charging stations in order to reduce greenhouse gas emissions and improve energy sustainability [18].

Solar PV technology has gained widespread attention due to its clean energy generation and decreasing installation costs. Several studies have highlighted the potential of solar powered EV charging stations to reduce the environmental impact of transportation systems while improving energy independence [19]. By utilizing locally generated solar energy, EV charging stations can reduce the load on traditional power plants and minimize transmission losses. However, integrating solar energy into EV charging infrastructure introduces several technical challenges related to system reliability and power quality [20].

One of the major challenges associated with EV charging stations is the presence of nonlinear loads. EV chargers typically use power electronic converters such as rectifiers and DC-DC converters to regulate battery charging. These converters draw non-sinusoidal currents from the grid and introduce harmonic distortion into the power system [21]. Harmonic distortion can lead to overheating of electrical equipment, malfunction of sensitive devices, and increased losses in transmission and distribution systems [22].

Power quality issues are further intensified when renewable energy systems are connected to distribution networks. Solar PV systems require inverters to convert direct current produced by photovoltaic modules into alternating current compatible with the grid. Although modern inverters are designed to improve energy conversion efficiency, they may still generate switching harmonics and voltage fluctuations that degrade power quality [23]. Therefore, advanced inverter control techniques are necessary to ensure that renewable energy systems operate efficiently while maintaining grid stability.

Researchers have proposed several techniques to mitigate power quality problems in renewable energy

integrated systems. Passive filtering methods were initially used to reduce harmonic distortion in power networks. Passive filters consist of inductors and capacitors tuned to specific harmonic frequencies [24]. While passive filters are simple and cost-effective, their performance is limited because they cannot adapt to varying load conditions and system parameters.

Active power filters have emerged as a more flexible solution for harmonic compensation. These filters use power electronic converters to inject compensating currents that cancel harmonic components in the system [25]. Active filters are capable of dynamically responding to changing load conditions and maintaining sinusoidal current waveforms. However, they require complex control algorithms and higher implementation costs.

In recent years, smart inverter technologies have been developed to improve the performance of renewable energy systems. Smart inverters incorporate advanced control algorithms that enable them to perform additional grid support functions such as voltage regulation, reactive power compensation, and harmonic mitigation [26]. These capabilities allow solar PV systems to contribute to overall grid stability rather than acting solely as energy generators.

Several studies have investigated advanced inverter control strategies for renewable energy integration. Pulse width modulation (PWM) is one of the most commonly used techniques for controlling inverter switching operations. PWM enables the generation of high-quality sinusoidal output voltage while minimizing harmonic distortion [27]. Advanced PWM techniques such as space vector modulation and sinusoidal PWM have further improved inverter performance in grid connected renewable energy systems.

Reactive power control is another important function of smart inverters. Reactive power compensation helps maintain voltage stability in distribution networks with high penetration of renewable energy sources [28]. By adjusting reactive power output, smart inverters can regulate voltage levels and reduce power losses in transmission lines.

Another area of research focuses on optimizing the operation of solar powered EV charging stations through intelligent energy management systems. These systems coordinate energy flow between solar generation, grid supply, and EV charging loads in order to maximize renewable energy utilization and minimize operational costs [29]. Advanced control algorithms enable EV charging stations to adapt to variations in solar irradiation and charging demand.

The concept of smart charging has also been introduced to manage EV charging loads more effectively. Smart charging strategies involve scheduling charging operations based on grid conditions, renewable energy availability, and electricity pricing signals [30]. This approach helps reduce peak demand on the grid and improves the efficiency of renewable energy utilization.

Despite these advancements, several challenges remain in the design of solar powered EV charging infrastructure. The intermittent nature of solar energy and the unpredictable behavior of EV charging loads require sophisticated control strategies to ensure stable system operation [31]. Advanced inverter control systems play a crucial role in addressing these challenges by regulating voltage, controlling power flow, and minimizing harmonic distortion.

Therefore, developing efficient inverter control techniques for solar powered EV charging stations is essential for improving power quality and enabling reliable integration of renewable energy into modern power systems.

### III. MATERIALS AND METHODS

The proposed smart solar powered EV charging station is designed to integrate renewable energy generation with advanced power electronic control in order to improve power quality and ensure efficient charging of electric vehicles. The system consists of several key components including a solar photovoltaic array, power conversion units, smart inverter controller, EV charging modules, and a grid interface.

### 3.1 System Architecture

The solar photovoltaic system serves as the primary source of renewable energy for the charging station. The PV array is composed of multiple photovoltaic modules connected in series and parallel configurations to achieve the desired voltage and power output. The output of the PV modules is direct current (DC) electricity, which varies depending on solar irradiation and temperature conditions.

To regulate the PV output voltage, a DC–DC boost converter is employed between the PV array and the inverter system. The boost converter increases the DC voltage to a suitable level for the inverter input and maintains a stable DC link voltage. Maximum Power Point Tracking (MPPT) algorithms are implemented within the converter control system to ensure that the PV array operates at its maximum efficiency under varying environmental conditions [32].

### 3.2 Smart Inverter Design

The regulated DC power from the boost converter is converted into alternating current using a three-phase voltage source inverter. The inverter is responsible for synchronizing solar generated power with the distribution grid and supplying energy to EV charging loads.

The inverter is equipped with an advanced control system designed to improve power quality. Pulse Width Modulation (PWM) is used to control switching operations of the inverter semiconductor devices. PWM techniques allow the inverter to generate nearly sinusoidal output voltage and reduce harmonic distortion in the power system.

In addition to PWM control, the inverter is capable of performing reactive power compensation. By adjusting reactive power output, the inverter can regulate voltage levels at the point of common coupling and improve the overall power factor of the system [33].

### 3.3 EV Charging Modules

The EV charging station consists of multiple charging units connected to the distribution network. Each charging unit contains an AC–DC rectifier followed by a DC–DC converter that regulates the charging current supplied to the vehicle battery. These converters ensure that the charging process is performed safely and efficiently according to battery specifications.

The charging modules are designed to support multiple charging levels including standard charging and fast charging modes. Intelligent load management algorithms coordinate the operation of different charging units to avoid excessive power demand and maintain system stability [34].

### 3.4 Simulation Model

To evaluate the performance of the proposed system, a detailed simulation model is developed using power system simulation software. The simulation model includes solar PV modules, DC–DC converter, three-phase inverter, grid interface, and EV charging loads.

The PV system is rated at approximately 50 kW, while the EV charging load varies between 20 kW and 40 kW depending on the number of vehicles connected to the station. Various operating conditions such as changes in solar irradiation, variations in charging demand, and grid disturbances are simulated to analyze system performance.

### 3.5 Performance Evaluation

The effectiveness of the proposed smart inverter control is evaluated using several power quality indicators. These include Total Harmonic Distortion (THD), voltage regulation, system power factor, and energy conversion efficiency [35]. Simulation results obtained under different operating conditions are used to assess the ability of the proposed system to maintain high power quality while efficiently utilizing renewable energy resources.

#### IV. RESULTS AND DISCUSSION

The performance of the proposed smart solar powered EV charging station was analyzed through simulation studies under different operating conditions. The objective of this analysis was to evaluate the effectiveness of advanced inverter control in improving power quality while ensuring efficient utilization of solar energy.

##### *4.1 Harmonic Distortion Reduction*

One of the major performance indicators considered in this study is Total Harmonic Distortion (THD). Harmonics are produced primarily due to nonlinear loads such as EV chargers and switching operations of power electronic converters. When the system operates without advanced inverter control, the current waveform drawn from the grid contains significant harmonic components. Simulation results showed that the THD level exceeded acceptable limits defined by international power quality standards.

After implementing the proposed advanced inverter control strategy, the harmonic distortion in the system was significantly reduced. The PWM based inverter control generated switching signals that produced nearly sinusoidal output voltage and current waveforms. As a result, the THD level was reduced to within acceptable limits specified by grid standards [36]. This reduction in harmonic distortion improves system reliability and prevents damage to electrical equipment.

##### *4.2 Voltage Regulation*

Voltage stability is another important aspect of power quality in renewable energy integrated systems. Variations in solar irradiation and sudden changes in EV charging demand can cause voltage fluctuations in the distribution network. In the proposed system, the smart inverter continuously monitors voltage levels at the point of common coupling and adjusts reactive power output to maintain stable voltage.

Simulation results showed that the smart inverter successfully maintained the load voltage within acceptable limits even during sudden changes in solar

power generation. The inverter dynamically injected reactive power to compensate voltage drops and stabilize the system [37].

##### *4.3 Power Factor Improvement*

Reactive power compensation provided by the smart inverter also contributed to improved system power factor. Without compensation, the EV charging loads caused the power factor to drop significantly due to reactive power consumption. After implementing advanced inverter control, the power factor improved to nearly unity. This improvement reduces reactive power demand from the grid and increases overall system efficiency.

##### *4.4 System Stability under Solar Variability*

The intermittent nature of solar energy can create challenges for EV charging stations, especially when charging demand remains high while solar generation decreases due to cloud cover or sunset. The proposed system addressed this issue through intelligent power flow control between the solar PV system, the EV charging loads, and the grid.

The simulation results demonstrated that the smart inverter maintained stable system operation under varying solar irradiation levels. The inverter balanced power flow between the PV array and the grid to ensure continuous charging of electric vehicles [38].

Overall, the results confirm that advanced inverter control significantly enhances the performance of solar powered EV charging stations. The proposed system effectively reduces harmonic distortion, stabilizes voltage levels, improves power factor, and ensures reliable system operation.

#### V. CONCLUSION

The rapid growth of electric vehicles and renewable energy technologies has created new challenges for modern power distribution systems. Solar powered EV charging stations represent an environmentally friendly solution for meeting transportation energy demands. However, the integration of renewable energy sources and nonlinear EV charging loads

introduces several power quality issues such as harmonic distortion, voltage instability, and reactive power imbalance.

This study proposed the design of a smart solar powered EV charging station that utilizes advanced inverter control techniques to enhance power quality and improve system reliability. The proposed system integrates a solar photovoltaic array, DC–DC boost converter, three-phase inverter with intelligent control, and EV charging modules within a grid connected architecture.

Simulation results demonstrated that the advanced inverter control system significantly improves power quality in the distribution network. The PWM based inverter control effectively reduces harmonic distortion generated by nonlinear charging loads. The system maintains sinusoidal current and voltage waveforms within acceptable limits defined by power quality standards.

The smart inverter also provides reactive power compensation, which improves the power factor and enhances voltage regulation in the distribution network. By dynamically adjusting reactive power output, the inverter stabilizes voltage levels during fluctuations in solar power generation and EV charging demand.

Another important contribution of the proposed system is its ability to maintain stable operation under varying solar irradiation conditions. Intelligent power flow control enables efficient utilization of solar energy while ensuring continuous EV charging even during periods of reduced solar generation.

The findings of this study indicate that advanced inverter control technologies play a critical role in enabling reliable integration of renewable energy into EV charging infrastructure. Smart inverter systems not only improve power quality but also enhance overall system efficiency and grid stability.

Future research may focus on implementing artificial intelligence based inverter control strategies, real time hardware testing, and integration with smart grid communication networks. These advancements will

further enhance the performance of solar powered EV charging stations and support the transition toward sustainable energy and transportation systems [39][40].

## REFERENCES

- [1] Chan, C. C. (2007). The state of the art of electric, hybrid, and fuel cell vehicles. *Proceedings of the IEEE*, 95(4), 704–718.
- [2] Emadi, A., Lee, Y. J., & Rajashekhara, K. (2008). Power electronics and motor drives in electric, hybrid electric, and plug-in hybrid electric vehicles. *IEEE Transactions on Industrial Electronics*, 55(6), 2237–2245.
- [3] Yilmaz, M., & Krein, P. T. (2013). Review of charging power levels and infrastructure for plug-in electric and hybrid vehicles. *IEEE Transactions on Power Electronics*, 28(5), 2151–2169.
- [4] Patel, H., & Agarwal, V. (2008). MATLAB-based modeling to study the effects of partial shading on PV array characteristics. *IEEE Transactions on Energy Conversion*, 23(1), 302–310.
- [5] International Energy Agency. (2023). *Global EV outlook 2023*. Paris: IEA.
- [6] International Renewable Energy Agency. (2022). *Renewable energy statistics 2022*. Abu Dhabi: IRENA.
- [7] Dugan, R. C., McGranaghan, M. F., Santoso, S., & Beaty, H. W. (2012). *Electrical power systems quality* (3rd ed.). New York: McGraw-Hill.
- [8] Bollen, M. H. (2000). *Understanding power quality problems: Voltage sags and interruptions*. New York: IEEE Press.
- [9] Arrillaga, J., & Watson, N. (2003). *Power system harmonics* (2nd ed.). New York: Wiley.
- [10] Singh, B., Al-Haddad, K., & Chandra, A. (1999). A review of active filters for power quality improvement. *IEEE Transactions on Industrial Electronics*, 46(5), 960–971.
- [11] Akagi, H. (1996). New trends in active filters for power conditioning. *IEEE Transactions on Industry Applications*, 32(6), 1312–1322.
- [12] Rashid, M. H. (2014). *Power electronics: Circuits, devices, and applications* (4th ed.). Pearson Education.

- [13] Blaabjerg, F., Teodorescu, R., Liserre, M., & Timbus, A. V. (2006). Overview of control and grid synchronization for distributed power generation systems. *IEEE Transactions on Industrial Electronics*, 53(5), 1398–1409.
- [14] Guerrero, J. M., Vasquez, J. C., Matas, J., de Vicuna, L. G., & Castilla, M. (2011). Hierarchical control of droop-controlled AC and DC microgrids. *IEEE Transactions on Industrial Electronics*, 58(1), 158–172.
- [15] Teodorescu, R., Liserre, M., & Rodriguez, P. (2011). *Grid converters for photovoltaic and wind power systems*. Wiley.
- [16] Liserre, M., Sauter, T., & Hung, J. Y. (2010). Future energy systems: Integrating renewable energy sources into the smart power grid. *IEEE Industrial Electronics Magazine*, 4(1), 18–37.
- [17] Kundur, P. (1994). *Power system stability and control*. McGraw-Hill.
- [18] Clement-Nyns, K., Haesen, E., & Driesen, J. (2010). The impact of charging plug-in hybrid electric vehicles on a residential distribution grid. *IEEE Transactions on Power Systems*, 25(1), 371–380.
- [19] Ackermann, T. (2005). *Wind power in power systems*. Wiley.
- [20] Momoh, J. A. (2012). *Smart grid: Fundamentals of design and analysis*. Wiley.
- [21] Singh, B., Chandra, A., & Al-Haddad, K. (2015). *Power quality: Problems and mitigation techniques*. Wiley.
- [22] Hingorani, N. G., & Gyugyi, L. (2000). *Understanding FACTS: Concepts and technology of flexible AC transmission systems*. Wiley.
- [23] Yazdani, A., & Iravani, R. (2010). *Voltage-sourced converters in power systems*. Wiley.
- [24] Bhattacharya, S., Divan, D., & Banerjee, B. (1993). Active filter solutions for utility interface of adjustable speed drive systems. *IEEE Transactions on Industry Applications*, 29(5), 934–942.
- [25] Mohan, N., Undeland, T. M., & Robbins, W. P. (2003). *Power electronics: Converters, applications, and design* (3rd ed.). Wiley.
- [26] Blaabjerg, F., Yang, Y., Yang, D., & Wang, X. (2015). Distributed power generation systems and protection. *Proceedings of the IEEE*, 105(7), 1311–1331.
- [27] Buso, S., & Mattavelli, P. (2006). *Digital control in power electronics*. Morgan & Claypool.
- [28] Turitsyn, K., Sulc, P., Backhaus, S., & Chertkov, M. (2011). Local control of reactive power by distributed photovoltaic generators. *IEEE Transactions on Smart Grid*, 2(3), 592–598.
- [29] Guerrero, J. M., Loh, P. C., Lee, T. L., & Chandorkar, M. (2013). Advanced control architectures for intelligent microgrids. *IEEE Transactions on Industrial Electronics*, 60(4), 1254–1262.
- [30] Sortomme, E., & El-Sharkawi, M. (2011). Optimal scheduling of vehicle-to-grid energy and ancillary services. *IEEE Transactions on Smart Grid*, 3(1), 351–359.
- [31] Tan, K. M., Ramachandramurthy, V. K., & Yong, J. Y. (2016). Integration of electric vehicles in smart grid: A review on vehicle-to-grid technologies and optimization techniques. *Renewable and Sustainable Energy Reviews*, 53, 720–732.
- [32] Esram, T., & Chapman, P. (2007). Comparison of photovoltaic array maximum power point tracking techniques. *IEEE Transactions on Energy Conversion*, 22(2), 439–449.
- [33] Akagi, H., Watanabe, E., & Aredes, M. (2007). *Instantaneous power theory and applications to power conditioning*. Wiley.
- [34] Yilmaz, M., & Krein, P. (2012). Review of battery charger topologies, charging power levels, and infrastructure for plug-in electric vehicles. *IEEE Transactions on Power Electronics*, 28(5), 2151–2169.
- [35] IEEE Standards Association. (2014). *IEEE Standard 519-2014: Recommended practice and requirements for harmonic control in electric power systems*.
- [36] Graovac, D., Purschel, M., & Kiep, A. (2009). MOSFET power losses calculation using the data-sheet parameters. *Infineon Application Note*.
- [37] Eltamaly, A. M., & Al-Saud, M. S. (2019). A review of power quality improvement techniques in renewable energy systems. *Renewable and Sustainable Energy Reviews*, 91, 79–95.
- [38] Lasseter, R. H. (2002). Microgrids. *IEEE Power Engineering Society Winter Meeting*.
- [39] Singh, B., Solanki, J., & Verma, V. (2011). Control of DSTATCOM for power quality

improvement in distribution systems.  
*International Journal of Electrical Power & Energy Systems*, 33(2), 288–296.

- [40] Khadkikar, V. (2012). Enhancing electric power quality using UPQC: A comprehensive overview. *IEEE Transactions on Power Electronics*, 27(5), 2284–2297.