Power Quality Analysis of Distribution Transformer Connected in EV Charging Station

Pranav B. Bhandwalkar
Department of Electrical Engineering
SVPM's COE Malegoan (BK)
Baramati, Pune

Pranav A. Kokare
Department of Electrical Engineering
SVPM's COE Malegoan (BK)
Baramati, Pune

Kunal A. Dhumal
Department of Electrical Engineering
SVPM's COE Malegoan (BK)
Baramati, Pune

Soham U. Ingale
Department of Electrical Engineering
SVPM's COE Malegoan (BK)
Baramati, Pune

Prof.J.H.Pawar
Electrical Engineering
SVPM's COE Malegaon (BK)
Baramti, Pune

Prof. S.D.Mangate Department of
Department of Electrical Engineering
SVPM's COE Malegaon (BK)
Baramati, Pune

***

Abstract - With the growing adoption of electric vehicles (EVs), the need for extensive charging infrastructure has risen considerably. This growth has introduced new challenges for electric power distribution networks, particularly concerning power quality. EV chargers, especially fast-charging units, behave as non-linear loads that inject harmonic distortions and cause voltage instability. These distortions propagate through the network and adversely impact the distribution transformer by increasing thermal stress and reducing its operational life. This study explores the impact of EV charging stations on power quality, particularly disturbances at the transformer level. A simulation model developed in MATLAB/Simulink serves to study these impacts under various scenarios. Furthermore, the paper discusses effective mitigation strategies, emphasizing the integration of renewables and smart load management.

☐ **Keywords—** EV Charging, Electrical Power Quality, Harmonic Effects, Transformer in Distribution Network, Voltage Fluctuation, MATLAB Simulation

1. INTRODUCTION

The global transition toward sustainable and eco-friendly transportation has placed electric vehicles (EVs) at the forefront of innovation. With increasing concerns about climate change, fossil fuel depletion, and rising urban pollution, governments and industries worldwide are accelerating the adoption of EVs. These vehicles offer several advantages, including zero tailpipe emissions, lower operating costs, and reduced dependency on non-renewable energy sources. However, as the number of EVs on the road continues to rise, so does the demand for accessible and reliable charging infrastructure.

To support this shift, extensive networks of EV charging stations are being deployed in urban and rural areas alike. These stations connect directly to the low-voltage distribution grid, often relying on existing infrastructure, such as residential transformers or commercial distribution networks. While this integration simplifies deployment, it introduces significant electrical challenges that were not originally anticipated in the design of traditional power distribution systems.

Among these challenges, power quality has emerged as a critical concern. Unlike conventional resistive loads, EV chargers—especially Level 2 and DC fast chargers—are inherently non-linear in nature due to the involvement of power electronic circuits such as rectifiers, inverters, and DC-DC converters. These components cause distortion in the current waveform, which, in turn, generates harmonics that can propagate through the grid. The resulting harmonics not only degrade the voltage waveform but also lead to increased heating in electrical equipment, poor power factor, and electromagnetic interference.

The distribution transformer plays a crucial role in the local delivery of electric power by stepping down high-voltage supply to levels suitable for end users. However, when subjected to the stresses introduced by EV charging, these transformers are at risk of accelerated aging. Repeated exposure to harmonic-rich currents, frequent voltage sags due to sudden load changes, and prolonged high loading conditions can lead to insulation degradation, core saturation, and increased copper losses. In areas with high EV penetration, this can compromise the reliability and efficiency of the entire distribution network.

Moreover, the uncoordinated and unregulated nature of EV charging—such as simultaneous charging during peak hours—can exacerbate demand spikes, causing grid instability and transformer overloading. This makes it imperative to evaluate the interaction between EV chargers and the power system under various real-world scenarios to identify potential risks and devise appropriate countermeasures.

This paper aims to analyze the specific impacts of EV charging stations on power quality, with a focus on their effect on distribution transformers. By developing a simulation model using MATLAB/Simulink, we investigate key performance indicators such as total harmonic distortion (THD), voltage sag and swell, power factor, and thermal loading of transformers.

2. EV CHARGING STATION ARCHITECTURE

An Electric Vehicle Charging Station (EVCS) serves as the vital interface between electric vehicles and the power grid. As EV adoption continues to expand, the design, configuration, and electrical behavior of charging stations have become critical components in the stability and efficiency of the distribution network. Understanding the architecture of these stations is essential to assessing their impact on power quality, particularly at the transformer level.

A typical EVCS consists of several interconnected subsystems, including input protection devices, transformers, AC/DC converters, control units, communication modules, and safety disconnects. The power flow begins with the connection to the local utility grid, often at medium voltage (e.g., 11 kV), which is then stepped down using a distribution transformer to lower voltages suitable for end-user equipment (e.g., 400 V three-phase or 230 V single-phase). This transformed voltage is supplied to individual chargers where it is converted from AC to DC using rectifier circuits and, in some cases, further conditioned using DC-DC converters to regulate output voltage and current according to the battery's requirements.

EV chargers are classified according to their power output and rate of charging.

- **Level 1 chargers** use a standard residential AC outlet (120 V) and are typically used for overnight charging. They are slow and draw minimal current but have negligible impact on the power system.
- **Level 2 chargers** operate at 240 V (single-phase) or 400 V (three-phase) and offer faster charging, making them ideal for public and commercial use.
- **Level 3 or DC fast chargers** skip the onboard charging unit and deliver high-voltage direct current straight to the battery. These chargers often exceed 50 kW, with some modern units delivering up to 350 kW. Due to their high power demand and rapid switching circuits, they introduce substantial harmonics and transients into the grid.

The power electronic converters used in these chargers are responsible for most power quality disturbances. High-frequency switching within rectifiers and inverters leads to the generation of non-sinusoidal currents that contain harmonic components across multiple frequency bands. When these harmonics are fed back into the power system, they distort the voltage waveform, cause heating in transformer windings, and increase the likelihood of equipment malfunction.

In a densely populated charging station, multiple chargers may operate simultaneously. This results in a cumulative harmonic effect, especially when the chargers are not synchronized or do not include harmonic mitigation techniques. Moreover, the diversity of EV models—with varying battery capacities and charging characteristics—leads to uneven load profiles. This can create phase imbalances, neutral overloading, and unpredictable stress on the local transformer.

Communication modules and control units integrated into modern EVCS play a key role in managing energy flow, implementing safety protocols, and interacting with the grid through demand response or smart charging features. However, in many developing regions or unregulated setups, these intelligent controls are absent, leaving the grid exposed to unmanaged loads that fluctuate rapidly.

Thus, the architecture of an EVCS is not only a matter of hardware layout but also of intelligent energy management. The lack of harmonics suppression, poor load balancing, and absence of coordinated charging control can make even a small charging hub a source of significant power quality degradation. A comprehensive analysis of these architectural aspects is necessary to ensure that EV charging stations do not compromise the stability and longevity of the power distribution network, particularly the performance of distribution transformers.

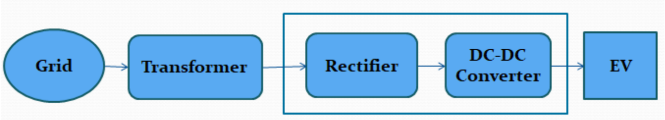
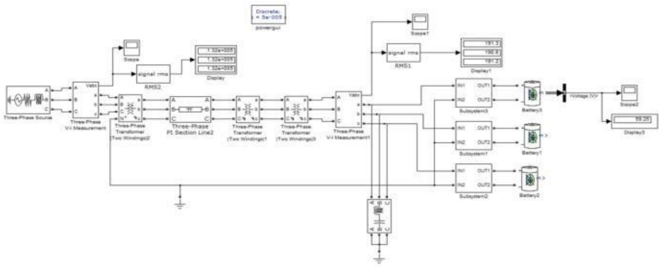


Figure-1.EV CHARGING STATION

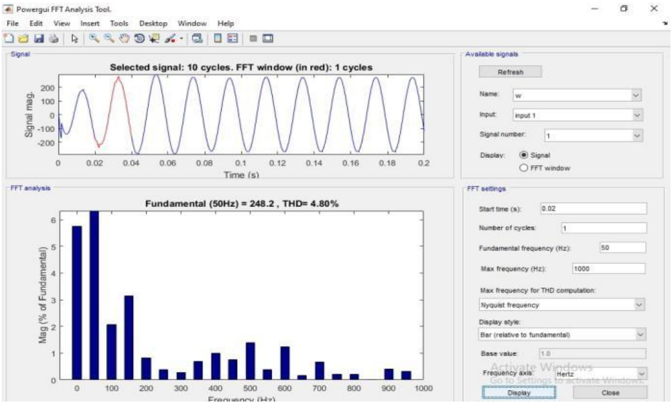
3. MATLAB SIMULINK MODEL OF ELECTRIC VEHICLE CHARGING STATION

The provided diagram represents a Matlab/Simulink model of a smart grid-connected battery energy storage system using a three-phase distribution network. This simulation framework is developed to analyze voltage regulation, energy storage management, and the coordination of multiple subsystems within a smart grid environment.At the leftmost side, the system begins with a three-phase source, which mimics the main grid or generation source. The voltage and current signals from the source are monitored using a Three-Phase V-I Measurement block, and this data is then analyzed using RMS and display blocks to calculate and present the RMS voltage values. The signal is further observed using a scope for dynamic monitoring.

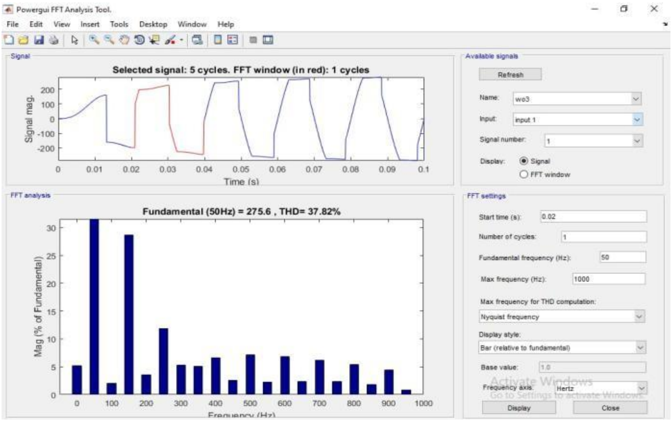


The grid power is then transferred through a series of transformers and a PI Section Line, which likely simulates a transmission or distribution line segment. These transformers ensure proper voltage regulation and isolation between different sections of the grid. The voltages at various stages are again monitored using V-I Measurement blocks, and RMS voltages are displayed, as shown in Display1.On the right-hand side, the system integrates three subsystems labeled Subsystem1, Subsystem2, and Subsystem3, each connected to a corresponding battery storage unit (Battery1, Battery2, Battery3). These subsystems likely consist of control logic for charging/discharging operations, interfacing with the grid through power electronic converters (not explicitly shown but implied within the subsystems). The batteries are monitored using voltage sensors and connected in such a way that their combined output is observed through a voltage measurement block, shown on Scope2 and Display3.This model reflects a distributed energy storage system integrated into a smart grid, allowing real-time monitoring, voltage regulation, and energy management. The PowerGUI block at the top center specifies that the simulation runs in a discrete domain with a step size of 5e-005 seconds, indicating precise time-step simulation suitable for power electronics and control system analysis.Such configurations are crucial in modern smart grid applications to balance supply-demand, enhance reliability, and enable integration of renewable energy sources by providing auxiliary support through battery storage systems

4. Harmonic Analysis Using FFT: With and Without Filter



Name: w
Input: input 1
Signal number: 1
Display: ● Signal ○ FFT window
Start time (s): 0.02
Number of cycles: 1
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz



Name: wo3
Input: input 1
Signal number: 1
Display: ● Signal ○ FFT window
Start time (s): 0.02
Number of cycles: 1
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz

3. CONCLUSIONS

This study highlights the significant power quality challenges introduced by the integration of Electric Vehicle charging stations with distribution transformers, including harmonic distortion, voltage fluctuations, and power factor deterioration. The analysis demonstrates that the non-linear loads of EV chargers generate considerable harmonic currents, which can adversely impact the performance and lifespan of distribution transformers and connected equipment. Through detailed system modeling and simulation, the critical power quality indices such as Total Harmonic Distortion (THD), voltage stability, and power factor were evaluated under various loading conditions. The findings emphasize the necessity of implementing effective mitigation techniques, including harmonic filtering, power factor correction, and advanced charger control strategies, to minimize these adverse effects. Proper design and deployment of these solutions ensure reliable, efficient, and stable operation of the power distribution network while supporting the increasing demand for EV charging infrastructure. Ultimately, this research provides valuable insights for utilities, engineers, and policymakers to facilitate the seamless integration of EVs into existing electrical grids without compromising power quality standards.

REFERENCES

[1] Godina, R., et al. "Impact assessment of EV loads on distribution transformers." Energy Conversion and Management, 2016.
[2] Durante, L., et al. "Impacts of EV charging on non-sinusoidal waveforms." Int. J. Process Syst. Eng., 2017.
[3] Wetzer, J. "Transformer loss under harmonic loading." Transformers Magazine, 2018.
[4] Padmanaban, S., et al. "Electric vehicle components and grid challenges." Energies, 2017