Implementing an Index of Quality for DC Electric Vehicle Charging Stations and Examining Voltage Performance

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Abstract

In order to assess DC rapid charging systems at various voltage levels (375V, 440V, and 500V), this research presents a revolutionary Charging Quality Performance Index (CQPI). We create voltage-specific coefficients for performance evaluation by experimentally analyzing a 30kW electric vehicle supply equipment (EVSE) and establishing weighted correlations between ripple features and efficiency. For current ripple (CR)/voltage ripple (VR), the correlation analysis produced different weight factors at each voltage level (375V: 0.9617/0.0383, 440V: 0.5672/0.4328, and 500V: 0.9621/0.0379). With a peak efficiency of 96.3% and a 1% decrease in current ripple, the testing findings show optimal charging performance at moderate state of charge (SOC) levels under high load conditions. This translates into a PCE improvement of around 1.45%. A quantitative approach for assessing and improving the performance of DC charging systems is offered by this index.

INTRODUCTION

The exponential proliferation of electric vehicles (EVs) has precipitated heightened scrutiny of battery charging systems and their consequential impact on electrochemical performance. The inherent presence of current and voltage ripples in these charging architectures represents a critical phenomenon that substantially influences both conversion efficiency and battery durability. The deleterious effects of high-frequency current ripple on Li-ion battery performance manifest through accelerated capacity deterioration and diminished power capability throughout the operational lifespan [1]. This multifaceted challenge is further exacerbated by the intricate relationships between DC charger output voltage ripple coefficients and their parametric dependencies on switching frequency modulation, duty cycle variations, and dynamic load conditions [2]. In response to these complexities, sophisticated control methodologies have emerged for attenuating power ripple in bidirectional AC-DC converters, striving to minimize adverse effects while preserving charging efficiency [3].

Empirical investigations utilizing specialized datasets have elucidated the intricate correlations between ripple current characteristics and battery aging mechanisms, demonstrating pronounced capacity degradation under sustained ripple stress conditions [4]. Contemporary analyses of AC Level 2 onboard charging systems have revealed significantly high-frequency ripple components that potentially compromise system integrity [5]. These findings have catalyzed the development of advanced suppression techniques for second-harmonic ripple voltage in integrated single-phase PWM rectifier charging systems [6]. The technological evolution of charging infrastructure has yielded substantial advancements in power quality optimization through sophisticated converter topologies [7]. This progression extends to vehicle-to-vehicle (V2V) charging paradigms, introducing novel methodologies for power flow orchestration within comprehensive grid integration frameworks. Particularly noteworthy are the developments in renewable energy integration, exemplified by solar-powered bidirectional chargers exhibiting cross-standard compatibility.

Recent innovations in GaN-based bi-directional on-board charger (OBC) architectures have demonstrated remarkable improvements in switching frequency capabilities and conversion efficiency. These advancements facilitate enhanced system performance while optimizing power density and economic viability. Concurrent research has addressed battery-ageing mitigation in series-level configurations, while the evolution of charging technologies encompasses a spectrum of standardization from rudimentary Level 1 to sophisticated Level 3 systems.

Table 1. Nameplate details of DC EVSE

SL. No.	Parameter	30kW
1	Topology	Vienna-PFC & LLC
2	DC Voltage Range	300-500V
3	DC Current Range	0-80A
4	Power Capacity	30kW
5	AC Voltage	400V (L-L)
6	AC Frequency	50Hz
7	Gun Type	CCS-2
8	Input power factor	>0.98
9	Efficiency at FL	>95%

The implementation of SiC-based technology has enabled revolutionary neutral leg designs with minimized capacitive requirements in three-phase four-wire EV chargers. Complementary advances in high-frequency magnetics and soft-switching methodologies have contributed to the development of more efficient differential mode superchargers, particularly crucial for high-power applications where expedited charging requirements must be balanced against system efficiency and reliability imperatives. Table 1 shows the nameplate details of the EVSEs under consideration. The main purpose of this study is to understand the effect of the current ripple on the power conversion efficiency (PCE) of DC EVSEs and propose a novel performance index.

EXPERIMENTAL METHODOLOGY

VR and CR in electrical systems, particularly in EV charging, are periodic fluctuations that occur during AC-to-DC conversion. Ripples significantly impact EV charging by causing battery heating, reduced lifespan, decreased efficiency, and control system interference. EV manufacturers typically specify a maximum ripple current below 5%. Control methods include:

- Large capacitive filters
- Multi-stage filtering
- PWM control strategies
- Active ripple cancellation

These measures ensure optimal charging performance while protecting battery life and system integrity. The equation

$$Vripple\% = \left(\frac{(Vmax - Vmin)}{2}\right) * \frac{100}{Vdc} \qquad \text{Eq (1)}$$

represents a fundamental metric in power electronics, specifically quantifying the quality of DC output in rectification systems. This particular formulation calculates the percentage of voltage ripple present in a DC power supply, where Vmax denotes the maximum peak voltage amplitude, Vmin represents the minimum trough voltage amplitude, and Vdc signifies the average direct current voltage level. The same formula applies to the percentage current ripple by using current values. Engineers and system designers utilize this parameter to assess the effectiveness of filtering components, such as capacitors and inductors, in smoothing the rectified output. A lower percentage value typically indicates superior power quality, which is essential for maintaining optimal battery charging conditions and preventing potential damage to sensitive electronic components.

The experimental setup used for evaluating the power conversion efficiency of EV chargers or EVSEs is provided in Figure 1. The laboratory setup consists of two 30kVA Programmable AC Source (Make: Keysight and Mode: SL1202A), a EVSE analyser (also known as Charging discovery system (CDS), Make: Keysight/Scienlab, Model: SL1201A), and a Battery emulator (Make: Keysight and Model: SL1202A) with capacity of 50kW DC and 30kVA AC. The complete system is controlled by two software in the same desktop/PC. One software is to control the DC emulation using CDS and another is for controlling input AC supply.

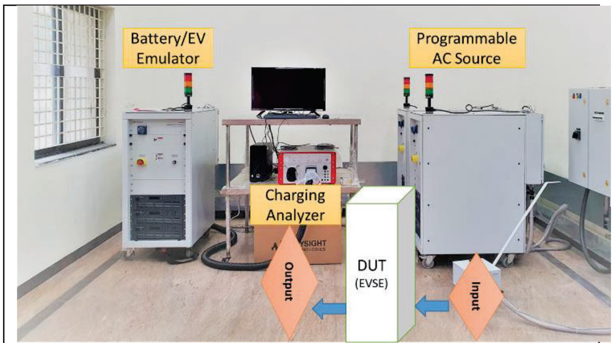

Fig.1. Experimental setup for EVSEs up to 50kW

EXPERIMENTAL RESULTS

The experimental study investigates the intricate relationships between voltage levels, current magnitudes, and battery SOC in a high-power DC charging system. Operating across three voltage platforms - 375V, 440V, and 500V - the investigation reveals compelling patterns in both ripple characteristics and power conversion efficiency. Table 2 and Table 3 provide the experimental data on the 30kW DC EVSE for their voltage and current ripples at various loads and the corresponding PCE data in Table 4. The test matrix encompasses a comprehensive range of operating points, with currents spanning from 6A to 80A and SOC levels from 10% to 79%, providing robust data for performance analysis. Figure 2 shows the variation of VR and CR with load current and efficiency of EVSE.

Table 2. Experimental data of current ripples

SOC (%)	Load Percentage at 375V				
	10%	**25%**	**50%**	**75%**	**100%**
	8A	**20A**	**40A**	**60A**	**80A**
10%	**8.858**	**3.8351**	**2.029**	**1.248**	**0.909**
30%	**9.345**	**3.61**	**1.944**	**1.175**	**0.945**
50%	**9.095**	**3.555**	**1.973**	**1.222**	**1.006**
80%	**8.861**	**3.776**	**1.993**	**1.194**	**0.987**
99%	**95.89**	**62.566**	**75.884**	**70.809**	**77.578**
SOC (%)	Load Percentage at 440V				
	10%	**25%**	**50%**	**75%**	**100%**
	6.8A	**17A**	**34A**	**51A**	**68A**
10%	**10.785**	**4.054**	**2.465**	**1.827**	**1.288**
30%	**10.222**	**4.046**	**2.704**	**1.845**	**1.191**
50%	**9.5336**	**4.029**	**2.428**	**1.637**	**1.337**
80%	**10.0136**	**7.5715**	**2.582**	**1.504**	**1.225**
99%	**8.79**	**-**	**87.95**	**-**	**-**
SOC (%)	Load Percentage at 500V				
	10%	**25%**	**50%**	**75%**	**100%**
	6A	**15A**	**30A**	**45A**	**60A**
10%	**12.038**	**5.0523**	**2.48**	**1.634**	**1.206**
30%	**13.001**	**4.999**	**2.673**	**1.526**	**1.197**
50%	**13.473**	**5.395**	**2.867**	**1.755**	**1.278**

80%	**13.659**	**5.058**	**2.507**	**1.635**	**1.233**
99%	-	**78.762**	**95.033**	**93.664**	**99.44**

Table 3. Experimental data of voltage ripples

SOC (%)	Load Percentage at 375V				
	10%	25%	50%	75%	100%
	8A	20A	40A	60A	80A
10%	**0.228**	**0.237**	**0.256**	**0.237**	**0.247**
30%	**0.227**	**0.128**	**0.237**	**0.255**	**0.264**
50%	**0.237**	**0.209**	**0.277**	**0.255**	**0.273**
80%	**0.246**	**0.237**	**0.246**	**0.255**	**0.264**
99%	**0.146**	**0.146**	**0.155**	**0.155**	**0.146**
SOC (%)	Load Percentage at 440V				
	10%	25%	50%	75%	100%
	8A	20A	40A	60A	80A
10%	**0.187**	**0.218**	**0.202**	**0.225**	**0.218**
30%	**0.194**	**0.202**	**0.21**	**0.233**	**0.225**
50%	**0.194**	**0.202**	**0.202**	**0.218**	**0.225**
80%	**0.187**	**0.218**	**0.202**	**0.2254**	**0.209**
99%	**0.124**	**0.139**	**0.132**	**0.124**	**0.132**
SOC (%)	Load Percentage at 440V				
	10%	25%	50%	75%	100%
	8A	20A	40A	60A	80A
10%	**0.178**	**0.178**	**0.178**	**0.185**	**0.171**
30%	**0.185**	**0.37**	**0.171**	**0.205**	**0.205**
50%	**0.178**	**0.185**	**0.171**	**0.192**	**0.185**
80%	**0.199**	**0.178**	**0.184**	**0.178**	**0.192**
99%	**0.109**	**0.116**	**0.116**	**0.116**	**0.116**

Table 4. Experimental data on PCE

SOC (%)	Load Percentage at 375V				
	10%	25%	50%	75%	100%
	8A	20A	40A	60A	80A
10	**89.065**	**96.353**	**95.519**	**95.417**	**94.9**
30	**89.948**	**96.181**	**95.388**	**95.381**	**94.799**
50	**89.058**	**96.029**	**96.259**	**95.275**	**95.333**
79	**90.033**	**95.592**	**96.24**	**95.347**	**95.355**
99	**44.701**	**65.708**	**59.461**	**30.119**	**50.395**
SOC (%)	Load Percentage at 440V				
	10%	25%	50%	75%	100%
	8A	20A	40A	60A	80A
10	**88.846**	**92.853**	**95.52**	**95.75**	**94.294**
30	**88.389**	**92.82**	**95.391**	**95.615**	**94.33**
50	**88.584**	**92.686**	**95.328**	**95.633**	**94.284**
79	**87.607**	**92.516**	**95.437**	**95.445**	**94.242**
99	**41.895**	**28.304**	**38.423**	**32.331**	**28.847**
SOC (%)	Load Percentage at 500V				
	10%	25%	50%	75%	100%
	8A	20A	40A	60A	80A
10	**83.765**	**92.453**	**94.452**	**95.772**	**95.036**
30	**84.772**	**92.986**	**94.362**	**95.772**	**95.024**
50	**83.843**	**92.522**	**94.549**	**95.732**	**95.004**
79	**83.932**	**92.527**	**94.48**	**95.686**	**94.959**
99	**32.495**	**40.2**	**33.757**	**39.485**	**18.138**

Current Ripple

At 375V operation, the system exhibits remarkable stability in ripple characteristics, demonstrating a consistent exponential decay pattern as the current increases. The ripple magnitude decreases significantly from 8.858% at 8A to a mere 0.909% at 80A, while maintaining impressive power conversion efficiency. Peak efficiency reaches 96.353% at moderate currents, suggesting an optimal operating point that balances switching losses with conduction losses. The system's behaviour remains notably consistent across different SOC levels, indicating robust control architecture. The 440V configuration presents intriguing characteristics, particularly in the relationship between ripple magnitude and charging current. Initial ripple levels start higher at 10.785% for 6.8A operation but rapidly diminish with increasing current. A notable anomaly appears at 17A under 80% SOC, where the ripple temporarily increases to 7.5715%, potentially indicating a resonant condition in the power stage. Despite this, efficiency maintains a steady improvement with current, peaking at 95.75% during the 51A operation. The 500V operating regime demonstrates the most pronounced voltage-dependent effects on ripple behaviour. Initial ripple magnitudes reach 13.659% at low currents, the highest among all voltage levels tested. However, the system shows remarkable recovery at higher currents, achieving ripple suppression comparable to lower voltage operations. Efficiency characteristics follow a similar pattern, with peak performance of 95.772% occurring at 45A, demonstrating the system's capability to maintain high efficiency even at elevated voltage levels.

Voltage Ripple

The experimental analysis of voltage ripples in the DC fast charging system reveals intriguing patterns across different voltage platforms and operating conditions. The comprehensive assessment encompasses three voltage levels (375V, 440V, 500V), with measurements taken across various load currents (8A-80A) and battery state of charge levels (10%-80%). The voltage ripple characteristics demonstrate notably different behavior compared to the previously analyzed current ripples. The 375V system exhibits the highest voltage ripple magnitudes, ranging from 0.228% to 0.277%, with a distinctive trend toward increased ripple at higher current levels. This behavior contrasts with current ripple characteristics, which typically diminish at higher currents. The system shows relatively consistent performance across SOC levels, though slight variations emerge at higher load currents, particularly above 60A. Operating at 440V, the system demonstrates improved voltage ripple performance, with values typically ranging between 0.187% and 0.233%. A notable anomaly occurs at specific operating points, such as the 30% SOC at 20A load, where an unexpected spike to 0.37% is observed. This anomaly suggests potential resonance conditions or control loop interactions at these specific operating points. However, the overall trend shows more stable voltage ripple characteristics compared to the 375V system.

The 500V configuration achieves the most stable voltage ripple performance, with values consistently remaining below 0.205% across most operating conditions. This superior performance at higher voltage levels indicates effective voltage regulation and filtering strategies in the power conversion stage. The ripple characteristics show minimal sensitivity to both load current variations and SOC levels, suggesting robust control architecture at this voltage level. These findings demonstrate inverse relationship between operating voltage and ripple magnitude, contrasting with the current ripple behavior. The stability improvement at higher voltages likely results from better utilization of the filtering components and more effective switching control at elevated voltage levels.

EXPERIMENTAL ANALYSIS

Correlation Analysis

The investigation utilized a 30kW DC fast charging system operating at three voltage levels: 375V, 440V, and 500V. Current measurements ranged from 6-80A across different SOC levels (10%, 30%, 50%, 79%). Ripple measurements demonstrate exponential decay with increasing current, from maximum values of 13.659% at low currents to minimum values below 1% at high currents.

Data analysis reveals several key patterns:

Higher voltage systems (500V) exhibit larger initial ripples (12-13%) but converge to similar values (~1-2%) at high currents

Maximum efficiency peaks (96.353%) occur at moderate currents (20-40A)

Power conversion efficiency shows minimal dependence on SOC levels (-0.007 correlation)

The 375V system demonstrates optimal ripple-efficiency trade-off at high currents

The in-detail correlation analysis as shown in Figure 3 reveals important relationships in the EV charger's performance:

1. CR (-0.813): As the charging current increases, the ripple significantly decreases, indicating better power quality at higher currents. This strong negative correlation suggests that operating at higher currents provides more stable DC output, likely due to better filter performance and reduced relative impact of switching noise.
2. Current-PCE (0.657): Higher currents lead to improved efficiency, showing the charger operates optimally at higher power levels. This positive correlation reflects the reduced impact of fixed losses at higher currents, though the relationship plateaus at very high currents.
3. VR (0.151): Higher voltage levels slightly increase ripple, though the correlation is weak. This suggests voltage level has minimal impact on ripple performance, with other factors being more dominant.
4. Voltage-PCE (-0.243): Higher voltages show a slight negative impact on efficiency, possibly due to increased switching losses and component stress at higher voltages. However, the correlation is weak enough that other factors likely have more influence.
5. SOC-PCE (-0.007): Battery state of charge has negligible impact on charging efficiency, indicating consistent charger performance across different battery charge levels. This independence is beneficial for reliable operation throughout the charging cycle.

The load percentage correlations mirror those of load current, confirming consistent behaviour across the operational range. This statistical analysis provides crucial insights for optimizing charging system design, particularly in selecting operational points that balance ripple suppression with conversion efficiency. A 1% reduction in the current ripple corresponds to approximately 1.45% PCE improvement.

Charging Quality Performance Index (CQPI)

The Charging Quality Performance Index (CQPI) introduces a novel quantitative framework for evaluating DC EV charger performance by synthesizing critical operational parameters including current ripple, voltage ripple, and power conversion efficiency. This dimensionless index (as provided in equation 2), scaled from 0-100, employs voltage-dependent weighted coefficients for CR and VR derived from experimental correlation (Pearson) analysis. At 375V, the current ripple showed a strong correlation (0.8895) with efficiency, while the voltage ripple exhibited minimal correlation (0.0355), resulting in weight factors of 0.9617 and 0.0383 respectively. The 440V operation demonstrated more balanced correlations (CR: 0.9396, VR: 0.7169), yielding weights of 0.5672 for the current ripple and 0.4328 for the voltage ripple. At 500V, the analysis showed the strongest current ripple correlation (0.9899) with minimal voltage ripple impact (0.0390), leading to weights of 0.9621 and 0.0379. These weight coefficients were calculated as the proportion of each parameter's correlation to the total correlation magnitude, ensuring the sum of the weights to unity while reflecting their relative influence on system performance.

	Voltage Level	Load Current	State of Charge	Load Percentage	Current Ripple	Voltage Ripple	Efficiency
Voltage Level	1.00	0.00	0.00	0.00	0.15	-0.45	-0.24
Load Current	0.00	1.00	0.00	1.00	-0.81	0.12	0.66
State of Charge	0.00	0.00	1.00	0.00	-0.01	0.09	-0.01
Load Percentage	0.00	1.00	0.00	1.00	-0.81	0.12	0.66
Current Ripple	0.15	-0.81	-0.01	-0.81	1.00	-0.09	-0.60
Voltage Ripple	-0.45	0.12	0.09	0.12	-0.09	1.00	0.03
Efficiency	-0.24	0.66	-0.01	0.66	-0.60	0.03	1.00

Comprehensive Correlation Matrix of EV Charger Parameters

Blue: Positive correlation | Red: Negative correlation | Color intensity indicates correlation strength

This data-driven approach to weight determination ensures the CQPI accurately represents the varying impact of ripple characteristics across different operating voltages. The CQPI demonstrates that optimal charging performance (CQPI > 95) occurs within specific operational boundaries: 375V operation at 30-80% SOC and 75-100% load, achieving peak values of 100, while 500V operation maintains excellent performance (CQPI > 93) at similar loading conditions. Figure 4 shows the CQPI Score of DC EVSE at different voltage

levels. Its practical significance lies in identifying optimal operating zones, with the highest CQPI values consistently observed at moderate SOC levels (30-80%) and higher loads (>75%), offering crucial insights for system design and operational strategy development. The CQPI's integration of multiple performance parameters into a single, comprehensive metric represents a significant advancement in charging system evaluation methodology, facilitating more informed decision-making in charger design, certification, and operational optimization.

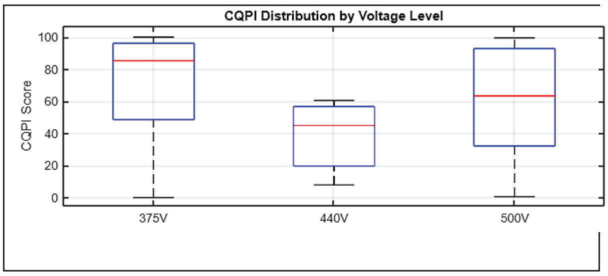

Fig. 4. CQPI Score of DC EVSE at different voltage levels

CONCLUSION

The development of the CQPI provides a standardized methodology for evaluating DC charging system performance. The analysis reveals distinct operational characteristics across voltage levels, with 375V operation showing superior overall performance (mean CQPI: 65.66) compared to 500V (56.80) and 440V (39.39) operations. The voltage-dependent correlation analysis demonstrates the varying impact of ripple characteristics, particularly at 440V where voltage

ripple shows significant influence (43.28% weight factor) compared to other voltage levels (~4%). These findings establish clear guidelines for optimal charging system operation, with the CQPI serving as a valuable tool for system design and performance verification. Future research should focus on thermal analysis at identified optimal points and CQPI validation across different power ratings.

REFERENCES

1. Uddin, K., Moore, A. D., Barai, A., & Marco, J. (2016). The effects of high frequency current ripple on electric vehicle battery performance. In Applied Energy (Vol. 178, pp. 142–154). Elsevier BV. https://doi.org/10.1016/j.apenergy.2016.06.033

2. Zeng, Z., Chen, J., Zheng, L., Wei, Y., & Chen, Y. (2018). Study on Output Voltage Ripple Coefficient of DC Charger Based on Orthogonal Test. In IOP Conference Series: Materials Science and Engineering (Vol. 452, p. 042175). IOP Publishing. https://doi.org/10.1088/1757-899x/452/4/042175

3. Ramos LA, Van Kan RF, Mezaroba M, Batschauer AL. A Control Strategy to Smooth Power Ripple of a Single-Stage Bidirectional and Isolated AC-DC Converter for Electric Vehicles Chargers. Electronics. 2022; 11(4):650. https://doi.org/10.3390/electronics11040650

4. Goldammer E, Gentejohann M, Schlüter M, Weber D, Wondrak W, Dieckerhoff S, Gühmann C, Kowal J. The Impact of an Overlaid Ripple Current on Battery Aging: The Development of the SiCWell Dataset. Batteries. 2022; 8(2):11. https://doi.org/10.3390/batteries8020011

4. Chad E. Kennedy and Richard D. Kirby, Megahertz-Sampled Observations of AC Level 2 Onboard Electric Vehicle Charging, 25th Annual Georgia Tech Fault and Disturbance Analysis Conference, Atlanta, Georgia, May 1–2, 2023 (Source accessed on 12th September 2023 at https://selinc.com/api/download/138271/)

5. Zhang, Y., Fang, J., Gao, F., Song, T., Gao, S., & Rogers, D. J. (2020). Second-Harmonic Ripple Voltage Suppression of Integrated Single-Phase Pulsewidth Modulation Rectifier Charging System for EVs. In IEEE Transactions on Power Electronics (Vol. 35, Issue 4, pp. 3616–3626). Institute of Electrical and Electronics Engineers (IEEE). https://doi.org/10.1109/tpel.2019.2937745

6. R. Kushwaha and B. Singh, "An EV battery charger based on PFC Sheppard Taylor Converter," 2016 National Power Systems Conference (NPSC), Bhubaneswar, India, 2016, pp. 1-6, doi: 10.1109/NPSC.2016.7858944.

7. E. Ucer et al., "A Flexible V2V Charger as a New Layer of Vehicle-Grid Integration Framework," 2019 IEEE Transportation Electrification Conference and Expo (ITEC), Detroit, MI, USA, 2019, pp. 1-7.