A|R|J
Amrit Research Journal April 2024, Vol. 4, Issue 2, 52-63
ISSN: 2738-9553
RESEARCH ARTICLE

Smart EV Charger With Reactive Power Compensation and Surge Protection

Nirajan Bhandari[1], Pratik Pandey[1], Bibek Adhikari[1], Ashish Dhungel[1], Deepak Thapa[1], Ankit Ghimire[1]*

[1]*Department of Electrical Engineering, Institute of Engineering (IOE) Pulchowk Campus, Lalitpur, Nepal*

[*]*E-mail: nirajanb22@gmail.com*

(Received: August 2, 2023, Received in revised form: February 25, 2024, Accepted: February 25, 2024, Available Online)

DOI: https://doi.org/10.3126/arj.v4i2.65545

Highlights

- The paper proposes integrating compensating functions into fast EV charging stations to enhance grid reliability and reduce reliance on costly devices like STATCOMs and Capacitor Banks used to solve voltage drop issues caused by EV adoption.
- Using a cross-coupling strategy, a PID controller manages the leading current to supply reactive power to regulate voltage at the connection node.
- An ILPS with SPD safeguards the charger from lightning or other induced surges.
- The smart EV charger developed in this project demonstrates both dynamism and reliability. Beyond operating at unity power factor, the charger possesses the capability to supply reactive power to the electrical grid, aiding in the maintenance of the necessary grid voltage at the point of common connection.
- This versatility allows the EV charging station to function in three distinct modes, showcasing its intelligence, adaptability, and cost-effectiveness

Abstract

The paper proposes integrating compensating functions into fast EV charging stations to enhance grid reliability and reduce reliance on costly devices like STATCOMs and Capacitor Banks used to solve voltage drop issues caused by EV adoption. The developed smart fast EV charger functions as a boost rectifier while simultaneously providing surge protection and compensating reactive power in the grid during charging. Using a cross-coupling strategy, a PID controller manages the leading current to supply reactive power to regulate voltage at the connection node. An ILPS with SPD safeguards the charger from lightning or other induced surges. The charger can operate in three modes: charging the battery at unity power factor, acting as a STATCOM without connecting the battery, or charging the battery while supplying reactive power to the grid in a bidirectional manner.

Keywords: *Electric Vehicle (EV), Reactive Power, Surge Protective Device (SPD), Static Var Compensation (STATCOM), Internal Lightning Protection System (ILPS).*

Introduction

Any vehicle that is led by one or more electric motors is considered an electric vehicle. With the development of technology, vehicles that emphasize renewable energy and the possibility of reducing the impact of transportation on climate change and other environmental challenges have become more and more popular. [1]. Electric vehicles have significantly driven innovation across various domains, including advancements in electric motors, the storage of substantial energy quantities for extended durations, power transfer technology, and more [2]. Charging remains a critical aspect, emphasizing the importance of delivering

[*]*Corresponding author*

optimal power with minimal losses and ensuring adaptable operation under diverse conditions [3]. Preventing additional stress on transmission lines and generators is crucial, making it a top priority for charger manufacturers to enhance stability and flexibility when adding chargers without requiring reactive power compensating mechanisms at the distribution side. A notable challenge in the charging infrastructure is its limited presence [5]. While there are existing chargers, the infrastructure still requires substantial development. As the number of electric vehicles in the market grows, there will be a demand for various charger types, including level 2 AC charging at home and fast DC chargers at different locations. With each expansion of charger numbers, the need for improved power regulation rises. Therefore, the charger under development aims to address the complexity of power regulation at the distributed level, offering flexibility for additional chargers where needed, without the necessity for power compensating mechanisms at substations. Despite the increasing adoption of electric vehicles (EVs), there has been a heightened discussion surrounding voltage drops within distribution grids [6]. Lightning is a natural occurrence that can cause an electric power system to experience overvoltage or overcurrent. Surge protection devices (SPD) are widely used to prevent electrical equipment from overvoltage and overcurrent produced by lightning strokes. A direct or indirect lightning strike could result in overvoltage and overcurrent issues for the fast-charging station equipment for electric vehicles. Mounting the SPD in the fast-charging station is important in order to prevent overvoltage and overcurrent in the electric vehicle supply equipment (EVSE) [4].

Overall Connection Architecture

Here, the grid represented a 400V three-phase AC system. The distribution line parameters represent the resistance and inductance of the distribution line. The load requirement of the particular region is represented by the home loads, and a fast-charging station is connected in parallel. An SPD is connected in parallel to the fast-charging station in order to protect against transient surge conditions Because of the significant power required to charge these EVs' batteries, powering them has a significant influence on the distribution networks and the power grid. When electric cars (EVs) are charged from the grid, they create non-linear loads that are different from traditional loads and put stress on the power system. Thus, as a result, the node voltage decreases beyond the pre-determined value. Under-voltage can therefore lead to a variety of issues with electrical devices, including overheating, malfunctioning, premature failure, and shutdown, particularly with regard to motors (such as those found in air conditioners, refrigerators, and dryers).

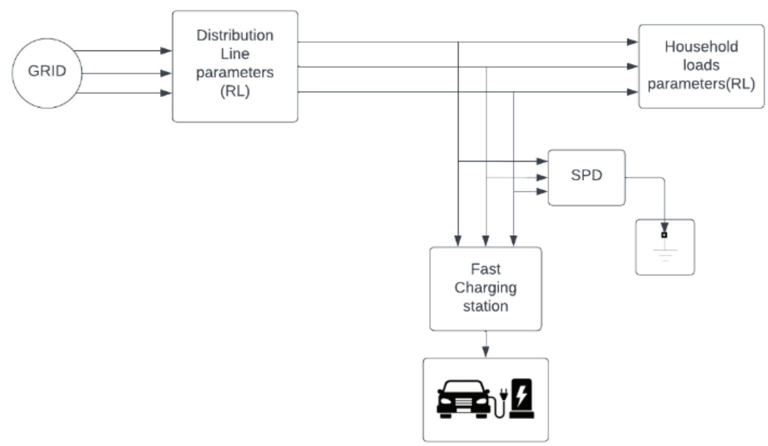

Fig. 1. Block diagram of the proposed smart charger

Electric Vehicle Charger Architecture

A power electronic converter with variable output voltage and current that transforms AC power into DC power is called a current-controlled boost rectifier. This particular DC-DC converter employs a boost topology and operates under the influence of a current control loop. The fundamental functionality of a current-controlled boost rectifier involves elevating the input voltage to a higher magnitude by utilizing a switch and an inductor. Typically, the switch is a power MOSFET or an IGBT, with the inductor serving to store energy during the switch's on-time and discharging it during the off-time. The duty cycle of the switch, which is established by

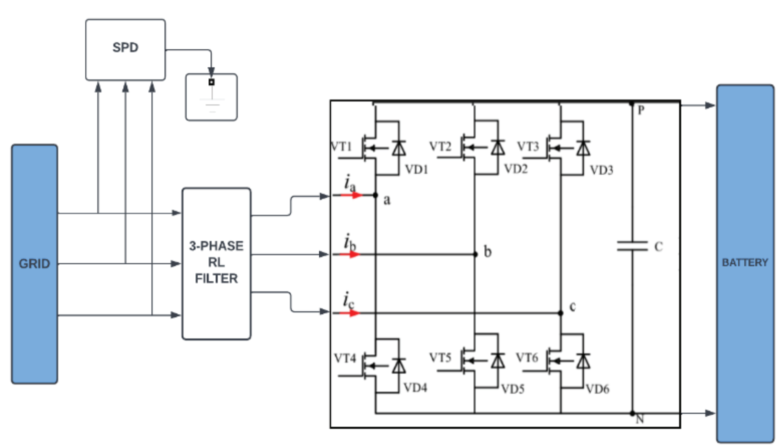

Fig. 2. Block diagram of EV Charger Architecture.

the current controlled loop, regulates the output voltage of the boost rectifier The output voltage is determined by controlling the inductor current through the current control loop. The current control loop can do more than only regulate the output voltage; it can also control the input current and adjust power factor. There is always a boost DC voltage across the DC-Link capacitor. Here, the phases are first passed through an RL filter which acts as a Low-pass filter. The phases are then connected across the bridge rectifier circuit as shown in the figure. The circuit functions as a boost rectifier circuit and controls the flow of both active and reactive power inside the system with the aid of a control system, which also generates the gate signals. The output of the bridge rectifier is a DC signal. A capacitor is connected across the end terminals of the bridge rectifier circuit in order to smooth out the output DC signal. An EV is connected for fast charging at the endpoint.

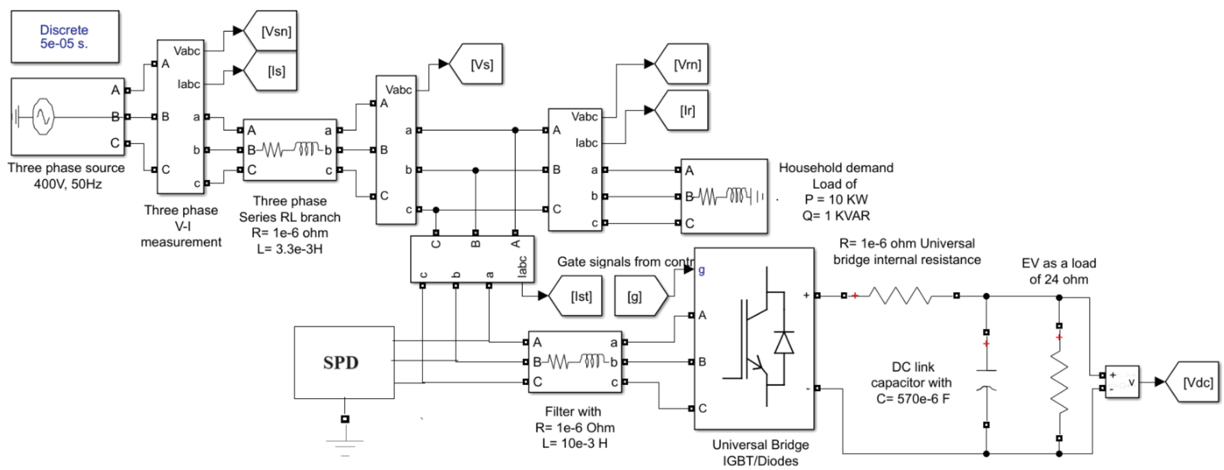

Fig. 3. MATLAB Simulation of EV Charging Station

The simulation was done in MATLAB Simulink. This simulation is a prototype model of a distribution grid with an EV charging station connected along with a household load. The supply is of a Three-phase 400V, 50Hz AC supply. The output of the Fast EV Charging station is maintained at 1200V DC. The EV charging station is modeled as a 60KW fast charger. Whereas, the household has a load demand of 10.0498 KVA.

Control Strategy

Based on the d-q axis theory, a cross-coupling control approach is used to generate the reference voltages. Here, the AC side of the converter's current is regulated by its Id and Iq components. The cross-coupling strategy is utilized to generate reference signals for Id and Iq. Let us understand the mathematical expression for V_d and V_q in an inductor:

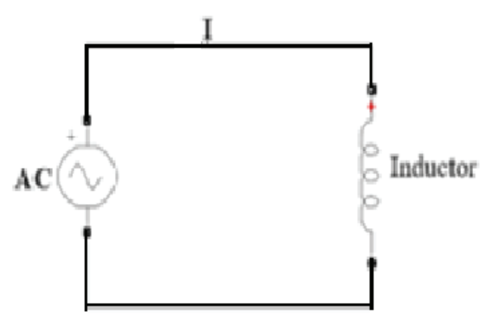

Fig. 4. A Inductor Connected to the AC Source

The total voltage across the inductor is given by:

$$V_{inductor} = L\frac{di}{dt} \tag{1}$$

$$V_d + jV_q = L\frac{di}{dt} \quad (2)$$

$$V_d + jV_q = L\frac{d(Id + j\,Iq)}{dt} \quad (3)$$

$$V_d + jV_q = jwL*(I_d + jI_q) \quad (4)$$

$$V_d + jV_q = jwL*I_d + (-wL*I_q) \quad (5)$$

Thus, comparing the real and imaginary parts we get,

$$V_d = -wL*I_q \quad (6)$$

$$V_q = wL*I_d \quad (7)$$

Thus, by using the above mathematical relation, we can generate the reference V_d and V_q signals.

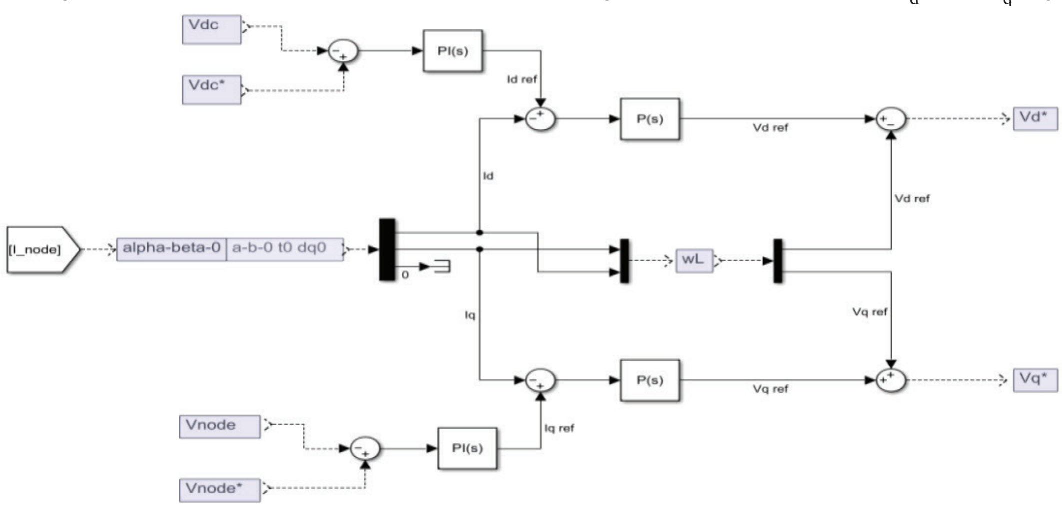

Fig. 5. Cross-Coupling Control Strategy

Thus, by adjusting the active and reactive current commands, we can control the power flow in the system which is explained in detail.

Active current command of a three-phase PWM boost rectifier/inverter

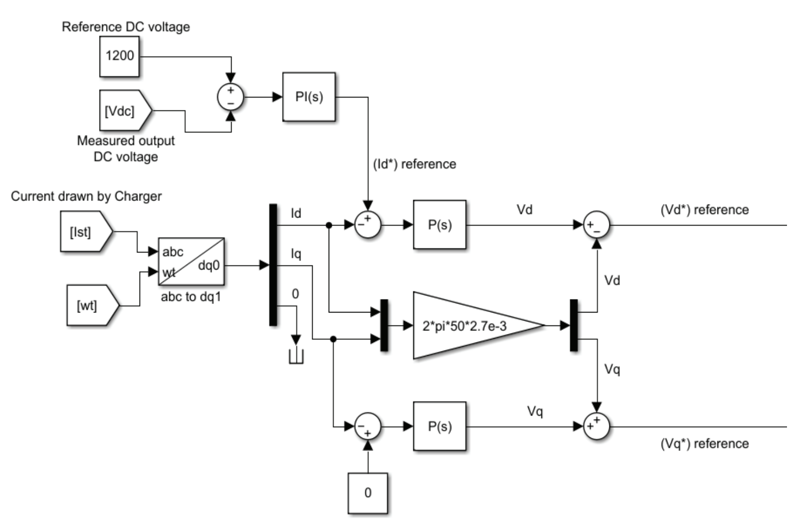

Fig. 6. Active power flow Control Strategy

The charger receives only active power when the active current command is altered in the three-phase pulse width modulation boost rectifier/inverter, with the reactive current command set to zero. In this situation, active power flows from the source to the charger, causing the phase voltage and line current phasors on the AC side of the single-phase PWM boost rectifier/inverter to align with each other.

Reactive current command of a three-phase PWM boost rectifier/inverter

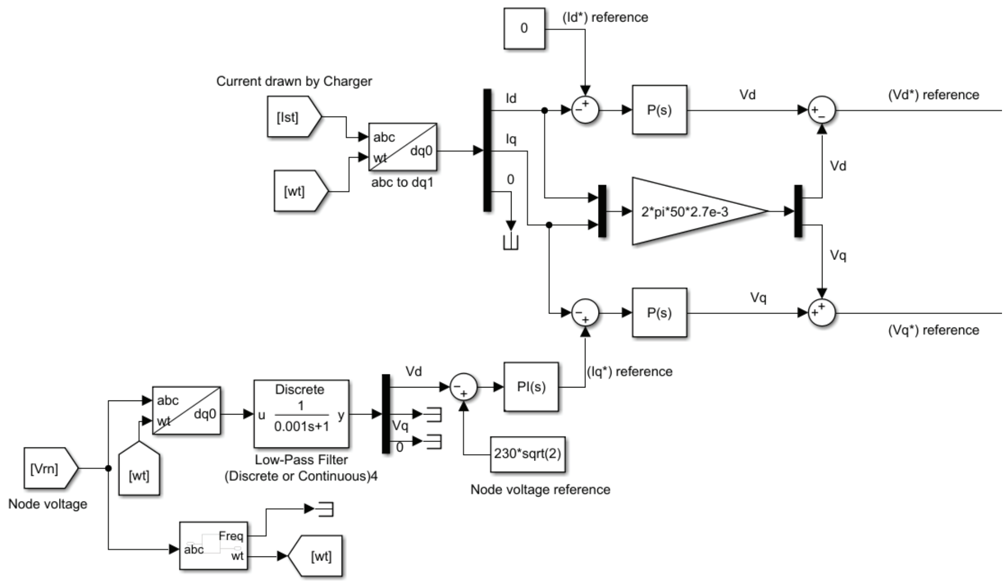

Fig. 7. Reactive power flow Control Strategy

When the active current command of the three-phase PWM boost rectifier/inverter is set to zero and the reactive current command is adjusted, only reactive power traverses the line. In this scenario, the power flows from the charger back towards the source. It is imperative to closely monitor the waveforms of phase voltages and currents on the AC side of the single-phase PWM boost rectifier/inverter during this modification of the reactive current command.

Active current command and reactive current command of a three-phase PWM boost rectifier/inverter

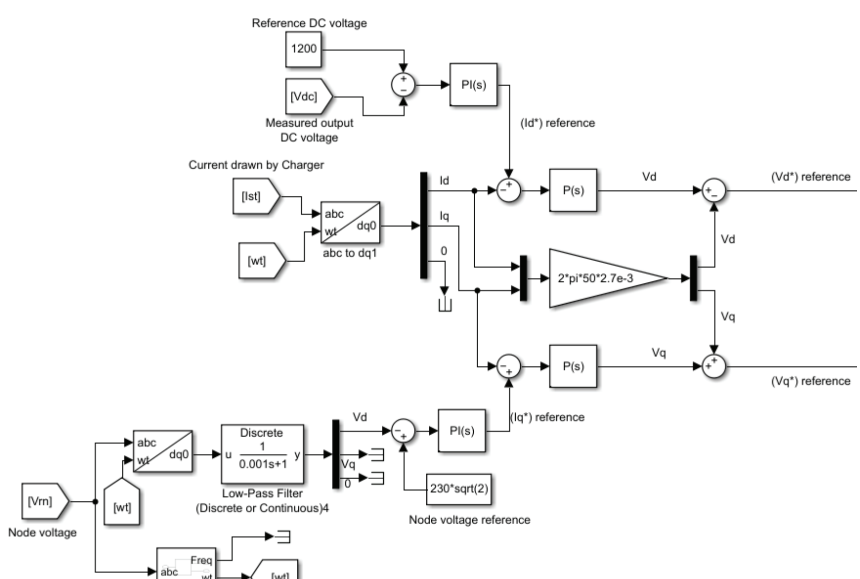

Fig. 8. Active and Reactive Power Flow Control Strategy

When adjustments are made to both the active and reactive current commands of the three-phase PWM boost rectifier/inverter, a concurrent flow of active and reactive power occurs. Active power flows from the source to the charger, while reactive power flows from the charger to the source. Monitoring the waveforms of phase voltages and currents on the AC side of the single-phase PWM boost rectifier/inverter is essential during this modification of active and reactive current commands.

Gate signals Generation

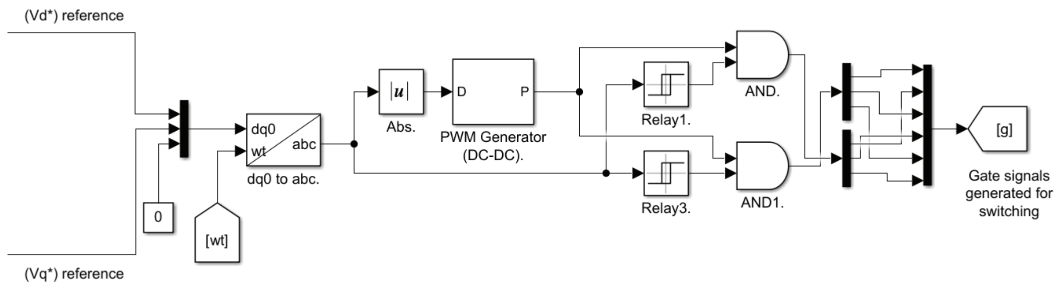

Fig. 9. **Gate signals generation for switching**

After the generation of reference voltages in d-q reference, the signals are converted into a three-phase system. The generated signals in a three-phase system are then passed through a PWM generator (DC-DC) and relays. By using AND gates, six gate signals are generated and are fed to a three-phase bridge rectifier circuit, and by operating in different modes, different gate signals are generated.

Result and Discussion

Initially, data collection within the simulation involved the variation of various parameters such as Id and Iq. By operating the charger in different modes, we scrutinized the waveforms of current and voltage, power transmission to and from the grid, and node voltages. The comprehensive findings from these observations are thoroughly illustrated below.

Active power control

In this context, the reactive component of the current (Iq) is fixed at zero, and only the active component (Id) is subjected to variation. Consequently, the ensuing observations have been made.

Waveform of voltage and current

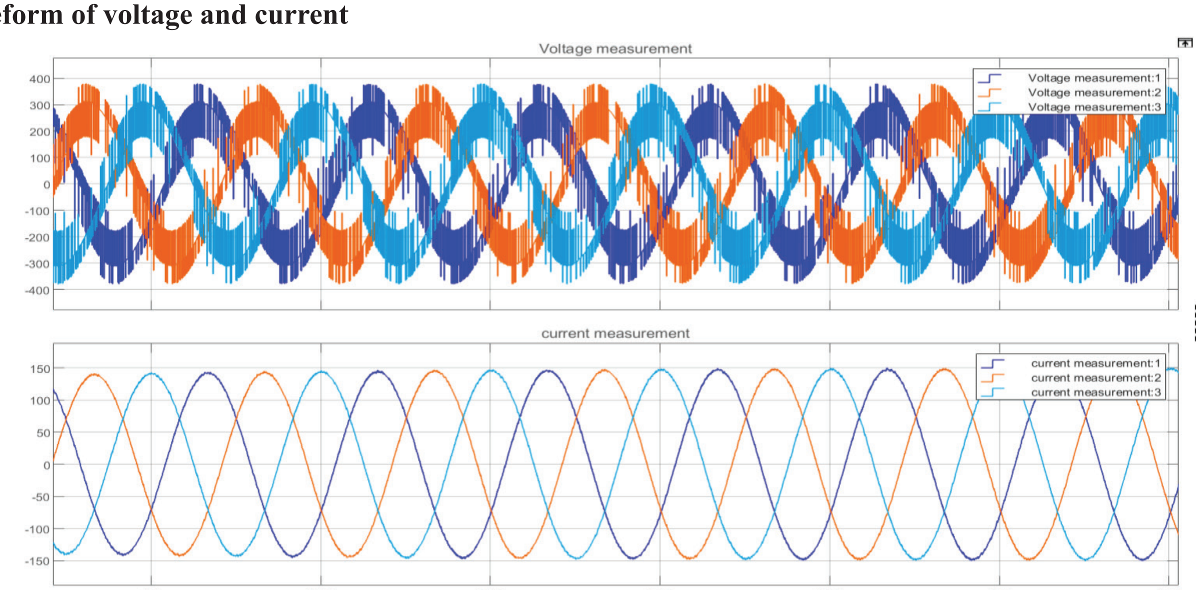

Fig. 10. Waveform of V & I at the point of connection

In this particular scenario, the current and voltage exhibit a phase alignment. Consequently, the converter exclusively utilizes active power. The flow of active power originates from the source and moves towards the charger, given that the current is measured from the source to the charger side and aligns in phase with the voltage. This configuration results in a positive power flow, signifying that the charger operates at a unity power factor.

Voltage measurement

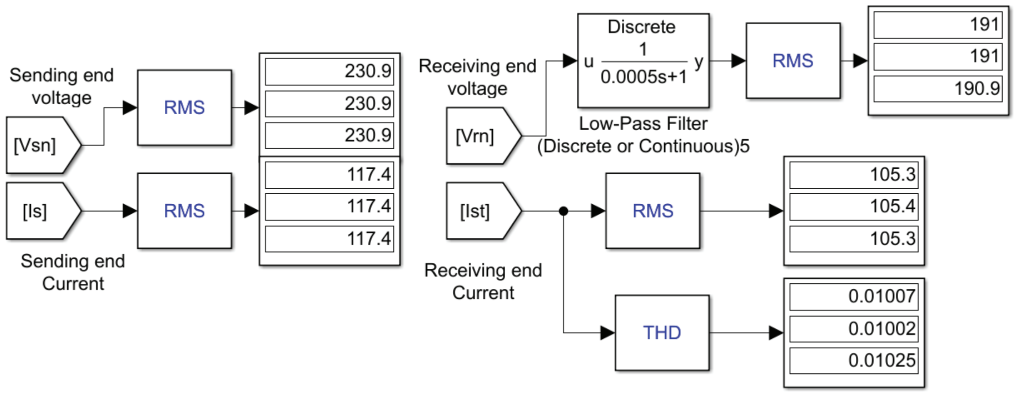

Fig. 11. Sending and receiving end Voltage measurement

In this context, the system voltage was reduced to 191V at the receiving end from the 230V sending end. The implementation of the unity power factor correction strategy significantly reduces the total harmonic distortion of the current.

$$\text{Voltage regulation (V. R)} = \frac{(V_{noload} - V_{fullload})}{V_{fullload}} * 100\%$$

$$= 20.41\%$$

Power measurement

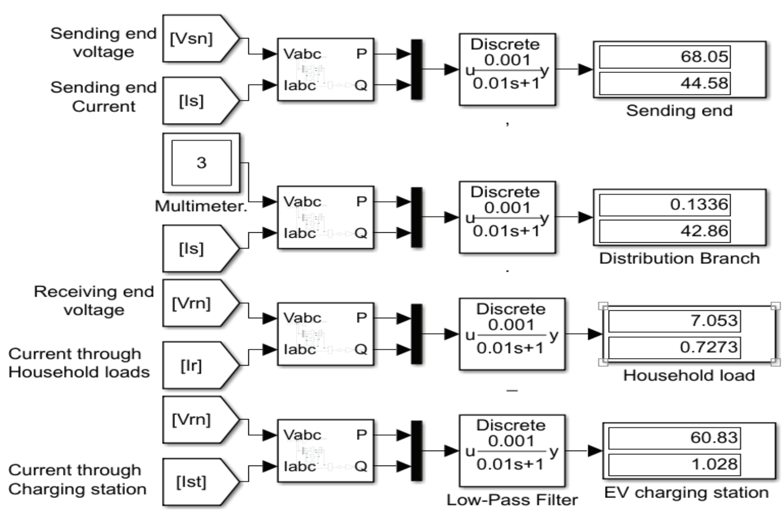

Fig. 12. Power measurements

In this scenario, both chargers are drawing their rated capacity of 60KW across three phases. However, owing to voltage drop issues at the receiving end, the residential load is unable to receive its designated power, posing a potential risk of damage to household equipment. In the modeled three-phase system, the residential load is designed for 10KW and 1KVAR. Unfortunately, due to the voltage drop at the receiving node, only 7KW and 0.7KVAR are being supplied by the source. Notably, the branch absorbs reactive power to the extent of 42.86KVAR.

Reactive power control

In this context, the reactive component (Iq) of the current is subject to variation, while the active component (Id) is kept at zero. This configuration transforms the charger into a STATCOM, ensuring the constant voltage of the connecting node and supplying reactive power to the electrical grid. In this operational mode, electric vehicles remain unplugged, and the charger exclusively delivers reactive power to the grid connection, particularly during periods of high traffic and heavy load. Consequently, the ensuing observations have been made.

Waveform of voltage and current

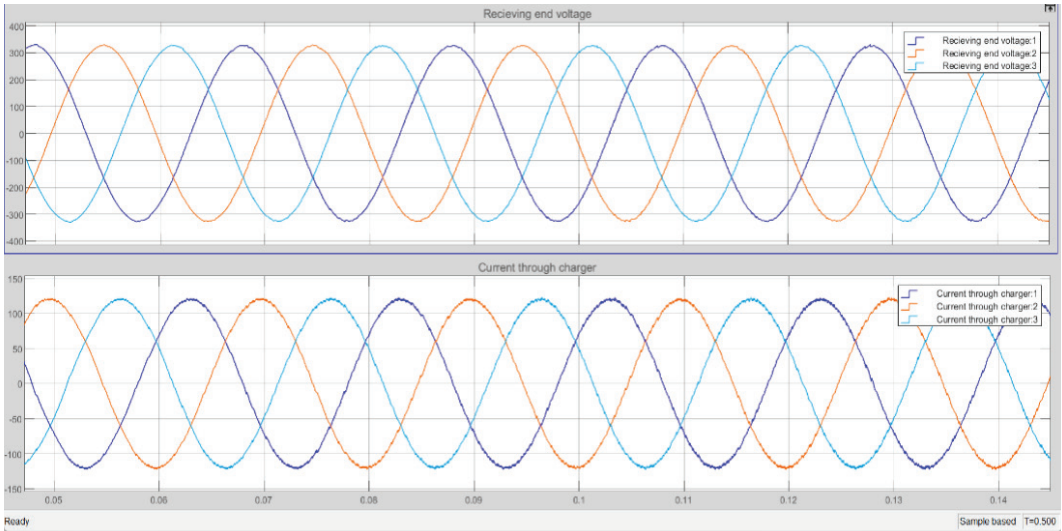

Fig. 13. Waveform of V & I at the point of connection

A noticeable observation is the current leading the voltage by 90 degrees, resembling the effect of a capacitor and facilitating the supply of reactive power to the network. This mode finds practical application, especially during instances of heavy traffic in the grid when electric vehicles are not connected. Consequently, in this mode, the charging station functions as a compensatory device, akin to a capacitor bank or STATCOM.

Voltage measurement

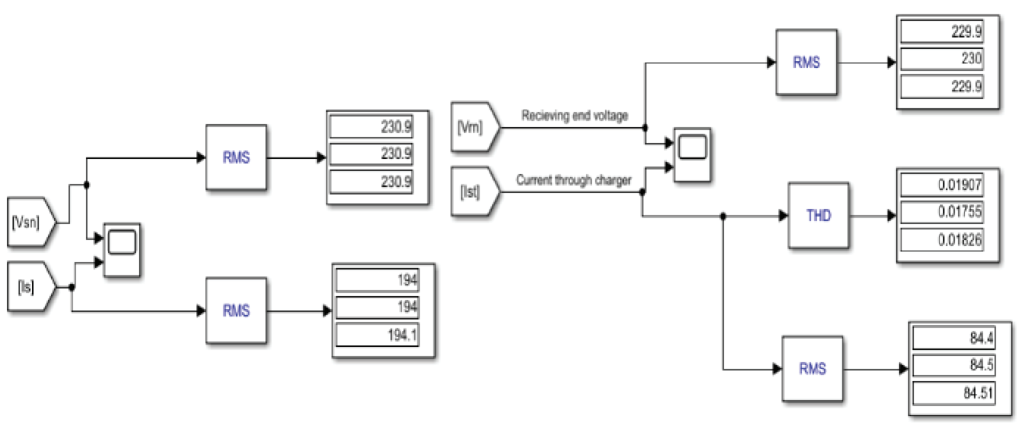

Fig. 14. Sending and receiving end Voltage measurement

The observation reveals that the voltage at the receiving end closely approximates the voltage at the sending end in both systems. In this situation, the charging station regulates the grid's voltage by injecting reactive power into the grid and operating as a STATCOM. Additionally, in both systems, the total harmonic distortion (T.H.D) of the current is significantly reduced, measuring at 1.708%.

$$\text{Voltage regulation (V. R)} = \frac{(V_{noload} - V_{fullload})}{V_{fullload}} * 100\%$$

In this context, the voltage regulation is maintained at less than 2%. Consequently, the system attains a high level of reliability and stability.

Power measurement

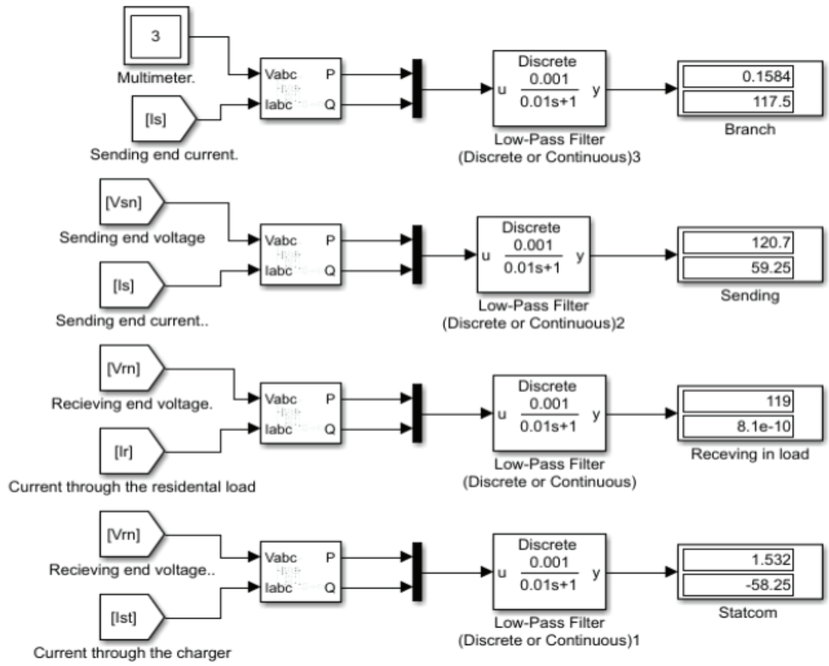

Fig. 15. Power measurements

For heavy traffic demonstration, we increased the residential load to 120KW. Now the node voltage as well as household demand meets the specified values. As a result, the source and charger work together to supply reactive power to the distribution branch and residential loads.

Both Active and Reactive power control (Bidirectional)

Here, the current's active and reactive components, Id and Id, are both modified, and the ensuing observations are made. Both active and reactive power can be managed in this mode of operation, which also includes the charging battery linked.

Waveform of voltage and current

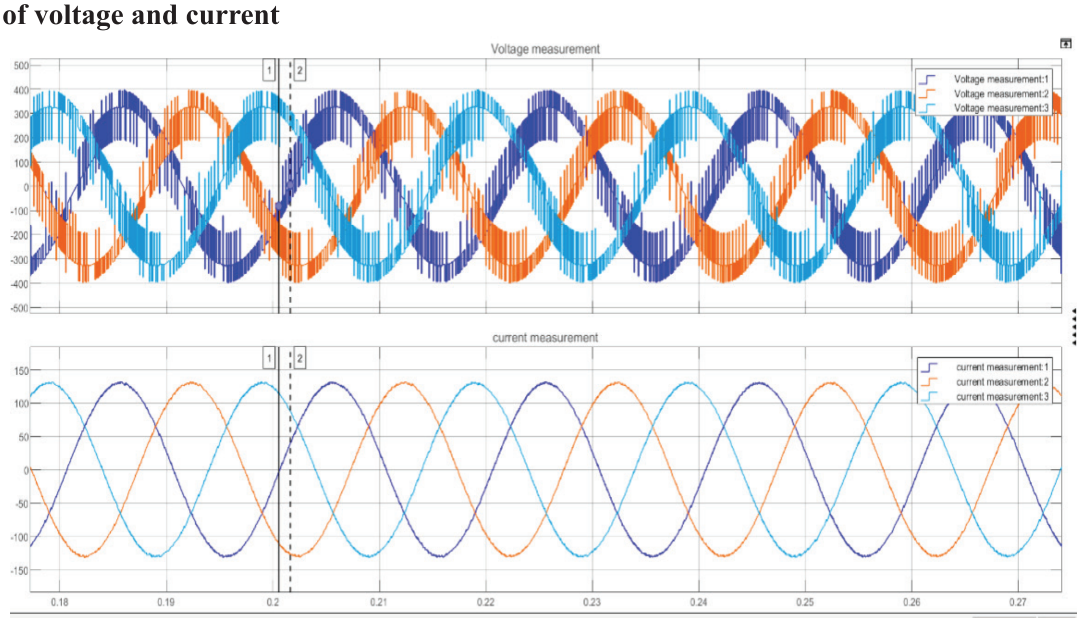

Fig. 16. Waveform of V & I at the point of connection

In this scenario, for voltage regulation at the receiving end during battery charging, the charger's generated reactive power is modulated using a PID controller. Consequently, the current assumes a leading position relative to the voltage by a specific angle.

The closed-loop control system, incorporating the cross-coupling strategy, precisely governs the degree by which the current leads the voltage. This control methodology adeptly aligns to maintain the grid voltage in consonance with the transmitting end voltage.

Voltage measurement

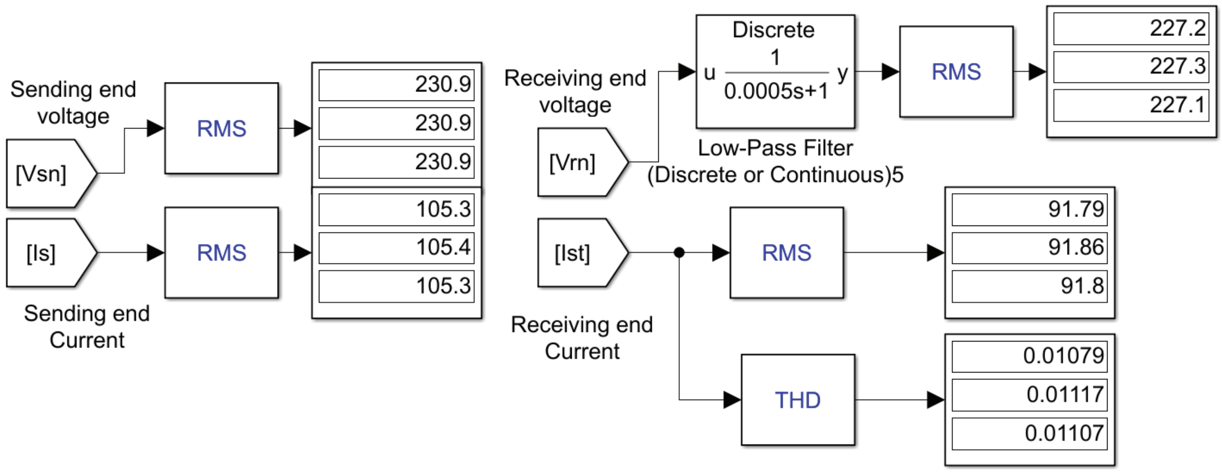

Fig. 17. Sending and receiving end Voltage measurement

In this instance, noticeable regulation is evident in the voltage at the receiving end, closely approximating the voltage at the sending end. In this operational state, the charger simultaneously charges electric vehicles and provides reactive power to the grid, effectively balancing the grid's voltage. Additionally, across both systems, the total harmonic distortion of the current is significantly reduced, measuring at approximately 1.1%.

Voltage regulation (V. R) = $\frac{(V_{noload} - V_{fullload})}{V_{fullload}} * 100\%$

In this configuration, the voltage regulation remains below 2%, imparting a high degree of reliability and stability to the system.

Power measurement

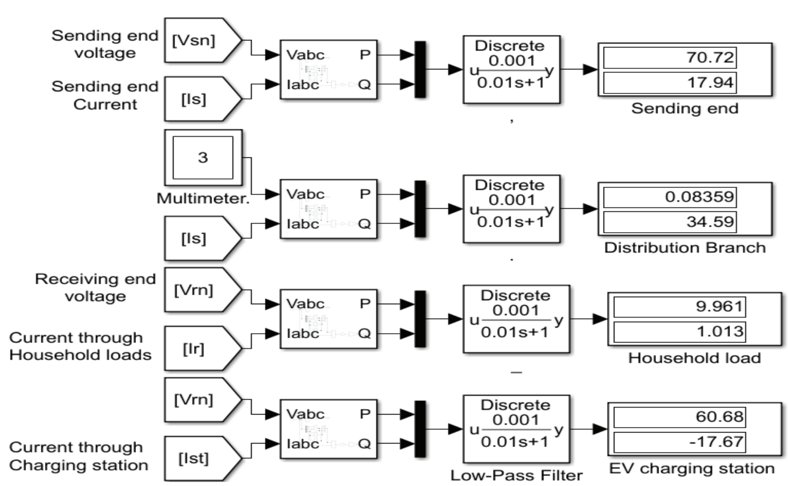

Fig. 18. Power measurements

In this context, for voltage control at the point of connection, the charger employs 60KW of active power and injects 17.72KVAR of reactive power into the grid. As a result, the residential load now consumes its rated power, specifically 10KW and 1KVAR. This adjustment contributes to stabilizing the grid, rendering it more reliable.

DC Voltage measurement

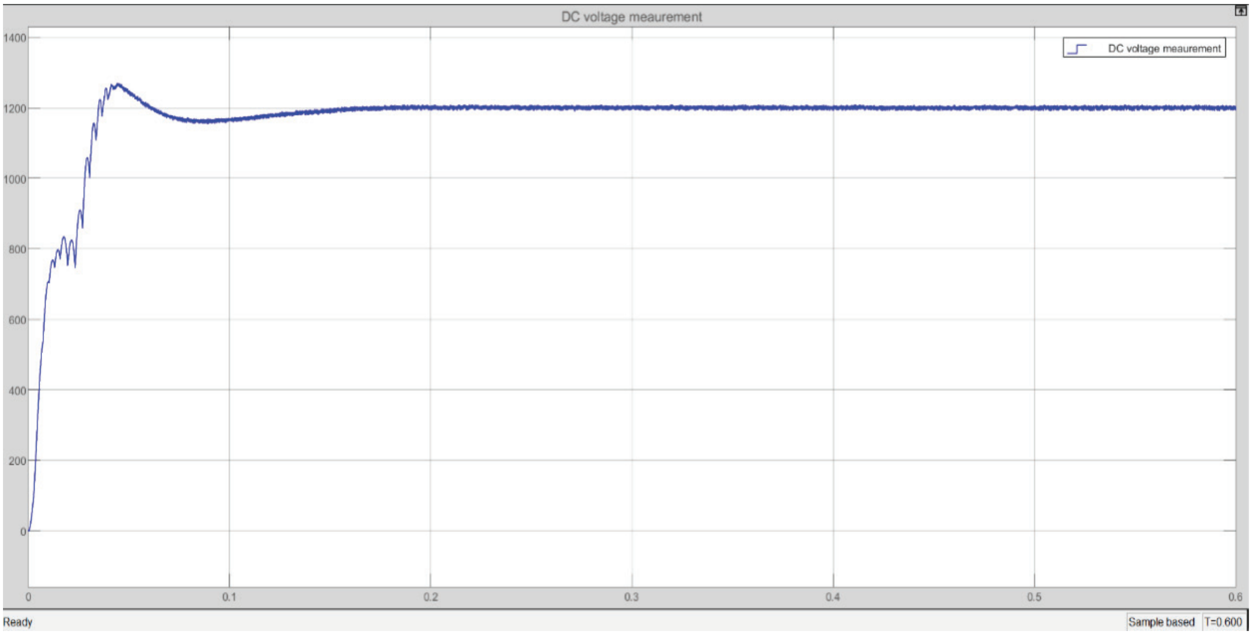

Fig. 19. Output DC voltage of charging station

The output DC voltage was consistently maintained at 1200V to facilitate the charging of the 60KW battery.

Gate signals

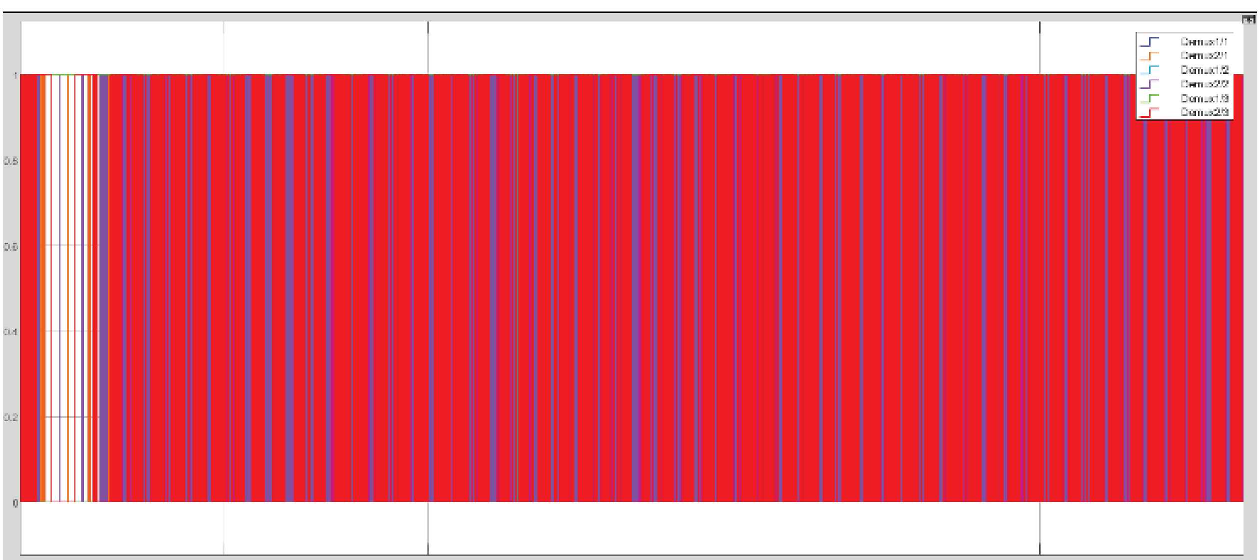

Fig. 20. Gate signals generated by the control system for switching purposes.

The output of the control system is fed to the gates of the bridge rectifier and thus by proper switching according to the command given, gate signals are generated accordingly. The above-shown gate signal is during the bidirectional mode. To operate a three-phase bridge rectifier circuit, the control system in a three-phase system generates a total of six gate signals. The frequency at which the gate signals are produced is 27 KHz. As a result, 27 KHz is the switching frequency.

Conclusions

The ability of a charging station to concurrently charge EVs and supply reactive electricity to the grid has been examined in this research. A technique for compensating reactive power in electric vehicle applications has been introduced. MATLAB/Simulink is used to model and simulate the entire system. The modeling results indicate that the onboard charger can be programmed to inject a specific quantity of reactive power into the power grid without affecting its functionality. Most crucially, the suggested technique simply requires a firmware update and no additional hardware to be used with the current charging stations. The smart EV charger developed in this project demonstrates both dynamism and reliability. Beyond operating at unity power factor, the charger possesses the capability to supply reactive power to the electrical grid, aiding in the maintenance of the necessary grid voltage at the point of common connection. This versatility allows the EV charging station to function in three distinct modes, showcasing its intelligence, adaptability, and cost-effectiveness.

References

1. K. Sinjari and J. Mitra, "Electric Vehicle Charging with Reactive Power Compensation to Distribution Systems," *2020 IEEE Industry Applications Society Annual Meeting*, Detroit, MI, USA, 2020, pp. 1-6, doi: 10.1109/IAS44978.2020.9334838.
2. C. C. Chan and K. Chau, “An overview of power electronics in electric vehicles,” IEEE Transactions on Industrial Electronics, vol. 44, no. 1,pp. 3–13, 1997.
3. J. Carlos Gómez and M. M. Morcos, "Impact of EV battery chargers on the power quality of distribution systems", IEEE Trans. Power Del., vol. 18, no. 3, pp. 975-981, Jul. 2003
4. Sivaraman Palanisamy; Sharmeela Chenniappan; Sanjeevikumar Padmanaban, "Surge Protection Device for Electric Vehicle Fast-Charging Infrastructure," in *Fast-Charging Infrastructure for Electric and Hybrid Electric Vehicles: Methods for Large-Scale Penetration into Electric Distribution Networks*, IEEE, 2023, pp.129-137, doi: 10.1002/9781119987772.ch8.
5. R. C. Leou, C. L. Su and C. N. Lu, "Stochastic analyses of electric vehicle charging impacts on distribution network", IEEE Trans. Power Syst., vol. 29, no. 3, pp. 1055-1063, May 2014.
6. Dharmakeerthi C. Mithulananthan N. Saha T.: ‘Impact of electric vehicle fast charging on power system voltage stability ’, Int. J. Electr. Power Energy Syst., 2014, 57, pp. 241–249.