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Power Modulation and Phase Switching Testing of Smart Charger and Electric Vehicle Pairs

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Abstract—De-coupling transport sector from the use of petroleum is giving way to the rise of electric mobility. As compromising the user’s comfort is not an option managing the power system becomes a tall challenge, especially during peak hours. Thus, having a smart connection to the power system, such as an electric vehicle (EV) smart charger, is considered part of the solution. This paper focuses on assessing the capabilities of smart chargers in the context of helping the electrical network without compromising the user’s comfort. By using a Tesla Model S P85, Renault Zoe, and Nissan LEAF, the paper first evaluates differently controlled (centralized and distributed) smart chargers against the IEC 61851 standard. Second, it tests smart features such as peak-shaving, valley-filling, and phase balancing. Being representatives of the state-of-the-art, both chargers exceed standard requirements and offer new grid service possibilities. However, the bottleneck for providing faster grid services remains the EV on-board charger. The results from this article can help to better simulate the dynamic charging behaviors of EVs.

Index Terms—smart chargers, charging modulation, phase switching, electric vehicles

I. INTRODUCTION

As the EV technology matures and becomes a more commercially viable option for the masses, it is expected to gain high market share. This is reflected in the relatively large amount of research being done on vehicle-to-grid integration and user behavior [1]. Furthermore, in European countries, EVs being batteries on wheels, are on average parked 97% of the time with an average driving between 40-80 km/day [2]. Here, the fulfillment of charging needs, if left uncontrolled, may harm the distribution grid [3]. The authors of [4] describe potential harmful impacts on the distribution grid as i) increase in peak demand and power losses; ii) voltage instability and power quality issues; iii) grid components overloading. Thus, EVs can become a large flexibility asset for the power system by coordinating their flexible demand according to the system needs (also called demand-side management) [5]. To be able to take advantage of this flexibility from EVs, there is a need for large coordination between flexibility resources, flexibility markets, aggregators, energy communities, and system operators at the distribution and transmission levels [6]. In addition, a hidden layer is the charging behavior of end-users, which is still quite early to have a sufficient understanding and makes flexibility allocation prone to overestimation [7]. Nonetheless, authors of [8] quantify the driving energy demand to be covered 78% from households and the rest outside the private household environment. Furthermore, to determine the residential flexibility margins, authors of [9] look at driving requirements, parked period, battery capacity, and charging speed. By doing so, they propose a certain charging coincidence factor (CF) that reflects the frequency of charging on the residential ground. More specifically, the larger the number of EVs, smaller becomes the CF and it is more dependent on charging power rather than the EVs’ battery capacity. To complement this, the authors of [10] investigated the non-systematic plug-in behavior. They concluded that a larger battery size EVs offers less flexibility in terms of power (kW) and storage (kWh) due to a lower plug-in frequency and higher energy needs per charging session. Therefore, to tackle these challenges, a smart infrastructure, such as smart chargers, promises to unravel the complexity for the end-user. Especially beneficial is the coupling of residential flexibility for the safe operation of the grid with economic and environmental benefits for the EV owner [11]. Previously, smart charger was defined as "a device offering communication, protection and at minimum scheduling or at maximum modulation and phase curtailment for the charging process" [12]. Therefore, by focusing on smart chargers, the main contributions of this paper are as follows:

1) Test the capabilities of representative smart chargers (centralized and distributed architecture) to offer grid services.

2) Assess the performance (accuracy, precision and time delays) of the smart chargers and three EVs against the requirements of IEC 61851 standard [13].

The remainder of this article is structured as follows. Section II describes the control architecture and methodology behind choosing smart chargers, while Section III introduces case studies and Section IV provides the results of the tested chargers. Finally, Section V concludes the article.

II. CONTROL ARCHITECTURE

A. Smart chargers state-of-the-art

The technological aspect of smart chargers, especially the control method is crucial in scaling up the charging infrastructure. The authors of [14] explain three control possibilities: i)
centralized; ii) decentralized; and iii) distributed. Due to the implementation simplicity, the early stage of smart chargers belongs to the centralized control approach [12]. However, recent initiatives follow the distributed control approach introduced in [15]. The rationale behind exploiting distributed control is the increased robustness to malfunctions on a large-scale deployment and the reduction of required communication together with the communication delays [16]. For both control approaches, the goal is to follow a given power setpoint by modulating or scheduling the charging process. Here, Fig.1 explains the difference between the control approaches. The intelligence in the centralized approach resides in the cloud aggregator, while on the distributed case, the intelligence resides in the virtual aggregator (VA), and the cloud aggregator serves to coordinate across areas. On the distributed case, the cloud aggregator gathers grid or market signals to better optimize the controlling actions of the local virtual aggregator. Furthermore, these smart charger control capabilities, namely scheduling or modulating the charging process, should be evaluated in relation to what is beneficial to the grid. This paper does not intend to be exhaustive on the grid service front but rather evaluates some important well-researched features such as peak-shaving, valley-filling, and phase-balancing actions. Based on previous work [12], [17], we take as state-of-the-art representatives for the centralized control approach the Zaptec charger, while the charger developed in the ACDC project for the distributed control approach from [15].

![Diagram of control approaches on current EV chargers technology. VA accounts for the virtual aggregator.](image)

### B. Smart chargers assessment

Before comparing and testing the different control architectures on a complex environment, it is important to test and compare chargers directly through their communication ports. However, such testing has its limitations because smart chargers are part of the EV on-board charger. Therefore, their main control duty is to provide a pulse-width modulation (PWM) signal, which corresponds to the maximum allowed charging current, to the vehicle on-board charger. In addition, the PWM precision is defined by the IEC 61851 standard through the allowed oscillator resolution [13]. The oscillator frequency should be 1 kHz ± 0.5%, pulse width should be ± 25 μsec, and the duty cycle tolerance is ±1% (or 0.6 Amps). Due to technical improvements, the tested charger manufacturers offer a much better modulation resolution than 0.6 Amps, thus, PWM timing is the only feature to be tested [18], [19]. The IEC 61851 standard demands for the smart charger a maximum of 10 seconds for the change of the pulse-width in response to external signals.

Furthermore, the IEC 61851 standard requires the EV on-board charger to respond within five seconds to a PWM change (denoted as time delay in Fig.2). Additionally, having the possibility to test different EVs Fig2 illustrates the evaluation process for the vehicle on-board charger. The vehicle on-board charger is responsible for the vehicle charging dynamics. To evaluate such dynamics, we use the following key performance indicators (KPIs): i) the accuracy between receiving the PWM signal and the charging current, ii) the time delay between receiving a PWM signal and responding to it (the maximum allowed time is five seconds) and iii) the precision of the charging current. In summary, the time delay between the two chargers, the verification of charging modulation, and three-to-one phase switching can be tested.

![Diagram of time delay accuracy and precision indicators.](image)

### III. Case study

This paper presents two case studies. The first one is a centralized architecture, while the second one is a decentralized architecture. Moreover, Fig3 describes the laboratory setup for experiments presented in section IV. Two Zaptec chargers are connected to a lab cell (or the external grid) via a three-phase 63 Amps breaker. The size of the breaker quantifies the maximum current allowed for point of common coupling (PCC). Zaptec chargers have a certified meter inside the unit that is used to send data back to the Zaptec cloud. Furthermore, Zaptec chargers use the cloud to coordinate between them and follow a certain power threshold. In addition to that, the test setup has a DEIF multimeter connected to the University (DTU) cloud, which offers high-resolution measurements. The operator, who is conducting the experiments can utilize the web interface from the Zaptec cloud to send commands to the chargers and record the data through deif meters with a higher resolution. The difference for the ACDC charger is that it uses the DEIF multimeter connected to the DTU cloud and the PCC capacity is limited maximum 32 Amps or 22.1 kW. In both cases, the PCC capacity is intended to change, by controlling...
the PWM signal of the smart chargers. In doing so, we emulate the load-curtailment behavior performed by the Zaptec/ACDC charger.

Lastly, Fig 4 displays the Syslab facilities where smart chargers are tested. It is important to highlight that according to the IEC 61851 standard [13] smart chargers are responsible to deliver a PWM signal (corresponding to the duty cycle) to the EV on-board charger. The quality of the PWM signal is determined by the chosen oscillator from the charger manufacturer. Such control action through the PWM signal is the end result of smart charging strategies that can include single or stacking services, for example frequency control, voltage regulation, or congestion management [22], [23].

IV. RESULTS

This section presents the results from the testing of smart chargers and vehicle on-board chargers. Before elaborating on the testing procedure, it is important to highlight that both ACDC and Zaptec chargers can modulate below 0.6 Amps. The former (ACDC) can modulate in 0.06 Amps and the latter in 0.1 Amps.

The second case is modulating the allowed consumption of the chargers or virtually adjusting the PCC capacity. This attempts to emulate a peak-shaving or valley-filling action. Fig 6 displays the charging modulation at 5-minute intervals for Zaptec chargers.

The physical electrical connection allows for 44 kW; however, at time 12:29:10 it is artificially reduced (39% power reduction) to 27 kW emulating a peak-shaving action. This big step reduction was chosen to evaluate the performance of the smart charger and the on-board charger dynamics. The Zaptec cloud assesses which charger should reduce the charging power, and the one corresponding to the Tesla reduces most of the charging power. This occurs because the Zaptec chargers are by default designed to be on equal priority regarding power distribution between them. The PWM signal dictates how much power is available for each vehicle (maximum limit). Following the IEC 61851 standard (hereafter referred to as the standard) [13], EVs on-board charger should recognize the PWM signal and decide to charge according to their battery needs. One interesting aspect is the charging initial dynamics. Because the standard does not define a time for the vehicle to start drawing current, different EV manufactures have different dynamics. Furthermore, Fig 7 presents the same case, albeit for the ACDC charger. The same vehicle (Renault Zoe) is used to modulate the charging power. However, in this case, Zoe has a lower state-of-charge (SOC) (54%). The vehicle receives the PWM signal from the ACDC charger and in this case, Fig 7 Renault Zoe can better follow the PWM signal.
The authors of [18], [19] measured such cloud communication delays using an oscilloscope and pinging the Internet service for 24 hours. If the measuring device had been in the 100-200 ms range, we would have experienced, on average, a 300-400 ms shift in time for the PWM signal and the charging dynamics. The shift in time means that the ACDC charger is faster than the Zaptec one, due to lack of cloud communication delay.

In addition to testing three-phase vehicles, Fig. 9 presents testing of a single-phase charging [EV] with the ACDC charger.

Here, a Nissan LEAF 24 kWh is used, which can be charged to a maximum of 3.68 kW (16 Amps). The bottom plot of Fig. 9 displays the voltage behavior during the modulation of the charging current. Nissan LEAF is charging in the first phase, which corresponds to voltage V1. As expected, once the [EV] is charging in full power (time 10:28-10:32), the voltage reduces, and while the charging power decreases (time 10:32-10:42), the voltage increases.

Fig. 10 and Fig. 11 display a new feature offered by recent smart-chargers, which is the ability to switch the charging of a three-phase [EV] from a three-phase to one-phase. In addition, the three-to-one phase switching can be manually or automatically decided by the operator. Such capability is successfully demonstrated by both chargers. Both, Tesla and Zoe, are initially charging with 32 Amps on three-phase. After 15 seconds, the switch phase command is initiated. During the transition from three-phase to one-phase charging (Figs. 10 and 11), [EVs] do not consume power from the grid and are
not disconnected from the charging process. The three-to-one phase switching similarly initiates a single-phase charging with 32 Amps. However, the transition period is different for the tested EVs.

**Fig. 10:** Switch phase command from three-phase to one-phase charging on a Tesla Model S P85 with Zaptec charger.

In this regard, Fig. 12 displays the time difference of the phase-changing action. Although both EVs react quite similarly to power reduction, there is a significant difference when one-phase charging re-starts. Another important result to mention is that the transition to one-phase charging can only be achieved through the first phase of the EV on-board charger. The vehicle enters an error state if an attempt to charge is made in a single phase through the second or third phase of the vehicle’s on-board charger, as presented in Fig. 13. For changes in the PWM signal, the IEC 61851 standard requires a time delay of less than five seconds, which is the case for all tested EVs. However, the results point out that the delay from the chargers is quite small (400 ms and 100 ms) when compared to the EV on-board chargers (1 to 4 sec).

**V. CONCLUSIONS**

This paper introduced a feature assessment of differently controlled (centralized and distributed) state-of-the-art smart chargers. First, the chargers were tested for potential peak-shaving, valley-filling, and phase-balancing actions. Second, by utilizing KPIs such as accuracy, time delay, and precision the manuscript evaluates the smart chargers and available EVs on-board charger. The results of both smart chargers show a successful execution of the smart actions mentioned above. Charge modulation is successful and relatively fast and precise.
when tested with Tesla Model S, Renault Zoe, and Nissan LEAF. Furthermore, the three-phase EVs can charge in a single phase; however, that single phase must be the first phase of the on-board charger.

The current modulation resolution is 0.1 Amps and 0.06 Amps for Zaptec and ACDC charger, respectively. In terms of the accuracy of charging power (following the PWM signal), it is correlated with the vehicle SOC. For a high SOC, the vehicle requires less charging current, thus, the accuracy deteriorates. With respect to time delay, the downward modulation is almost instantaneous, while the upward modulation is subject to the vehicle on-board charger dynamics. Finally, precision is the sole responsibility of the vehicle’s on-board charger, as smart charger manufacturers incorporate very precise oscillators in their chargers. Nissan LEAF is the fastest and most precise of the tested vehicles. Overall, all tested EVs respond within the five seconds requirement for changing charging current. However, the speed of response of the on-board charger is the bottleneck to providing faster ancillary service. The results presented in this article help to better simulate the charging behavior for future dynamic investigations. For future work, it is necessary to understand the subsecond time delays for both chargers. To do so, it will require higher resolution meters.

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