Impact Assessment of Electric Vehicle Charging on The Electric Power Grid

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Abstract

Electric power systems now face additional difficulties as a result of the quick rise in the use of electric vehicles (EVs), mainly with regard to load management and power quality. Because uncontrolled EV charging uses non-linear power electronic converters, it can result in higher peak loads, voltage swings, and the injection of harmonic currents. With a focus on power quality degradation as determined by Total Harmonic Distortion (THD), this study examines how EV charging affects the electrical system. MATLAB/Simulink is used to implement and test a Shunt Active Filter (SAF) in order to address these problems. In order to compensate for the harmonics produced by EV chargers, the SAF is built using a current management method. Simulation results demonstrate that, in the absence of harmonic mitigation, the system experiences a THD of 18.3%. After deploying the SAF, the THD is effectively reduced to 3.7%, complying with IEEE 519 standards. These results confirm the effectiveness of SAFs in improving power quality and ensuring reliable grid operation in EV-integrated scenarios. The proposed model serves as a reference for grid planners and engineers seeking practical solutions for maintaining power quality in modern distribution networks.

Keywords: Electric Vehicle (EV) Charging, Power Quality, Total Harmonic Distortion (THD), Shunt Active Filter (SAF), MATLAB/Simulink, Harmonic Compensation, Grid Integration, IEEE 519 Standards, Non-linear Loads, Smart Grid.

I.   INTRODUCTION

To minimize greenhouse gas emissions and reliance on fossil fuels ,it is required to bring the rapid deployment of electric vehicles (EVs), which is causing a significant upheaval in the transportation industry [1], [2]. Governments and industries worldwide are promoting EV adoption through policy incentives, technological innovation, and infrastructure development [3]–[5]. While EVs present environmental and economic advantages, their large-

scale integration poses significant challenges to the existing electric power grid [6], [7]. One of the primary concerns is the increased load demand and power quality degradation associated with EV charging. Uncontrolled or uncoordinated EV charging, especially during peak hours, can result in transformer overloading, voltage instability, and peak demand escalation [8], [9]. Furthermore, power electronic converters used by EV chargers, especially rapid and Level 2 chargers, function as non-linear loads and introduce harmonic currents into the grid [10], [11]. These harmonics can cause a rise in Total Harmonic Distortion (THD), leading to overheating of transformers, malfunction of protection devices, and reduced equipment lifespan [12]. The effects of EV charging on grid voltage profiles, power losses, and frequency stability have been emphasized in a number of studies [13]–[15]. Modeling and simulation-based approaches, such as those using MATLAB/Simulink and PSCAD, have been employed to evaluate EV load behavior under different penetration levels and control strategies [16], [17]. Among various power quality solutions, Shunt Active Filters (SAFs) have proven effective in mitigating current harmonics and improving the overall quality of power [18], [19]. SAFs operate by injecting compensating currents that cancel out harmonics produced by non-linear loads [20]. To regulate SAF performance under dynamic load situations, a number of control schemes have been devised, including synchronous reference frame (SRF), instantaneous power (p-q) theory, and hysteresis current control. [21]–[23]. According to recent studies, SAFs help with reactive power compensation, voltage regulation, and THD reduction in EV-integrated distribution systems [24].

The IEEE 519-2014 standard specifies that the THD at the point of common coupling (PCC) should remain below 5% for systems below 69 kV [25]. However, in scenarios involving high EV penetration, THD values often exceed this limit without adequate compensation [26]. Experimental and simulation-based studies confirm that the application of SAFs can effectively bring the harmonic levels within acceptable bounds, thus enhancing the reliability and efficiency of the power network [27]–[29].

The purpose of this article is to examine how EV charging affects the electric power grid, with an emphasis on power quality concerns[30]-[33]. To model the harmonic impacts of EV chargers and the associated compensation provided by SAFs, a MATLAB/Simulink model is created. The performance is evaluated in terms of THD reduction and compliance with IEEE standards. The study provides insights into the practical implementation of SAFs for supporting clean and stable integration of EVs into modern power systems.

II. SYSTEM DESCRIPTION

The suggested solution uses a Shunt Active Filter (SAF) to show harmonic mitigation and examine the power quality impact of EV charging on the distribution network.Figure 1 displays the block diagram of the suggested system, with an EV charger represented by the non-linear load. The following are the primary components of the entire system, which is modeled and simulated using MATLAB/Simulink.:
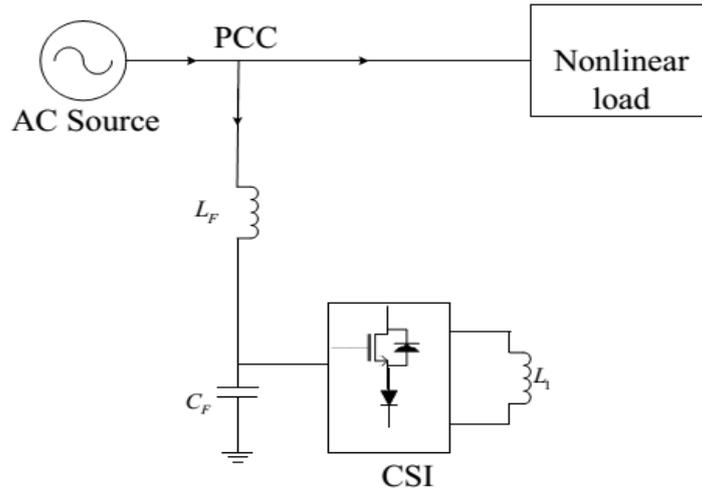
Figure 1. Block diagram of Proposed CSI based shunt active power filter

A. Electric Vehicle Charging Station Model

The EV charging station is modelled as a three-phase system connected to the distribution grid. The charging station is equipped with multiple Level 2 chargers, each incorporating power electronic converters that act as non-linear loads. These converters are modelled as uncontrolled diode bridge rectifiers followed by DC-link capacitors and constant power loads to replicate real-world charging behaviour [30].

- Input: 415 V, 50 Hz, three-phase AC supply
- Output: Controlled DC load simulating EV battery charging
- Load Profile: Time-varying, reflecting simultaneous charging events

The aggregated behaviour of multiple EV chargers leads to significant harmonic injection and reactive power demand, especially during peak charging hours.

B. Power Distribution System

A simplified radial distribution system is used to represent a low-voltage feeder supplying both linear residential loads and non-linear EV charging loads. The system parameters are selected to mimic realistic conditions found in urban distribution networks.

- Feeder Voltage: 11 kV/415 V via step-down transformer
- Load Mix: 60% linear (resistive and inductive) and 40% non-linear (EV loads)
- Transformer Rating: Typically 100 kVA to 250 kVA depending on load density

C. Shunt Active Filter (SAF)

In order to counteract the harmonics produced by the EV chargers, the SAF is linked in parallel at the point of common coupling (PCC). A DC-link capacitor, a coupling inductor, and a voltage source inverter (VSI) make up the SAF. After detecting the load current, it separates the harmonic components and cancels them by injecting equal and opposite currents.

- Control Strategy: Instantaneous Reactive Power Theory (p-q) or Synchronous Reference Frame (SRF) theory

- PWM Scheme: Hysteresis current controller or Sinusoidal PWM

- DC Link Voltage: Maintained constant through a Proportional-Integral (PI) controller

- Coupling Inductor: Provides smoothing and limits switching ripple

The filter dynamically adjusts its output to track the harmonics generated by the non-linear loads in real-time.

D. Measurement and Monitoring Subsystem

Important metrics are continuously tracked, including voltage, current, active power, reactive power, and total harmonic distortion (THD). The Fast Fourier Transform (FFT) block in Simulink is used to analyze THD at the PCC both with and without the SAF in operation.

- THD Calculation: Based on IEEE Std. 519-2014

- Measurement Points: PCC, feeder input, SAF output

- Scope Outputs: Waveforms of voltage, current, and injected harmonic components

III. CONTROL OF PROPOSED SYSTEM WITH SLIDING MODE CONTROL

The Shunt Active Filter (SAF) requires a strong and dynamic control technique in order to provide efficient harmonic compensation when non-linear and time-varying loads, like EV chargers, are present. In this study, a Sliding Mode Control (SMC) approach is implemented due to its inherent robustness against system uncertainties, parameter variations, and external disturbances.
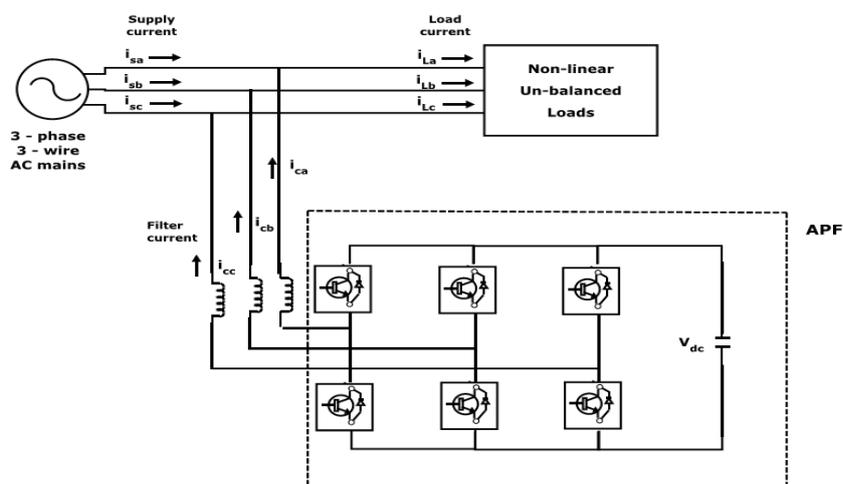

Figure 2. Phase three-wire APF

A. Overview of Sliding Mode Control

The idea behind the non-linear control method known as "sliding mode control" is to make the system state trajectories "slide" along a predetermined surface, or "sliding surface." The controller is designed such that the system is first brought to this surface (reaching phase), and then constrained to move along it (sliding phase), resulting in a dynamic response that is largely insensitive to modelling inaccuracies and disturbances.

SMC is particularly suitable for power electronic converters due to its fast transient response, stability under parameter uncertainties, and ease of implementation in digital control systems.

B. Control Objectives

The main objectives of the SAF control using SMC are:

- To determine the load current's harmonic component.

- To generate reference compensating currents that cancel harmonics at the Point of Common Coupling (PCC).

- To regulate the DC-link voltage of the inverter within desired limits.

- To ensure robust tracking of reference signals under varying load and grid conditions.

C. Generation of Reference Compensating Currents

The total load current $i_L(t)$ consists of a fundamental component if(t) $i_f(t)$, and a harmonic component $i_h(t)$. The goal of the controller is to inject a current $i_{inj}(t) = i_h(t)$, such that the source only supplies the fundamental component.

The load current is monitored and filtered using methods like a low-pass filter or Synchronous Reference Frame (SRF) transformation in order to find the reference current i_{inj}^*. The SAF is then referenced to the retrieved harmonic current.

D. Design of Sliding Surface

Let $e_i(t) = i_{inj}^*(t) - i_{inj}(t)ei(t)$ represent the current tracking error for each phase. The sliding surface $s_i(t)$ is then defined as:

$$s_i(t) = \frac{d}{dt} e_i(t) + \lambda e_i(t) \qquad\qquad (1)$$

where λ is a positive constant that defines the slope of the sliding surface and influences convergence speed.

When the system state lies on the surface $s_i(t) = 0$, the tracking error converges to zero exponentially.
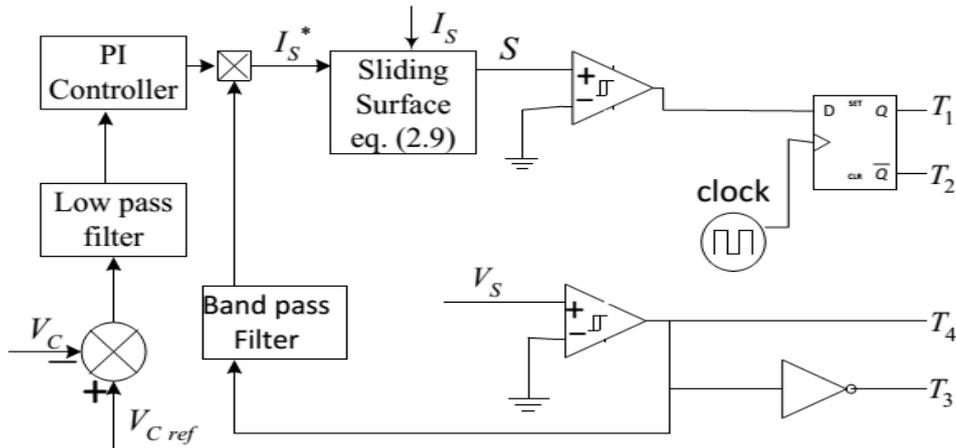
Figure 3. Analog sliding mode controller for shunt APF

E. Control Law

The control input is derived by ensuring the sliding condition is satisfied:

$$\frac{d}{dt} s_i(t) = -\eta \cdot \text{sgn}\big(s_i(t)\big) \qquad (2)$$

where:

The sliding surface's attractiveness is guaranteed by the positive constant η.

$sgn\big(si(t)\big)$ is the signum function.

The inverter switching signals are then determined based on the sign of the control input, which ensures the current injected by the SAF follows the desired reference.

F. DC-Link Voltage Regulation

The SMC is usually used in conjunction with a PI controller to maintain a steady DC-link voltage. By varying the reference current vector's magnitude, the discrepancy between the real and reference DC voltage is reduced.

$$e_v(t) = V_{dc}^* - V_{dc}(t) \qquad (3)$$

$$I_{ref}^* = K_p e_v(t) + K_i \int e_v(t)dt \qquad (4)$$

This reference current magnitude is combined with the unit current vectors in each phase to form the final reference signals for SMC.

G. Chattering Reduction

A common challenge in SMC is the high-frequency oscillation known as chattering, caused by the discontinuous nature of the sign function. To mitigate this, a boundary layer approach using a saturation function is applied:

$$sat(s/\delta) = \begin{cases} 1, & s > \delta \\ s/\delta, & | s | \le \delta \\ -1 & s < - \delta \end{cases} \qquad (5)$$

where δ defines the width of the boundary layer. This modification helps reduce chattering while retaining the robustness of the control.

IV. RESULTS & DISCUSSION

Grid current (before filtering): Distorted with high THD (~20–25%)

Grid current (after filtering): Sinusoidal with THD < 5% (as per IEEE 519 standards)

SAF current: Harmonic waveform that cancels the load harmonics

DC-link voltage: Regulated within ±5% of reference value

Table 1: System Parameters:

Component	Parameter	Value	Remarks
Power Grid Source	Line Voltage (L-L)	415V	Balanced 3-phase system
	Frequency	50 Hz	Standard grid frequency
Distribution Transformer	Primary Voltage	11,000 V	Step-down transformer
	Secondary Voltage	415 V	To match EV charger input
	Power Rating	50 kVA	
EV Chargers (per unit)	Input Voltage	415 V (L-L)	3-phase AC input
	Output DC Voltage	350 V	DC link voltage
	Power Rating	5 kW	Five chargers totaling 25 kW
	Rectifier Type	Diode Bridge	Passive front end
DC-Link Capacitor (SAF)	Capacitance	2200 μF	Maintains voltage stability
	Voltage Rating	800 V	Slightly higher than peak of 415 V
SAF Inverter	Topology	3-phase VSI	Controlled by SMC
	Switching Devices	IGBTs	Fast-switching devices
	Switching Frequency	10 kHz	Typical for harmonic compensation

Coupling Inductors (SAF)	Inductance	2.5 mH	Filters high-frequency components
	Resistance	0.1 Ω	Parasitic resistance
Sliding Mode Controller	λ (lambda – sliding surface slope)	300	Adjusts convergence rate
	η (eta – reaching gain)	100	Ensures reaching condition
	DC-link Voltage Reference	700 V	For voltage regulation
Measurement & Analysis	THD Target (After Filtering)	< 5%	IEEE 519 standard compliant
	Analysis Tool	Powergui – FFT	Calculates THD in simulation

A. Simulink Diagram of Proposed System:

Five EV chargers connected in parallel at the DC side. Each EV charger is modelled using a three-phase diode bridge rectifier followed by a DC-link capacitor ending with a controlled DC load (representing battery charging). Using Universal Bridge for AC-DC conversion and Capacitor and Controlled Current Source for DC-link and charging load. Each EV charger is tuned to draw slightly different charging currents to reflect realistic asynchronous behaviour.
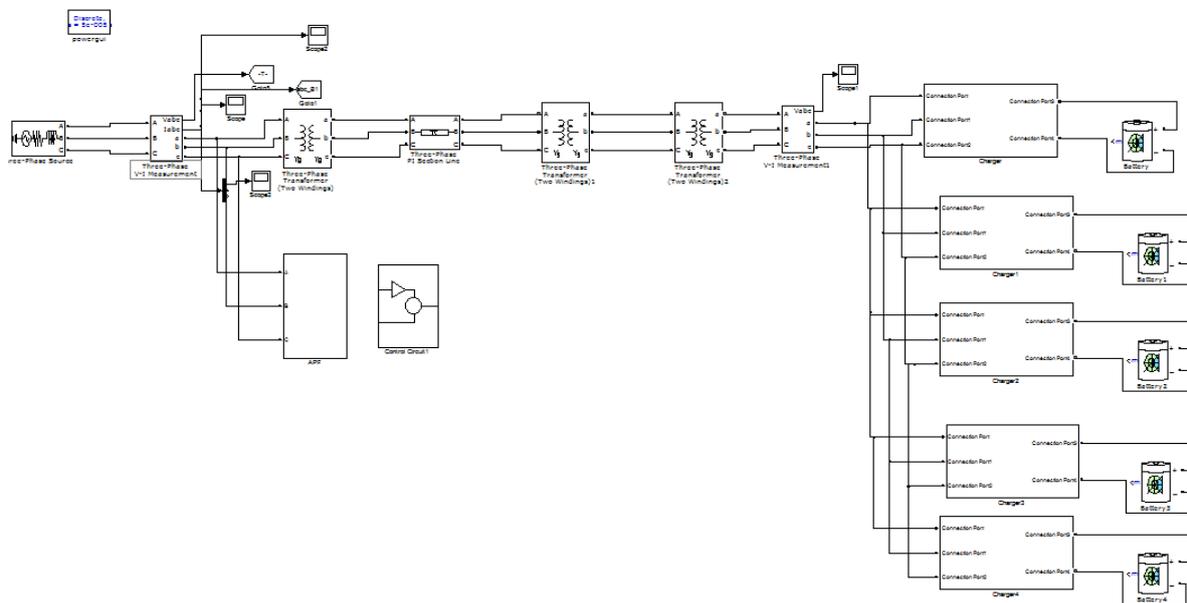

Figure 4. Simulink diagram of proposed system(5 EV chargers are connected at a charging station) with Active Power Filter.
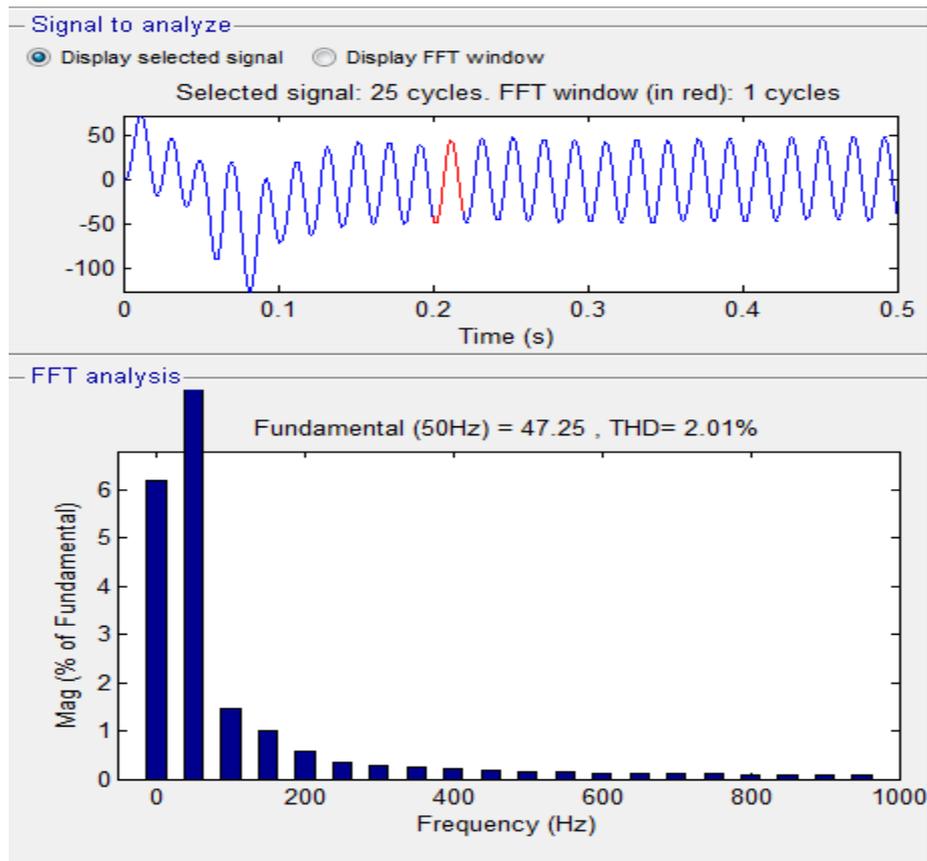
Figure 5 Harmonics, when 5 EV chargers are connected at a charging station with charging Station with Active Power Filter.

V.   CONCLUSION

The integration of Electric Vehicle (EV) charging stations into the power grid introduces significant challenges related to harmonic distortion and reactive power demand, which can deteriorate power quality. Implementing a Shunt Active Filter (SAF) controlled by Sliding Mode Control (SMC) effectively addresses these issues by compensating for harmonics and maintaining voltage stability at the point of common coupling. Simulation results in MATLAB/Simulink demonstrate a substantial reduction in Total Harmonic Distortion (THD) and improved dynamic performance of the SAF under varying load conditions. The robustness and fast response characteristics of the sliding mode controller make it well-suited for real-time compensation in grids with rapidly changing EV load profiles. Overall, this approach provides a reliable and efficient solution to enhance power quality and ensure stable operation of the grid amid increasing EV penetration.

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