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The Impact of Electric Vehicle AC Charging Stations on Distribution System Voltage

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Abstract. This study investigates the impact of the Tesla Wall Connector charging station on the voltage of the distribution system. We adopted an experimental testing approach, observing and recording the effects of an onboard charger on voltage variations at different charging speeds and under different distribution system loads. Experimental results revealed that as the charging speed increases, the voltage of the distribution system changes correspondingly. Under low-load conditions, the impact of the third-generation Tesla Wall Connector on the voltage of the distribution system is relatively small. However, as the load on the distribution system increases, especially when approaching its load limit, high-speed charging of the Tesla Wall Connector Charger leads to a significant drop in the voltage of the distribution system. These findings suggest that to maintain the stability of the distribution system, appropriate power management of the Tesla's third-generation Wall Connector is necessary, especially under high-load conditions. This study provides important empirical data for understanding and addressing the potential issues that electric vehicle onboard chargers may cause to the distribution system, and contributes to strategic recommendations for the proliferation of electric vehicles and the construction of future smart grids.

Keywords. EV charger, power quality, electric vehicle, Voltage Sag, Tesla Wall Connector

1. Introduction

As the global focus on reducing carbon emissions and mitigating climate change intensifies, Electric Vehicles (EVs) are playing an increasingly pivotal role in the transportation sector. Correspondingly, the impact of EV charging infrastructure, particularly charging stations, on the power distribution system is becoming increasingly evident. The performance and operational modes of charging stations directly influence voltage stability and load distribution of the distribution system, and may even lead to overload or voltage collapse.

Tesla, a global leader in EV manufacturing, offers its proprietary charging solutions including the residential Tesla Wall Connector. However, with the widespread adoption of charging devices in the power distribution network, their impact on grid health and stable operation warrants significant attention. This study specifically focuses on the impact of alternating current (AC) charging stations on the power distribution system,

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using the Tesla Wall Connector 3rd as the test subject, especially considering voltage variations under different charging speeds and load conditions.

Numerous international academic studies have addressed the effects of charging stations on the power distribution system. For instance, the proliferation of EV charging has shown considerable impacts on distributed networks, notably the harmonic impacts and power quality concerns as EV charging penetration increases [1-3]. By 2050, the penetration rate of EVs in the global transportation fleet is projected to rise from 0.7% in 2020 to 31%, equivalent to approximately 670 million EVs [1]. Another study presented at the 2018 Engineering Research Conference (MERCon) in Moratuwa, Sri Lanka, indicated that high EV charging penetration significantly affects the harmonics in a distributed network [2]. Researchers have also explored the power quality implications of rapid charging, especially when EV owners tend to charge their vehicles as fast as possible [3]. Another study proposed a method to ascertain the impact of high penetration rates of Full Electric Vehicles (FEVs) charging on the thermal aging of power distribution transformers [4].

Different studies offer insights when examining the effect of EV charging on grid stability. One research shows that unbalanced EV/PEV charging results in substantial voltage imbalance, exceeding the permissible 2% voltage limit [5]. On the other hand, a modeling overview of grid impact due to EV charging scenarios, by simulating driver behavior and regional configurations, has been presented [6]. Furthermore, a review article detailed the varying levels of EV charging and its implications for the stability of the public grid, discussing the prevalent and available charging station architectures [7]. Brown et al. conducted a detailed analysis concerning the impact of residential charging stations on the voltage of residential electrical networks [8]. These works provide vital background information in understanding how different EV charging technologies and strategies influence grid stability.

Integrating the above research, although several efforts have been made to understand the mutual effects between charging stations and power distribution systems, this study employs an empirical testing approach. It investigates the effects of AC charging stations on grid voltage under varying charging speeds and different load states in the power distribution system, utilizing the Tesla Wall Connector 3rd for the tests. The results aim to provide empirical data supporting the stable operation of the grid and will contribute to the construction and management of future smart grids.

2. System Structure

2.1. Software Structure

In recent years, with the advancements in computational and communication technologies, various emerging techniques have garnered significant attention from the academic community. This study employs the Raspberry Pi as a data controller, which has attracted specific interest due to its outstanding cost-performance ratio. Beyond its economic benefits, the Raspberry Pi boasts commendable processing capabilities, making it particularly suited for a multitude of Internet of Things (IoT) applications. In addition to its intrinsic hardware attributes, the Raspberry Pi is complemented by a rich peripheral ecosystem, encompassing a variety of sensors and modules. This allows developers to customize and expand based on the specific requirements of a given project.

Furthermore, the extensive developer community surrounding Raspberry Pi offers a wealth of tutorial resources and open-source projects, amplifying its versatility.

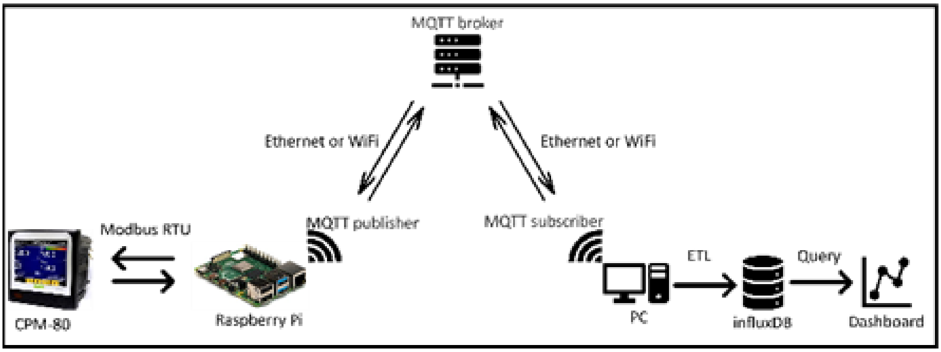

Figure 1. Software structure.

Figure 1 presents the software architecture utilized in this study. Within this framework, the MQTT protocol is employed as a lightweight messaging queuing system, uniquely tailored for devices and network environments with resource constraints. The protocol's inception primarily addresses the challenge of unstable connections between devices and servers. Owing to its minimal hardware resource consumption, limited bandwidth requirements, and pronounced resilience to network fluctuations, MQTT has gained extensive traction in the IoT domain. Operating on a publish/subscribe model ensures accurate message relay and is fortified with robust security measures. InfluxDB, an open-source time-series database designed specifically for timestamped data management, has garnered considerable academic attention. Its efficient data storage mechanism combined with rapid querying capabilities makes it especially apt for storing large volumes of time-series data, such as monitoring logs and system metrics. Notably, a hallmark feature of InfluxDB is its inherent flexibility, permitting developers to design data structures dynamically, thereby optimizing data storage and retrieval processes. Grafana, a widely adopted open-source data visualization tool employed across varied monitoring and analytical scenarios, also warrants an in-depth exploration in this context. Grafana offers a user-centric interface equipped with powerful visualization functions and extends support for multiple databases, thereby serving as a visualization solution for diverse data sources. Moreover, the Grafana plugin ecosystem further augments its capabilities, offering users myriad avenues for feature enhancement and integration.

2.2. Hardware Structure

Regarding hardware, the study employed the ADTEK CPM-80 power quality meter. This meter is capable of True RMS (Root Mean Square) measurements, boasting 256 points per cycle sampling rate. It offers an accuracy level of 0.2s for effective energy measurements, complying with the IEC62053-22 standard. Furthermore, the meter is equipped to measure voltage and current surges/dips and provides real-time waveform capture. Harmonic measurement from the 2nd to 63rd order is feasible with this device. It comes with dual communication ports, facilitating seamless connectivity. The meter's display features include a 3.5-inch TFT LCD full-color screen. Due to its communication capabilities and integrated relay function, the meter facilitates experiments with remote switching functionality.

Figure 2. Hardware structure.

The presented study details the design of an intelligent distribution board, as depicted in Figure 2. This board incorporates several cutting-edge components, including smart meters, relays, and counters, among others. The Raspberry Pi has been chosen as the core data controller for its performance and adaptability, which are particularly suitable for this application. To ensure data integrity and real-time communication, the RS-485 communication protocol is employed, enabling seamless data connectivity between the Raspberry Pi and the smart meter. This system offers remote control capabilities. Users can remotely operate the charging piles, either to initiate or terminate charging, and simultaneously retrieve precise electrical metrics, such as energy consumption, voltage variations, harmonic content, and power factor. For system stability and safety, electromagnetic contactors have been specifically integrated to control the high-current charging piles. To address the demands posed by the current on the electrical junction, a junction rated for a high current of 32A, combined with a timer, has been adopted. This ensures precise circuit control and mitigates potential damage to the charging pile during rapid switching or accidental short-circuits. When choosing the wiring, given the AC220V components and the 32A high-current requirement, we have meticulously selected wire gauges that adhere to regulatory standards, ensuring the system's operational efficiency and safety.

In this study, the Tesla Wall Connector 3, abbreviated hereafter as TWC3, has been adopted as the charging pile for testing. This third-generation home electric vehicle charging device from Tesla has been specifically crafted for Tesla's electric vehicle range. Beyond its superior industrial design and craftsmanship, the TWC3 also demonstrates technical performance enhancements. In terms of power specifications, the TWC3 supports charging powers ranging from a minimal 1.3 kW up to an impressive 22 kW, adjustable based on local grid infrastructure and user demands. With its remarkable charging efficiency, the TWC3 can rapidly recharge Tesla vehicles, ensuring users can swiftly resume their journeys. The TWC3's highly adaptable input voltage range and corresponding output current adjustability allow it to conform to varying grid conditions and norms across different regions. Furthermore, the TWC3 comes integrated with advanced communication features, facilitating data exchange with the vehicle and other smart devices. This not only empowers users with remote management capabilities over the charging process but also enables the intelligent adjustment of charging strategies, taking into account grid load conditions and fluctuating electricity prices.

3. Experimental Results

3.1. Experimental Results

In this study, the TWC3 was utilized for charging, with two types of power sources provided, specifically from the Taiwanese power grid system. These sources encompass single-phase 220 and three-phase 220 volts, enabling the 2022 Tesla Model Y to charge at varying maximum rates. As AC charging was employed for this research, it was imperative to utilize the vehicle's onboard charger for the process. An onboard charger, integrated within the vehicle, is designed to convert AC power to DC, facilitating energy storage in the battery. The specifications of this onboard charger are delineated in Table 1.

Table 1. Corresponding Specifications of the Onboard Charger for Tesla Electric Vehicles [7]

Model	Onboard Charger	Recommended Circuit Breaker for Wall Connector Installation
Model S	11.5 kW(48 amp)	60 amp circuit breaker
Model X	11.5 kW(48 amp)	60 amp circuit breaker
Model Y	11.5 kW(48 amp)	60 amp circuit breaker
Model 3 P	11.5 kW(48 amp)	60 amp circuit breaker
Model 3 LR	11.5 kW(48 amp)	60 amp circuit breaker
Model S	11.5 kW(48 amp)	60 amp circuit breaker
Model 3 Rear- Wheel Drive	7.7 kW(32 amp)	40 amp circuit breaker

In this study, the TWC3 charging infrastructure was employed. Utilizing different types of power sources, it can offer varying charging powers, as detailed in Table 2.

Table 2. Tesla Wall Connector 3 Technical Details (Power Source) [8]

Maximum output (amps)	230V(L-L) Single Phase Power Output (kW)	230V(L-L) Three Phase	Maximum output (amps)
32	7	10.5	22
25	5.2	9.5	13
20	3.5	6	11

In actual charging scenarios, the power output must take into consideration the limitations of the onboard charger, the TWC3, and the laboratory power configuration. Given these constraints, the tested charging powers for this research were set at 7KW and 10.5KW. By utilizing the Tesla App to restrict the output current, the tests were conducted at both 100% of the maximum current and at 50% current values, resulting in actual tested charging powers of 3.5KW and 5.25KW, respectively, as summarized in Table 3. In different environments and settings, various output powers can be observed. Through this methodology, the study aimed to understand the influence of different charging powers on voltage fluctuations.

Table 3. Distinct power sources and their corresponding charging capacities

	Single Phase Delta-Connect The line-to-line voltage is 220V	Three Phase Delta-Connect The line-to-line voltage is 220V
50% Output Current - 16A	Charging power 3.5KW	Charging power 5.25KW
100% Output Current - 32A	Charging power 7KW	Charging power 10.5KW

3.2. Discussion

In this experiment, charging cables of identical material and length were employed, with charging conducted using different power settings to regulate the current flow. Data measurements, taken at one-second intervals, recorded voltage, current, and charging power, particularly emphasizing their dynamic states. This data was subsequently stored in the influxDB database and visualized through the Grafana interface. Four experiments were conducted in total, with the associated data and information presented below.

Figure 3. Test 1, single-phase delta-connect line-to-line voltage is 220. (32A)

As illustrated in Figure 3, the voltage variation during the charging process is described as follows:

The peak voltage (prior to charging) is approximately 224V. Upon the initiation of charging, the voltage dips to its lowest point of around 222V. This results in a voltage drop of approximately 2V. Relative to the initial 224V, this drop constitutes approximately 0.89%. As observed in the figure, this decrement initiates around 12:25 and persists until approximately 12:50, spanning a duration of about 25 minutes.

Regarding the voltage escalation post-charging cessation:

Before discontinuing the charge, the voltage is at its nadir of approximately 222V. Post cessation, the voltage swiftly elevates to around 224V, marking an elevation of 2V. When viewed against the 222V, this rise computes to roughly 0.9%. As evident in the graph, this increment begins shortly after 12:50 and is quite rapid, potentially transpiring within a short span of 1 to 2 minutes.

Figure 4. Test result，single-phase delta-connect line-to-line voltage is 220. (16A)

As depicted in Figure 4, the voltage variation during the charging phase is detailed below:

The peak voltage (prior to charging) measures approximately 224V. Upon the initiation of charging, the voltage reaches its nadir of about 221V. This results in a voltage drop of around 3V. When assessed against the initial 224V, this decline represents approximately 1.34%. As discerned from the figure, this decrement commences around 13:05 and reverts back to its initial state at about 14:05, indicating a total duration of approximately 1 hour.

Regarding the voltage escalation post-charging cessation:

Before discontinuing the charge, the voltage is at its minimum of approximately 221V. Upon halting the charge, the voltage swiftly ascends to about 224V, marking an elevation of 3V. Relative to the 221V, this surge constitutes 1.36%. As deduced from the graph, this increment ensues shortly after 14:05 and is quite rapid, potentially occurring within a brief span of 1 to 2 minutes.

Figure 5. Test result，three-phase delta-connect line-to-line voltage is 220. (28A)

As illustrated in Figure 5, the variation of voltage during the charging process is detailed as follows:

The highest voltage level (prior to charging) stands at approximately 224.5V. At the onset of charging, the voltage reaches its minimum of about 222V. This constitutes a drop of roughly 2.5V. When benchmarked against the initial 224.5V, the relative percentage decrease is approximately 1.11%. The figure showcases this reduction starting around 14:45 and reverting back to its original state by 15:05, spanning an interval of roughly 20 minutes.

Regarding the voltage escalation post-charging cessation:

Before discontinuation of the charging process, the voltage is at its nadir, approximately 222V. After halting the charge, there's a swift ascent in the voltage up to about 224V, indicating an increase of 2V. When measured against the 222V, this increment represents around 0.9%. As gleaned from the diagram, this rapid rise ensues immediately post 15:05, enduring for a relatively brief period, likely within a range of 1 to 2 minutes.

Figure 6. Test result, three-phase delta-connect line-to-line voltage is 220. (14A)

As depicted in Figure 6, the voltage drop during the charging phase is elaborated as follows:

Prior to initiating the charge, the voltage peaks at approximately 224V. As charging commences, the voltage hits a minimum of around 222V, resulting in a decline of approximately 2V. In relation to the starting 224V, the percentage decrease equates to approximately 0.89%. The graph illustrates this descent initiating around 12:25 and continuing until about 12:50, spanning a duration of roughly 25 minutes.

Regarding the voltage escalation post-charging cessation:

Before the charging discontinuation, the voltage settles at its lowest, roughly 222V. Subsequent to halting the charge, there's an immediate surge in the voltage, rising to about 224V, marking an elevation of 2V. When gauged against the initial 222V, this increase is roughly 0.9%. As discerned from the figure, this ascent commences swiftly post 12:50, enduring for a relatively short span, approximately within 1 to 2 minutes."

Table 4. Experimental results indicate the correlation between varying charging powers and the corresponding voltage drop magnitude

	Charging Current (A)	Charging Power (KW)	The magnitude of the voltage drop (%)
Single Phase Power	16	3.5	0.89
Single Phase Power	32	7	0.89
Three Phase Power	14	5.25	1.02
Three Phase Power	28	10.5	1.02

Voltage Behavior: Throughout the four experimental sets, the initial voltage prior to charging hovered around 224V to 224.8V. As charging commenced, there was a noticeable decline in voltage, reaching its nadir between 222V and 222.5V. This signifies a drop of approximately 0.89% to 1.02% relative to the initial voltage. Upon halting the charging, the voltage swiftly reverted to its initial value.

Duration of Charge and Voltage Recovery: The duration of the voltage drop varied depending on the charging context, with the observed maximum duration being around 60 minutes. In all scenarios, post-charging, the voltage rebound was rapid, mostly occurring within a span of 1-2 minutes.

Current, Power Factor, and Active Power Behavior: As anticipated, the commencement of charging caused a distinct surge in current, corresponding to the decline in voltage. The power factor remained relatively steady throughout the experimental process. Active power, meanwhile, escalated with the start of charging and diminished upon its cessation.

Impact of Power on Voltage Drop: Data from the four experimental sets revealed that high-power charging, compared to low-power charging, resulted in a more pronounced voltage drop. This underscores the importance of maintaining system voltage stability during high-power charging scenarios.

4. Conclusion

This research embarked on a meticulous experimental study of the effects on voltage by the Tesla Wall Connector charging station under various charging speeds and power system load conditions. The experimental environment incorporated charging voltages of single-phase three-wire 220V and three-phase three-wire 220V, and conducted four distinct charging experiments under currents of 16A and 32A.

Results indicate that under low-load conditions, the third-generation Tesla Wall Connector's charging had a minor impact on the distribution system's voltage, favorable for stable system operation. However, as system load augmented, particularly nearing its limit, high-speed charging significantly affected the distribution system's voltage, causing a conspicuous drop. Charging under 16A and 32A currents, the three-phase three-wire 220V charging mode, in contrast to the single-phase, was more likely to induce voltage instability. This warrants serious attention.

To preserve distribution system stability, power measurements were conducted on the Tesla Wall Connector 3rd in scenarios of high-load and high-speed charging. Potential management measures may include dynamically adjusting charging speed, limiting the number of vehicles charging concurrently, or enhancing grid infrastructure.

This study offers invaluable empirical data, bearing significance in comprehending and addressing potential impacts of EV charging equipment on distribution systems. With the rapid evolution of EVs and smart grids, these data and recommendations will hold practical implications for ensuring grid stability and efficient operation. Lastly, it's worth noting that this investigation is preliminary. Further studies are required to corroborate these observations and put forth more actionable solutions, providing a foundation and direction for subsequent research.

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