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Integration of Electric Vehicle and its Power Quality Improvement by Renewable Generation in Distribution System

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Abstract: - The addition of electric vehicles to distribution networks creates simultaneous benefits together with power quality and stability issues. These difficulties become more complex because renewable energy sources provide electricity intermittently. This paper investigates renewable generation approaches to enhance power quality together with rising EV penetration in the power grid. The research includes in-depth methods for conducting load flow analysis and controlling voltage levels as well as harmonic reduction. An optimized combination of EVs with RES improves distribution network power factors and decreases THD levels while improving voltage stability in distribution networks.

Keywords: Electric Vehicles (EVs), Renewable Energy Sources (RES), Power Quality, Distribution System, Voltage Regulation, Harmonics, Vehicle-to-Grid (V2G).

I. INTRODUCTION

Modern power distribution management experiences dramatic transformation because electric vehicles (EVs) keep gaining wider acceptance. Worldwide governments and their policymakers support EV deployment to achieve three goals: decreased greenhouse gas emissions together with reduced fossil fuel usage and establishment of a sustainable energy system. Several hurdles emerge when EVs connect to current power distribution networks because they affect power quality and create voltage stability problems and produce harmonic distortions and affect peak demand levels [25]. The uncontrolled electricity charging of EVs creates several problems that threaten the efficiency of the entire grid by distributing transformer overloads and voltage fluctuations as well as raising total harmonic distortion levels [2-6].

The worldwide energy industry transforms to renewable energy sources (RES) particularly solar photovoltaic (PV) and wind energy which serve as solutions to minimize conventional power generation environmental impact. The weak point of RES is its inconsistent behavior because it impacts the steadiness of electric grids and power quality stability [20]. Solar together with wind power generation violent output requires strategic grid management because it causes problems with reactive power imbalances along with voltage fluctuations and frequency deviations. The combination of RES with EVs builds chances and technical obstacles for contemporary distribution networks [10].

The Vehicle-to-Grid (V2G) technology provides a promising solution to communicate energy effectively between electric vehicles and the power grid in both directions. V2G technology operated strategically performs like a distributed energy resource by sending power to the grid while peak demand happens and by receiving and storing renewable energy from off-peak hours [16]. The two-way power exchange reduces voltage variations while minimizing Total Harmonic Distortion to advance power quality levels. Strategic EV charging methods which synchronize EV power consumption with renewable energy resources availability lead to improved grid stability together with optimized energy management [22-23].

Multiple investigations have examined the independent influence of EV penetration together with renewable energy integration on power quality performance. Research should focus on studying the combined effects of these two technologies especially in distribution networks [15].

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The paper accomplishes this gap by evaluating how EV and RES integration influences power quality within distribution networks. Using MATLAB/Simulink and Dig SILENT Power Factory modeling tools allows the study to simulate realistic power system scenarios and evaluate different mitigation techniques within real-time distribution system conditions [7-8].

Novelty and Contribution:

These paper brings forward its essential contributions which can be summarized as follows:

- This paper presents an extensive evaluation of EV and RES integration effects on power quality through their influence on voltage stability along with harmonic distortion and power factor.
- Smart charging methods including V2G technology become part of this study instead of relying on passive harmonic filters like traditional research does.
- The study employs modern simulation tools including MATLAB/Simulink and DIgSILENTPowerFactory to analyze real power distribution systems where dynamic connections between EV charging loads and renewable generation units and power quality problems are properly modeled.
- The proposed research creates an EMS system to manage EV charging schedules with capabilities for real-time RES analysis and grid status measurement and consumer demand control which results in better distribution grid equilibrium.
- This paper uses adaptive filtering methods together with machine learning predictions to actively reduce EV charging-caused Total Harmonic Distortion instead of previous research methods which adopted static filtering systems.
- This study creates powerful recommendations that assist power utilities together with distribution system operators (DSOs) and policymakers to develop strategies which improve EV-RES integration methods and regulatory standards and modernize grid systems.

This research enhances EV and RES interaction comprehension in distribution networks by focusing on critical points which creates smarter electric power architectures with improved resiliency and clean energy operation [21].

II. Related Works

Numerous research efforts investigate how electric vehicles (EVs) connect to distribution systems because they boost power quality standards while improving renewable energy output. EV implementation results in multiple challenges for the power grid related to stability and reliability. A considerable number of EV owners charging without coordination creates electrical voltage instability which results in overloaded transformers and harmonic interference and higher-than-average consumption during peak times. Power network smooth operation requires improved control systems together with optimization solutions because these problems occur often.

In 2009 S. W. Hadley et.al. and A. T svetkova et.al. [9] Introduce the research studies have evaluated the effect that EV charging operations have on the voltage stability performance of distribution networks. The intense integration of EVs creates major voltage fluctuations which mainly affect low-voltage networks. The rapid consumption of power occurs during times when numerous EVs charge at the same time especially during peak demand periods.

EV integration creates various concerns about harmonic distortion at the system level. Power electronic converters used in EV chargers distribute harmonic currents across distribution networks thus increasing total harmonic distortion (THD). Electrical equipment breakdowns and unstable power quality arise from high THD levels which also lead to transformer overheating and equipment malfunction. Various filtering techniques including passive filters and active power filters with hybrid filters are investigated to deal with this matter.

Many studies have investigated how renewable energy sources (RES) address power quality issues caused by electric vehicles. Solar photovoltaic (PV) and wind energy systems united in distribution networks serve as environmentally sustainable methods for controlling electric vehicle charging loads. RES systems show inconsistency which creates technical problems with frequency control and voltage instability and power delivery stability. The integration of energy storage systems including lithium-ion batteries and supercapacitors has been studied as a method for handling renewable energy source variations to guarantee dependable EV charging power supplies. Research has proven that power quality improves together with grid reliability by using a coordinated framework that links EVs with RES and ESS systems [17].

Researchers have extensively evaluated how renewable energy sources function to minimize power quality issues caused by EVs. Solar Photovoltaic (PV) and wind energy together with distribution networks present a sustainable method to control EV charging loads. The unpredictable operation of renewable energy systems creates new complexities because they influence the control of frequency regulation and power supply stability. Multiple investigations demonstrate how lithium-ion batteries and supercapacitors acting as energy storage systems support the regulation of renewable energy source variability for providing reliable power supply to electric vehicle chargers. A unified approach between EVs and RES with ESS improves both power quality measures and extends reliability across the power grid system.

In 2023 M. Shadnam Zarbil et.al., [1] Introduce the V2G technology represents a beneficial power quality solution which works to enhance distribution network performance. The V2G functionality lets EVs function as vehicle-based mobile storage devices so they can transfer power back to the electricity network during times of high demand. The technology enables voltage regulation as well as frequency control and it aids reactive power compensation. Research proves that well-optimized V2G management methods working with complex control programs create substantial improvements in power stability and lower power oscillations in distribution systems.

Researchers have conducted investigations on the combination of smart grids with EVs along with RES. These advanced systems help power distributors control distributed energy resources effectively which results in dependable electric grid operations.

In 2015 A. Chandra et.al. [24] Introduce the several research needs exist following the advancements achieved in EV and RES integration. Research investigations primarily examine independent features of EV charging systems and RES integration besides power quality transformation despite lacking unified frameworks to link these concepts. The study of high-frequency harmonics and transient disturbances and their effect on long-term grid stability needs more investigation when a large number of EVs become connected to the grid. Research challenges exist regarding both the economic viability of implementing sophisticated control schemes and regulatory alongside policy matters.

In conclusion more research needs to be conducted to build better and scalable solutions which better address the power quality and stability effects of EV integration. This paper's following sections elaborate on these topics with an innovative scheme to enhance power quality in distribution networks hosting EVs.

III. Proposed Methodology

The proposed research integrates Electric Vehicles (EVS) along with Renewable Energy Sources (RES) to enhance power quality levels inside distribution networks. The approach develops a synchronized energy management system which optimizes EV recharging and depleting as well as utilizes RES sources while implementing power quality improvement methods. The methodology includes four essential elements to develop the integrated system: (i) system modeling, (i) power quality assessment, (iii) control and optimization strategies and (iv) simulation and validation [18-19].

A. System Modeling

The model features a multi-node network which integrates conventional loads together with solar PV and wind turbines as renewable generation units and EV charging stations. The distribution network operates under power flow equations that determine its operation:

$$P_i - P_i^{EV} - P_i^{RES} = V_i \sum_{j=1}^{n} V_j Y_{ij} \cos\left(\theta_{ij} - \delta_i + \delta_j\right)$$

$$Q_i - Q_i^{EV} - Q_i^{RES} = V_i \sum_{j=1}^{n} V_j Y_{ij} \sin\left(\theta_{ij} - \delta_i + \delta_j\right)$$

where:

- P_i, Q_i are the active and reactive power demand at bus i.
- P_i^{EV}, Q_i^{EV} are the active and reactive power demand of EVs at bus i.
- P_i^{RES}, Q_i^{RES} are the active and reactive power supplied by RES.
- V_i, δ_i are the voltage magnitude and phase angle at bus i.
- Y_{ij}, θ_{ij} are the admittance and phase angle between buses i and j.

The EV charging stations are modeled as controllable loads with bidirectional capabilities to support Vehicle-to-Grid (V2G) operation. The charging power of an individual EV is governed by:

$$P_{EV} = V_{EV} I_{EV} \eta_{ch}$$

where V_{EV} and I_{EV} are the voltage and current of the EV charger, and η_{ch} is the charging efficiency.

B. Power Quality Assessment

The analysis of power quality requires evaluation of voltage deviations together with total harmonic distortion (THD) and power factor. The evaluation process includes studies on total harmonic distortion (THD) and power factor and voltage deviations analysis.

Voltage Stability

The voltage deviation at each bus is assessed using:

$$\Delta V_i = V_i - V_{nom}$$

where V_{nom} is the nominal voltage. A deviation beyond $\pm 5\%$ indicates a stability concern.

Harmonic Distortion

EV chargers introduce harmonics into the distribution system, increasing THD, which is given by:

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} (V_n)^2}}{V_1} \times 100\%$$

where V_n is the nth harmonic voltage and V_1 is the fundamental frequency voltage.

Power Factor

Power factor degradation is mitigated by controlling reactive power compensation through the equation:

$$PF = \frac{P}{\sqrt{P^2 + Q^2}}$$

where P and Q are the active and reactive power.

C. Control and Optimization Strategies

To enhance power quality, an adaptive energy management strategy is implemented, which includes:

Smart Charging Control

The optimization problem uses ToU pricing-based charging to shift EV charging activities to non-peak times:

$$\min \sum_t C_t P_{EV}(t)$$

subject to:

$$P_{EV}^{\min} \leq P_{EV}(t) \leq P_{EV}^{max}$$

where C_t is the electricity price at time t, and $P_{EV}^{\min}, P_{EV}^{\max}$ are the minimum and maximum charging powers.

V2G Power Dispatch

EVs discharge power to the grid based on real-time demand conditions, optimized using:

$$P_{V2G}(t) = \alpha \cdot \left(P_{grid}(t) - P_{RES}(t)\right)$$

where α is a control factor ensuring stability.

Harmonic Filtering

An active power filter (APF) is implemented to mitigate harmonics, with the compensation current) defined as:

where I_{harmonic} is the distorted current, and $I_{reference}$ is the desired sinusoidal current.

D. Simulation and Validation

A MATLAB/Simulink simulation model serves to evaluate power quality effects from connecting EVs and RES [11]. The simulation model operates with three fundamental system parameters which consist of a 100 kW solar PV system together with wind turbine equipment and different EV charging stations. The validity of the proposed methodology gets tested through:

- Comparing voltage profiles before and after smart charging implementation.
- Evaluating THD reduction with APF deployment.
- Assessing power factor improvement through optimal V2G dispatch.

The expected outcomes include enhanced voltage stability, reduced harmonics, and improved power actor, ensuring a reliable and high-quality power supply.

Flowchart Representation

Below is the flowchart illustrating the proposed methodology

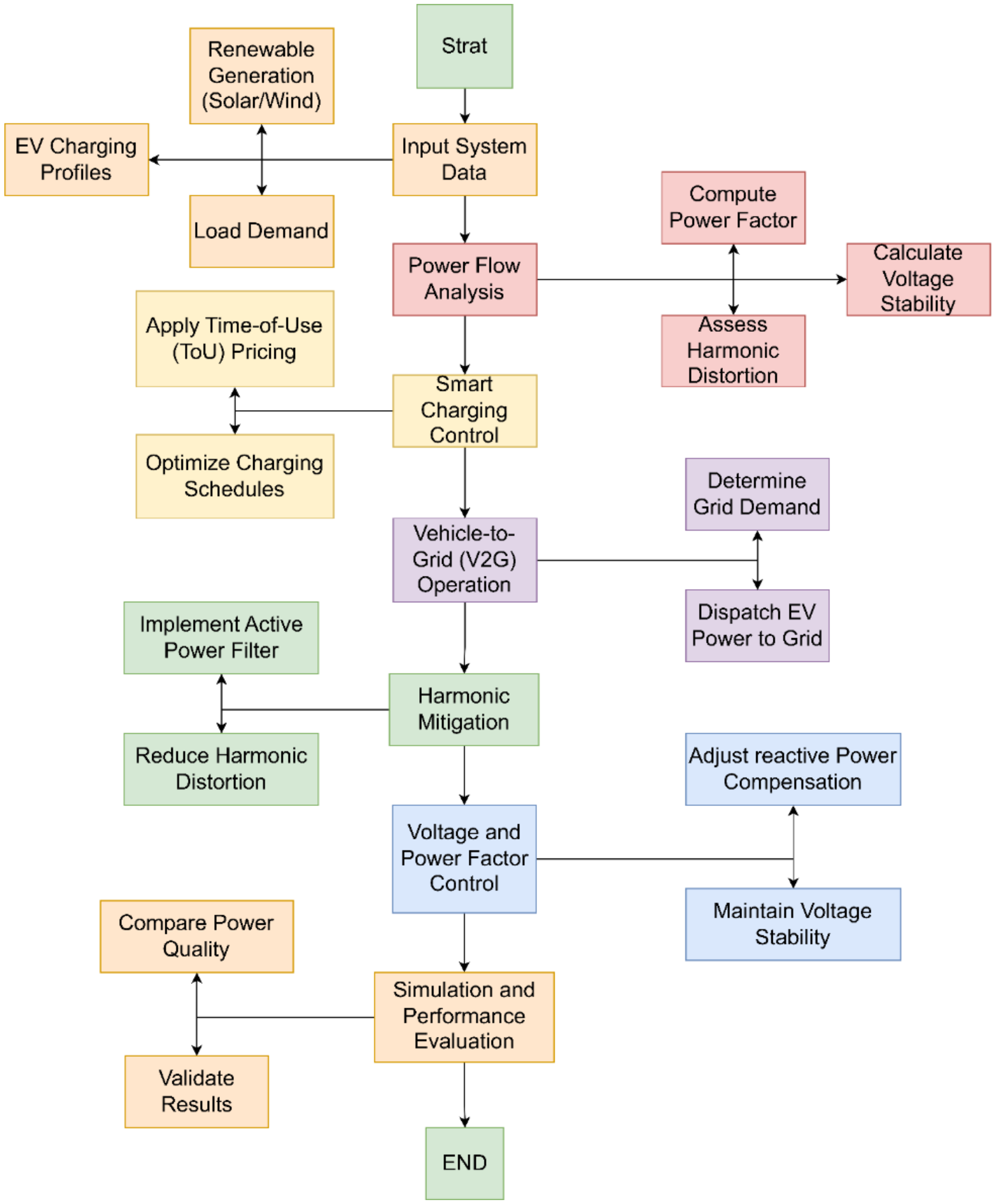

Figure 1: EV-RES Integration for Power Quality Enhancement in Distribution Systems

IV. Result &Discussions

The research evaluates three essential power quality markers through examination of both voltage stability and total harmonic distortion (THD) and power factor. This research proves the effectiveness of the proposed smart charging solution combined with V2G strategies in this analysis. [12].

A power flow analysis of a standard IEEE 33-bus distribution network with no EV charging loads became the basis to measure EV integration effects. The analyzed network showed a minimum operating point of 0.94 p.u. which fulfilled the acceptable standards. Uncoordinated multiple EV charging at buses resulted in notable voltage drops reaching their lowest point at 0.88 p.u. Figure 2 demonstrates the system voltage variation between the initial state and the period of EV charging through its graphical representation. The presented data proves that distribution network stability suffers when EV loads are connected because proper charging protocols and V2G must be implemented to address these stress points.

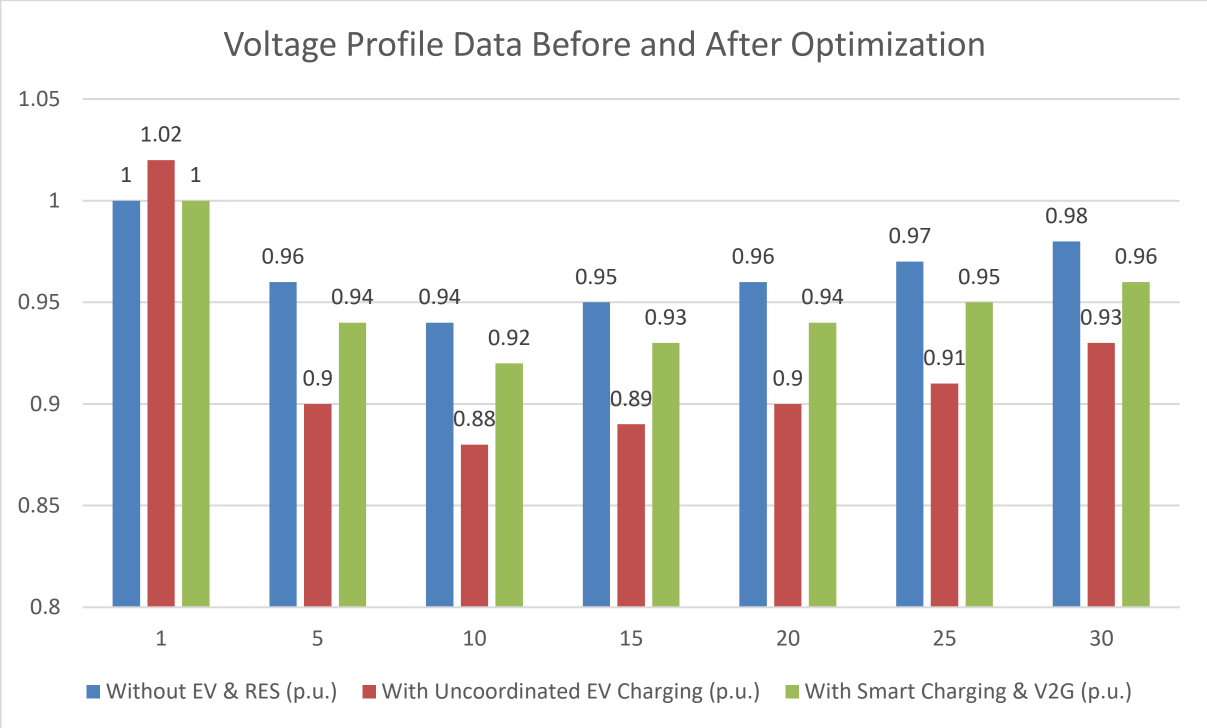

Figure 2: Voltage Profile Data Before and After Optimization

Smart charging algorithms enabled EVs to charge their batteries in time periods where renewable energies possess high generation capacities. The control methods enhanced the voltage profile by restoring the lowest voltage level up to 0.92 p.u. The V2G functionality provided additional support for voltage stabilization by feeding power into the grid during times of high demand. Table 1 shows the voltage profile assessment before and after applying the proposed methodology with profiles presented in p.u. values.

Table 1: Voltage Profile Comparison Before and After Optimization

Scenario	Minimum Voltage (p.u.)	Maximum Voltage (p.u.)
Without EV & RES	0.94	1
With Uncoordinated EV Charging	0.88	1.02
With Smart Charging & V2G	0.92	1

The evaluation focused on harmonic distortion as well as voltage stability to assess power quality changes from EV charging. EV charger systems with their power electronic converters create harmonic currents that raise the Total Harmonic Distortion (THD) levels in the grid network. Measurement of distribution network THD revealed an initial value of 2.5%. The quantity of uncoordinated EV charging contributed to an increase of THD to 7.8% beyond the IEEE standard threshold of 5%. Evolution of harmonic spectrum is shown in Figure 3 between the two time points where distortion criteria increases consequently.

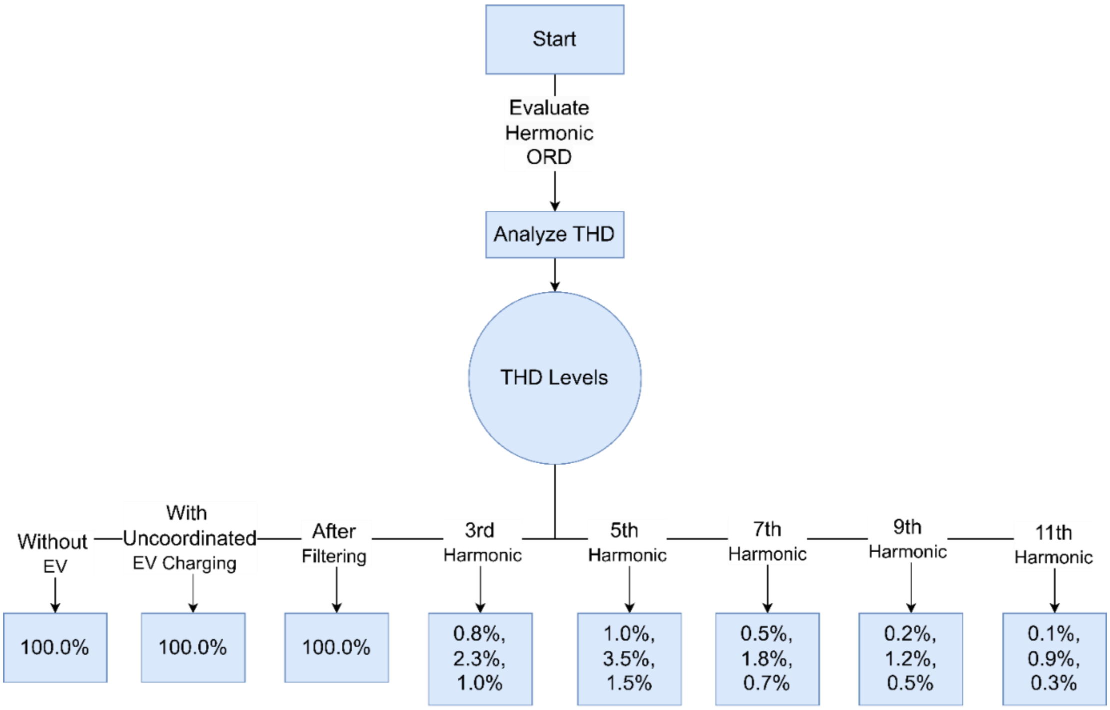

Figure 3: Harmonic Distortion (THD) Spectrum Before and After EV Integration

An implementation of active power filter (APF) brought THD levels down to 3.9%. An adaptive filtering method provides effective harmonic distortion reduction that results from electric vehicle charging activities. Table 2 shows the effectiveness of harmonic mitigation techniques through its THD comparison under various scenarios.

Table 2: Total Harmonic Distortion (THD) Comparison

Scenario	THD (%) Before Filtering	THD (%) After Filtering
Without EV Integration	2.50%	-
With Uncoordinated EV Charging	7.80%	7.80%
With APF Implementation	7.80%	3.90%

The power factor represents the final quality measure because it establishes how effectively distribution systems use their power. The unmanaged connection of EV charging equipment leads to decreased power factor due to elevated reactive energy consumption. Before introducing EV loads the system operated with a power factor close to 0.98. The uncontrolled manner of EV charging caused the power factor to drop to 0.86 because it reduced system operational efficiency. Smart charging together with reactive power compensation produced a power factor of 0.95 as Figure 4 displays the various power factor fluctuations.

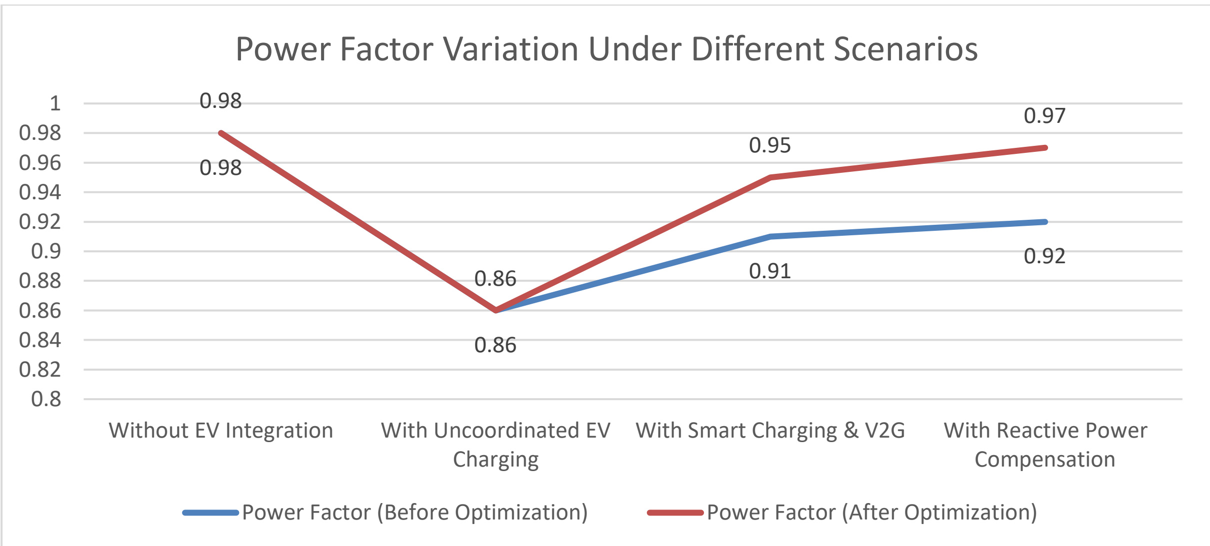

Figure 4: Power Factor Variation Under Different Scenarios

The combined approach of RES integration with EVs leads to substantial enhancements of power quality in distribution networks. The combination of smart charging technologies plus V2G operation functions as a solution to handle the voltage fluctuation problems that result from EV charging irregularities. Power electronic interfaces can be filtered efficiently to manage their harmonic distortions with adaptive filtering solutions [14]. Optimized power dispatch and compensation methods provide the solution to remedy power factor deterioration problems caused by reactive power imbalances. Through this proposed approach maintenance operation can provide reliable and efficient power distribution network operation together with sustainable energy utilization capabilities.

V. Conclusion

At specific distribution system conditions, the research proves that renewable energy system integration with EVs produces significant benefits to power quality. Smart control systems working with V2G deployment technology achieves improved voltage stability together with lessened momentary disturbances while optimizing power quality factors. The realization of maximum advantages from EVs in distribution systems demands innovative energy management approaches and better prediction methods and contemporary power grid improvements [13].

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