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Analysis of the Impact of Electric Vehicle Charging Stations on Power Quality Issues

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Abstract - The increasing penetration of electric vehicles introduces significant nonlinear charging loads into distribution networks and can adversely affect power quality. This paper analyzes the impact of an electric vehicle charging station on voltage, current, transformer loading, harmonic distortion, and battery charging behavior using a MATLAB/Simulink model. The modeled network consists of a 132 kV utility grid, three step-down transformers, a 50 km three-phase pi-section transmission line, three charger subsystems, and lithium-ion batteries. Each charger subsystem incorporates rectification and DC-DC conversion and therefore behaves as a nonlinear load. Simulation results indicate voltage sag and swelling, distorted current waveforms, increased transformer power loss, and substantial harmonic content after charger connection. For three electric vehicle chargers, the reported total harmonic distortion is approximately 12.35%, exceeding the 5% power-quality benchmark considered in the study. Battery output voltages also vary with simulation time. The results demonstrate that clustered electric vehicle charging can impose measurable stress on distribution infrastructure and highlight the need for harmonic mitigation, appropriate transformer selection, and coordinated charging strategies.

Index Terms - Electric vehicle charging station, harmonics, MATLAB/Simulink, power quality.

I. INTRODUCTION

Electric vehicles (EVs) are increasingly adopted because they can reduce local emissions, petroleum dependence, and transportation operating costs. Plug-in hybrid electric vehicles, hybrid electric vehicles, and battery electric vehicles use electric machines and battery energy storage in different configurations. Their large-scale deployment, however, transfers a significant portion of transportation energy demand to the electric power system.

EV chargers are power-electronic interfaces and therefore represent nonlinear loads. When many chargers are connected to a distribution feeder, the aggregate charging demand may degrade the voltage profile, distort current waveforms, increase transformer losses, and inject harmonics. Three-phase charging can provide higher charging power, while widely available single-phase charging may create localized loading and power-quality concerns. This work evaluates these effects through a MATLAB/Simulink model of a grid-connected electric vehicle charging station (EVCS).

The objective is to examine voltage and current disturbances, transformer power loss, harmonic distortion, and battery output at different simulation time periods. The study also considers solar energy as a renewable source that can support EV charging infrastructure.

II. LITERATURE REVIEW AND EXISTING SYSTEM

Prior studies identify grid loading, demand management, charging infrastructure, and renewable-energy integration as major research areas associated with EV adoption [1]– [4]. Smart charging, dynamic pricing, and load shifting are frequently proposed to reduce coincident charging demand. Transformer thermal stress and harmonic loading are also important because clustered EV charging can accelerate insulation aging and reduce available transformer capacity [2], [5].

Conventional two-level voltage-source converters are commonly used in charging interfaces, but semiconductor voltage and current limits, power-factor performance, and unidirectional power-flow capability can constrain system performance. The nonlinear nature of rectifier and converter stages is a principal source of harmonic current. Consequently, EVCS design must address both charging functionality and grid-side power quality.

III. SOLAR-ASSISTED EV CHARGING

Electric vehicles may be charged from grid electricity or renewable sources such as solar, wind, hydroelectric, and geothermal generation. Solar-powered charging stations convert incident solar energy directly into electrical energy using photovoltaic modules. The generated energy can be

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supplied to chargers directly through suitable power converters or stored in batteries for later use.

FIGURE 1. SOLAR CHARGING STATION CONCEPT USED TO ILLUSTRATE RENEWABLE SUPPORT FOR EV CHARGING.

Solar integration can reduce grid energy consumption and the carbon intensity of charging. Nevertheless, photovoltaic output depends on irradiance, weather, and installed array size. Therefore, practical solar-assisted charging stations require power-electronic conversion, energy management, and, where necessary, storage or grid support.

IV. DC-DC CONVERTER INTERFACE

A DC-DC converter changes a DC voltage from one level to another while maintaining DC power transfer. In EV charging systems, converters regulate the DC-link or battery-side voltage and current. Buck converters provide step-down conversion, boost converters provide step-up conversion, and buck-boost converters can either increase or decrease the voltage.

A. Buck Converter

The buck converter is a step-down topology. A controlled semiconductor switch alternates between ON and OFF states at high frequency. During the ON interval, the inductor stores energy while supplying the load. During the OFF interval, the inductor current continues through the freewheeling path. For an ideal converter operating in continuous conduction, the average output voltage is proportional to the duty ratio.

$$V_o = D\, V_i, \qquad (1)$$

where V_o is the output voltage, V_i is the input voltage, and D is the switching duty ratio.

B. Boost and Buck-Boost Converters

The boost converter produces an output voltage greater than the source voltage by storing energy in an inductor and transferring that energy to the output. Ideally, its conversion ratio is given by (2).

$$V_o = V_i / (1 - D). \qquad (2)$$

A buck-boost converter provides either step-up or step-down conversion and is useful when the source or DC-link voltage varies over a wide range. These converter families are widely applied in battery chargers, renewable-energy interfaces, automotive electronics, and regulated power supplies.

V. MATLAB/SIMULINK EVCS MODEL

MATLAB provides numerical computation, visualization, and algorithm-development facilities, while Simulink provides a block-diagram environment for dynamic-system modeling. Signals are transferred between functional blocks and subsystems, enabling electrical sources, converters, measurement blocks, and batteries to be integrated into a single simulation.

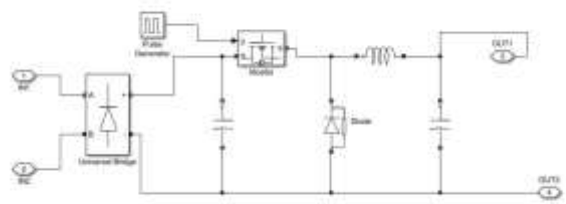

FIGURE 2. EVCS MODEL DIAGRAM SHOWING THE GRID, CONVERSION STAGES, AND CHARGING SUBSYSTEMS.

The EVCS model uses a three-phase utility source, a transmission line, cascaded transformers, and three charging subsystems. Each charging subsystem mainly consists of a rectifier and a DC-DC converter. Lithium-ion batteries are used as the EV energy-storage loads.

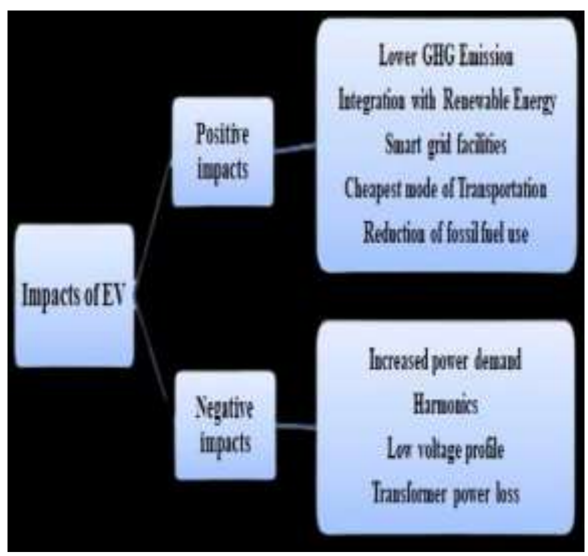

FIGURE 3. FUNCTIONAL BLOCK DIAGRAM OF AN ELECTRIC VEHICLE CHARGING STATION.

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TABLE 1. EVCS MODEL SPECIFICATIONS.

Parameter	Specification
Grid	132 kV, 50 Hz, short-circuit MVA: 200
Transformer 1	132/33 kV, 75 MVA
Transformer 2	33/11 kV, 20 MVA
Transformer 3	11/0.4 kV, 200 kVA
Transmission line	Three-phase π section, 50 Hz, 50 km
Subsystems	3; input 130–180 V AC; output 68/49/49 V DC
Battery	Lithium-ion, 60 V, 130 Ah, initial SOC 30%

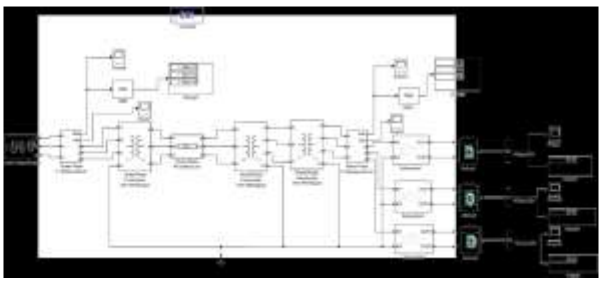

FIGURE 4. MATLAB/SIMULINK MODEL OF THE ELECTRIC VEHICLE CHARGING STATION.

VI. IMPACT OF EV CHARGING STATIONS

A. Power Demand and Harmonics

An EV battery draws energy from the distribution network during charging. The charging power depends on battery capacity, state of charge, charger rating, and charging duration. The gross EV demand is the sum of individual charging demands. Coincident charging can therefore create a rapid increase in feeder loading.

Harmonics are frequency components at integer multiples of the fundamental frequency. Nonlinear charger currents distort current and, through network impedance, can also distort voltage. Total harmonic distortion (THD) is used to quantify waveform distortion. The current THD may be expressed as

$$THD_i = \left[\sqrt{\left(\Sigma I_n^2\right)} / I_1\right] \times 100\%, \quad n \geq 2. \qquad (3)$$

where I_1 is the fundamental current and I_n is the nth harmonic current.

B. Voltage Profile and Transformer Performance

A sudden increase in charging load can reduce the distribution-end voltage and degrade voltage stability. Repeated or clustered charging may produce sag, swelling, and waveform distortion. Harmonic current also increases transformer load losses and heating. The transformer harmonic withstand capability can be represented using the K-factor, which weights harmonic current components according to harmonic order. Appropriate transformer selection and harmonic mitigation are therefore important for EV-dense feeders.

VII. SIMULATION RESULTS AND DISCUSSION

The modeled network assumes a 132 kV utility grid followed by 132/33 kV, 33/11 kV, and 11/0.4 kV step-down transformers. A 50 km three-phase π-section transmission line is included. Three charger subsystems supply lithium-ion batteries. The simulation compares grid-side behavior before and after charger connection.

A. Voltage and Current Disturbances

The distribution-end voltage decreases and becomes distorted when multiple EV subsystems are connected. The post-connection waveform exhibits sag and swelling together with harmonic disturbance. Current is also affected because the charger subsystems impose nonlinear loading.

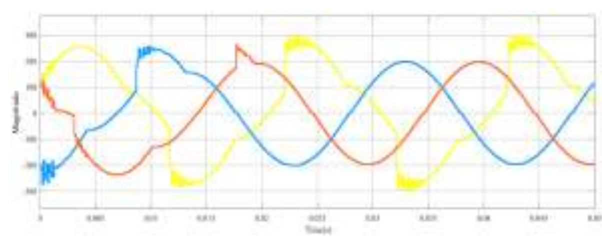

FIGURE 5. INPUT VOLTAGE AFTER CONNECTION OF THE EV CHARGING SUBSYSTEM, SHOWING WAVEFORM DISTURBANCE.

B. Transformer Power Loss

Clustered charging increases transformer loading and power loss. Harmonic currents contribute additional winding and stray losses and increase heating. As the number of connected EVs rises, the transformer experiences greater electrical and thermal stress. A transformer with a suitable harmonic withstands capability, together with charging coordination, can reduce the risk of overloading.

C. Harmonic Disturbance

The simulation reports approximately 12.35% THD when three EV chargers are connected to the charging station. This value is above the 5% benchmark considered in the project for power-quality assessment. The result demonstrates the aggregate harmonic effect of multiple nonlinear charging subsystems.

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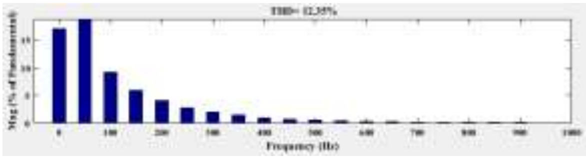

FIGURE 6. HARMONIC SPECTRUM WHEN THREE EV CHARGERS ARE CONNECTED AT THE CHARGING STATION.

D. Battery Output at Different Time Periods

The simulated battery-side output varies with the selected time period. At 0.025 s, the three outputs are 67.72 V, 55.27 V, and 55.31 V DC. At 0.05 s, they are 68.48 V, 49.66 V, and 49.67 V DC. At 0.1 s, the outputs are 68.53 V, 40.18 V, and 40.19 V DC. Battery 1 remains near 68 V, whereas Batteries 2 and 3 show a reduction in output voltage as the simulated time period increases.

TABLE 2. BATTERY OUTPUT VOLTAGE VERSUS SIMULATION TIME.

Time (s)	Battery 1 (V)	Battery 2 (V)	Battery 3 (V)
0.025	67.72	55.27	55.31
0.05	68.48	49.66	49.67
0.1	68.53	40.18	40.19

VIII. CONCLUSION

A MATLAB/Simulink model of an electric vehicle charging station was used to analyze grid-side power-quality effects and battery-side behavior. The results show that connecting multiple EV charging subsystems can disturb voltage and current waveforms, increase transformer power loss, and produce significant harmonic distortion. The reported THD of approximately 12.35% for three connected chargers indicates a need for harmonic mitigation in the studied configuration. Battery output results also show different voltage behavior over the simulated time periods. Future EVCS designs should combine appropriate transformer sizing, harmonic filters or active front-end converters, power-factor correction, coordinated charging, and renewable-energy integration. These measures can improve grid compatibility while supporting increased EV penetration.

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