Required Technologies for Grid Integration of Charging Infrastructure

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***Abstract* – This paper presents expected grid integration technologies for electric vehicle (EV) charging infrastructure which will be required to ensure the future stability of the power system. Technologies well known from modern inverter-based renewable energy systems are suggested to be implemented also in electric vehicle supply equipment (EVSE).**

The first chapter describes the challenges for the power system and for grid operators when electrifying the transportation sector to meet international climate goals. In the second chapter, a standard load profile for the charging process of EVs based on assumptions for the future electricity demand of the transportation sector and a standard business load profile is introduced. The third chapter reflects today's state-of-the-art grid integration of EVSE, whereas Chapter IV describes expected future levels of the grid integration of EVSE. Chapter V analyses the behavior of EVSE and EV in case of grid faults. A summary and outlook is given in Chapter VI.

Keywords – grid integration; charging infrastructure; grid integration levels; fault ride through (FRT); storage integration; grid code requirements

I. INTRODUCTION

Due to the environmental pollution by combustion engines together with the scarcity of fossil fuels, e-mobility becomes a strategic need for developed countries to be able to achieve their set climate goals. Therefore the numbers of electric vehicles (EVs) and the corresponding charging infrastructure are expected to increase significantly in the next years. Similar to the challenges grid operators (GOs) faced in the past decade due to increasing shares of inverter-based renewable energy systems (RES), nowadays the increasing use of EV bears new challenges.

The various charging technologies and strategies (slow or fast, AC or DC) as well as the individual user behavior of EV drivers lead to highly-fluctuating loads resulting in the need for bigger efforts to achieve frequency and voltage stability. Even in normal (non-faulted) operation, a high diversity of charging processes exists because charging current and time depend on several factors, such as the nominal characteristics of the battery and its state of charge (SoC), as well as the characteristics of the EV supply equipment (EVSE, i.e. charging station). As one example of the variety of charging processes, Figure 1 shows three different measurements of the charging current at one high power charger (HPC) over time.

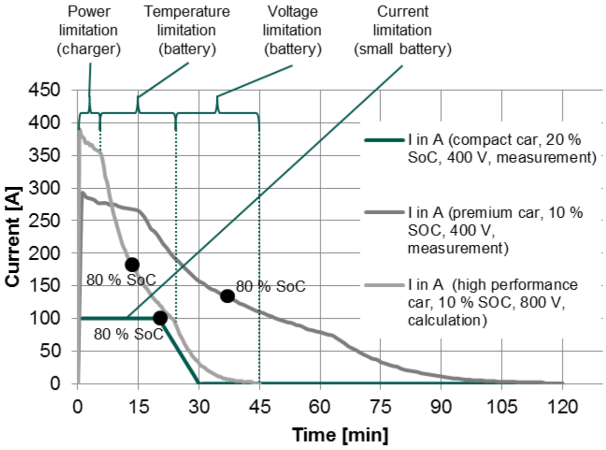

Figure 1. Charging current over time of different cars on a high power charger [1]

Despite the huge variety of publications about the influence of EVs on the grid, no set of generally applicable load profiles for EV / EVSE is available at present. Therefore all studies include some uncertainties due to the assumptions made for the charging processes. Nevertheless it is agreed that, to maintain a high security of supply, electrical loads like EV charging stations in addition to controlled charging, i.e. load shifting, should be required to contribute to the stability of the power system.

To fulfill the set climate goals, energy efficiency in all sectors (electricity, heat, mobility) has to be increased and electricity has to be produced CO_2-neutral with renewable energy sources. Reference [2] analyzes the future energy system of Germany which would be needed to achieve the two-degrees target. Reference [2] determines a future electricity demand for the transportation sector of 120 TWh per year in Germany. This results in an average additional power consumption of 13.7 GW in Germany caused by e-mobility. In this paper this will be referred to as the *100 % scenario*. Also in a scenario which achieves just 10 % of this electrification level, the electric energy consumption of the transport sector will be about 12 TWh and the additional average power consumption will be around 1.37 GW (*10 % scenario*).

Usually this load is not equally distributed throughout any given day or year, rather the energy is consumed with a characteristic load profile. In Chapter II, assumptions for a standard load profile for the total future charging infrastructure are deduced.

II. STANDARD LOAD PROFILE OF CHARGING INFRASTRUCTURE

To calculate the grid load, GOs use standard load profiles for different kind of loads. Those load profiles depend on weather conditions (winter or summer), the day of the week and the type of the loads. Each standard load profile bundles the behavior of many loads with similar characteristics. Typical standard load profile groups are:

- Private Households
- Businesses
- Farms
- Industry

All categories have subgroups. For example the business load profile can be differentiated between offices, shops, evening business (e.g. fitness studio), weekend business (e.g. restaurants) etc.

Today a standard load profile for charging infrastructure does not exist. For the consideration in this paper, a modified load profile for general business loads is used. Many business activities have a direct correlation with mobility requirements, therefore in future, charging events can be combined with business activities, such as:

- Charging of a truck or vessel can be done while loading and unloading cargo
- Visiting a supermarket/cinema/fitness studio can be combined with charging the car at the facility's parking lot
- Private cars are charged at home directly after the business activity, e.g. work or shopping.

Thus, using a standard business load profile as a basis for deducing a standard load profile for charging infrastructure is a valid approach. Indeed the cumulated charging load profile will most likely have a time delay to the various business activities, but it is mainly the spread between the low load and high load level which is of interest for this paper. Therefore the presentation of the correct load profile over time is not essential for the considerations made in this paper. Figure 2 shows the average weekly cumulated charging load profile for Germany for the *100 % scenario* and the *10 % scenario*. To derive the *100 % scenario* profile, the expected yearly electricity demand of the transportation sector of 120 TWh is allocated to the 15 min time slots of one year, with the same distribution as that of the standard business load profile from the German DSO Mitnetz [3]. An average week of this deduced *100 % scenario* profile is shown in dark blue, with the *10 % scenario* profile in dark green.

Additionally the annual average (fully smoothed load) is shown for both scenarios in light blue and light green.

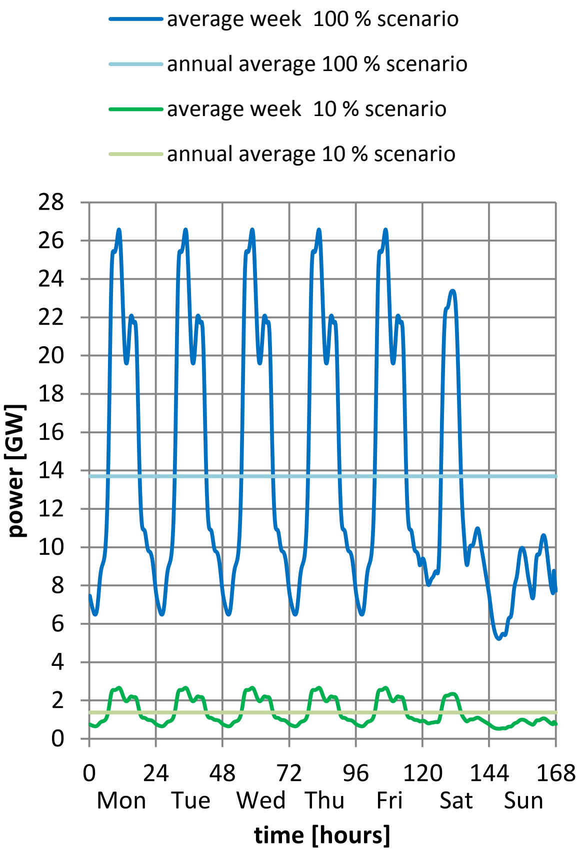

Figure 2. Cumulated charging load profile of Germany for an average week, based on a business load profile and the annual average for *100 %* and *10 % scenario*

The curves in Figure 2 show the difference in load level between the days of the week (on weekdays the EVs are used more frequently), and the load peaks in the morning (people have driven to work and charge up their EVs at work) and in the evening (people charge up their EVs at home). After a few hours all cars are fully charged; the load decreases and the demand reaches its minimum value at around 1 o'clock at night.

Figure 3 shows the deduced load profiles for different days of the *100 %* and *10 % scenario*:

- A day with average load
- A day with maximum load
- A day with minimum load
- The annual average

The maximum load due to EV charging processes can go up to 28.8 GW in Germany in the *100 % scenario*. Even in the *10 % scenario* the minimum load is still 550 MW at the weekend.

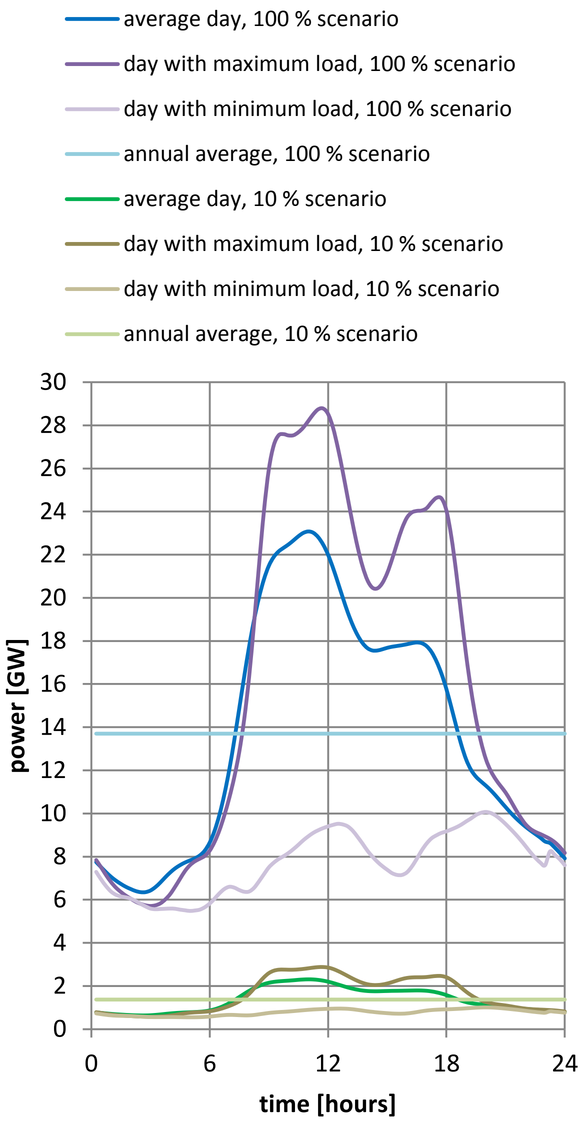

Figure 3. Cumulated charging load profile of Germany for one day (average day, day with maximum load, day with minumum load) based on a business load profile and the annual average for *100 %* and *10 % scenario*

III. STATE OF THE ART GRID INTEGRATION

The charging process of EVs is already well standardized by international standards such as IEC 61851 and IEC 62196. This is to ensure that by using the same combination of interfaces and protocols each EV can be successfully charged at every EVSE.

However the grid connection requirements for EVSE are defined locally by the respective Grid Code (GC) and therefore may differ. In most countries, the GCs refer to EVSE as normal loads which are not required to have any grid supporting features.

As shown in Chapter II, with the expected ramp up of EVs in the coming years, the additional electric load caused by simultaneous charging processes will become a relevant factor for grid operation.

Some countries introduce the concept of controllable loads in their GCs or national laws. This requirement can be met for example via ISO 15118 by so called *smart charging* where the charging process can be shifted in time to prevent high demand peaks that might cause an overload of the local electrical infrastructure.

But EVSE are not just necessarily an additional load, they could also actively support the grid. The authors refer to this as *grid integration* in contrast to *grid usage*.

IV. EXPECTED LEVELS OF GRID INTEGRATION

Since EVSE are connected to the grid via power electronics (similar to RES), it is possible to incorporate flexible grid features into their controls. The only premise for this is the use of active AC-DC-converters.

Accordingly Figure 4 shows conceivable grid integration levels for the near and mid-term future.

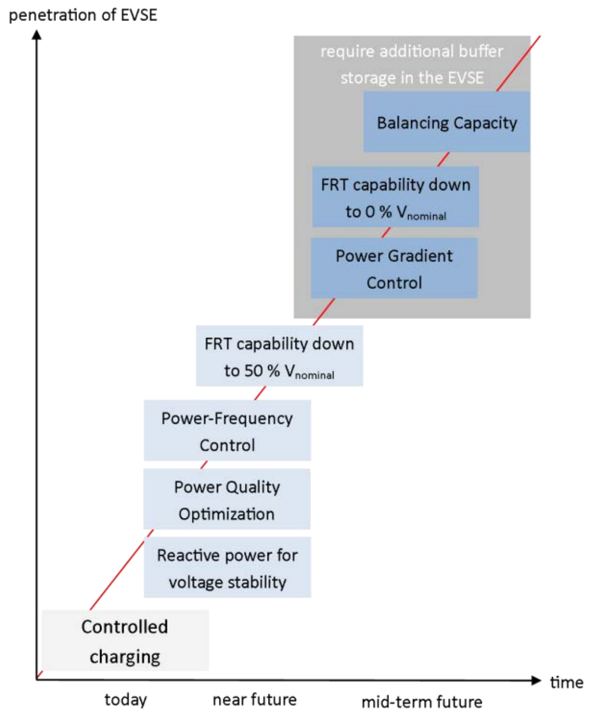

Figure 4. Conceivable grid integration levels for the near and mid-term future

Today:

- The benefit of controlled charging, in the sense of shifting the charging process in time to avoid high peak loads, was shown in several studies [4] and is already common. The required communication between EV and EVSE is implemented e.g. according to ISO 15118.

Near future:

- In the near future the AC-DC-converters of the EVSE can be controlled in the same way as currently done by RES. By providing reactive power to the grid, the EVSE can support voltage stability [1, 5 and 6] and by implementing a power-frequency control they can also support the frequency-stability. [4, 7]
- If active AC-DC-converters are used, requirements with regards to power quality, e.g. the limitation of

harmful harmonics, can also be met relatively easily. [8]

- In case of grid faults, Fault Ride Through (FRT) capabilities down to approximately 50 % grid voltage can be achieved without additional power supply.

Mid-term future:

- Once a significant amount of installed EVSE is reached, it will be important that those additional loads use their full potential of flexibility. By combining the EVSE with on-site storage or including a smaller buffer storage directly into the EVSE the currently-used charging power can be (at least partly) provided independently from the grid. This enables power gradient control as well as FRT down to 0 % residual grid voltage.
- Balancing capacity could also be provided by an integrated storage system.

As an example of the upcoming challenges and how they can be met by certain grid integration features, the behavior of EVSE and EV in case of grid faults is discussed in greater detail in Chapter IV.

In the course of the fundamental revision of the German GCs, special requirements for the operation of EVSE have been added. In the future, EVSE in Germany will have to support grid stability actively, by providing reactive power and having power-frequency control installed. [9, 10]

V. BEHAVIOR OF EVSE AND EV IN CASE OF GRID FAULTS

A. *Impact on the grid*

As shown in Chapter II, charging of EVs may cause an instantaneous load of up to 28.8 GW on the German grid. Compared to today's primary control reserve of 620 MW in the German regulation zone [11] this load is much higher. Therefore it is very important that the charging infrastructure will have no negative impact on the grid stability if a fault or other events happen. The most important requirement for the future is that EVSE stays connected to the grid in fault situations. Also other requirements like the limitation of the power gradient after the reconnection of a charging station after a fault are important for the stability of grids with a high amount of charging infrastructure. Additionally, providing system services like power-frequency support can become necessary with a high penetration of EVSE.

The major challenge is that grid faults lead to a disruption of the charging process, which today usually has to be restarted manually. Voltage dips in the transmission system can have a spread of several 100 km and lead to voltage dips at the terminals of a large number of installed EVSE, i.e. several GW. As of today's standards, this will lead to a simultaneous shut down of the affected EVSE, suddenly causing a significant imbalance of generation and load.

FRT requirements for loads, especially for EVSE and EV, have neither been implemented in standards or GCs nor have been in the focus of scientific discussions yet, whereas FRT requirements for generators are well known in modern GCs. In future scenarios with thousands of parallel EV charging processes, missing FRT requirements for EVSE and EV may result in significantly different post-fault grid loads compared to the pre-fault situation, followed by undefined load ramp-ups when the charging process restarts. Therefore the impact of the integration of large numbers of EVSE and EV on the overall grid stability is discussed in Chapter V.B.

Finally a dynamic (reactive) current feed-in in case of grid faults could be important in the future, especially in grids with low short circuit currents and grids with a high penetration of RES. In that case an additional fault current could be provided by some loads as well.

B. *Technical Consequences*

To support the grid in case of grid faults and prevent disconnection of a large number of loads, a modification of the hardware of today's standard EVSE and/or new control technologies are necessary. In fault situations, the grid voltage suddenly dips and therefore the possible power exchange with the grid is massively reduced. Since the charging process of the EV is decoupled from the grid, the main problem is that the charging process is not automatically reduced or stopped when the grid voltage dips. It will continue as long as the internal storage capacities, e.g. DC link capacity, can provide enough power to keep the charging parameters (current / voltage) within their defined limits. This will result in a power shortage in the EVSE and a subsequent shutdown.

To prevent a shutdown of the EVSE in case of (short) grid faults, the charging power has to be reduced rapidly as soon as an under-voltage in the grid is detected by the EVSE. Another possibility is a storage implementation to prevent power shortages in the DC link. Since the capacity of the DC link is usually quite small, the reaction of the power reduction or the storage activation has to occur in only a few milliseconds. Figure 5 shows an EVSE consisting of a three-phase converter on the grid side, a decentralized DC link, an integrated storage system, and three parallel DC/DC converters on the car side.

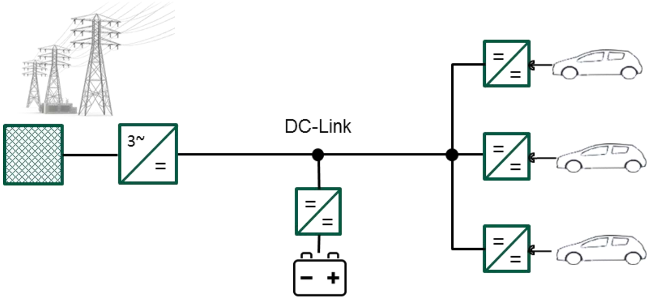

Figure 5. EVSE with integrated storage system

The first challenge is to manage the power balancing in such a short time. Usually the grid-side converter controls the DC link voltage using a droop control, see Figure 6a. One possible solution could be an additional DC link voltage regulation by the car-side converters in case of an under-voltage in the DC link, see Figure 6c. The DC link voltage only is controlled by the car-side converters when the current limit of the grid-side converter is reached and the grid voltage drops below a defined level, so that the grid-side converter cannot feed enough power into the DC link.

Whenever the grid voltage is in normal operation the DC link control by the car-side converters in deactivated. Also, a storage implementation could be realized with a decentralized DC link control, see Figure 6b. The main advantage is that no communication is necessary between the different devices connected to one DC link.

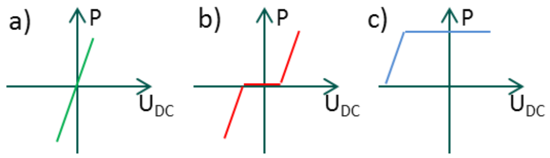

Figure 6. a) P-U characteristic of the grid-side converter; b) P-U characteristic of the converter of the storage system; c) P-U characteristic of the DC/DC converter on the car side

The second challenge is to keep the charging process in operation from the car side. Today a short power reduction is not defined in the car interface and the car might interrupt the charging process, when the charger suddenly reduces the power for a short time. To implement a proper FRT capability in the EVSE without additional storage, the possibility to reduce the charging power on demand of the EVSE without causing a termination of the charging process has to be introduced in the standards.

In case of under-voltage situations in the grid down to 50 % of the nominal grid voltage, a modern charger can stay in operation if the charging power is reduced accordingly. Also an additional current feed-in to stabilize the grid in case of under-voltage is possible with modern technologies, down to 50 % of the nominal grid voltage. Fault ride through for lower retained voltages requires additional storage in the DC link to cover the losses in the system, because power supply from the grid is no longer possible.

To avoid a secondary fault due to high post-fault load gradients, it is important that those EV and EVSE which disrupted the charging process during the primary fault follow a defined process for restarting the charging process once the grid parameters are back within their normal operation range. Therefore a limitation of the power gradient for the post-fault restart should be defined.

VI. SUMMARY AND OUTLOOK

The expected ramp-up of EVs, with the corresponding expansion of charging infrastructure will have a significant impact on the electricity grid. This paper has discussed some grid integration features of charging infrastructure that will contribute to grid stability and can minimize the need for grid expansion.

Using the example of Germany, a cumulated charging profile based on a standard business load profile [3] and the expected electricity demand for the transportation sector [2] has been deduced. It shows that charging of EVs can cause a simultaneous load of up to 28.8 GW connected to the German grid. Compared to the maximum load of 77.9 GW in 2017 [12] this is likely to have a noticeable impact on the power system. Especially in fault scenarios, the influence of EVSE on grid stability has to be considered.

Since today's standards do not define a desired behavior of EVSE in case of grid faults, they usually lead to a disruption of the charging process. To make sure that voltage dips due to minor grid faults do not lead to critical post-fault imbalances between generation and load, a defined FRT behavior similar to what is well known from RES should also be required for EVSE.

Any equipment that is installed today will influence the grid for at least the next ten years. Therefore requirements for the grid integration technologies of charging infrastructure should be introduced in modern GCs. As long as GCs include no or minimal additional requirements for EVSE, most of the installed EVSE will not have grid supportive features. Advanced grid integration technologies for EVSE can be achieved easily by using the same features that are already well known from RES.

To define the most useful grid integration requirements and their detailed configurations, it is advisable to put the effects and interactions of a large number of installed EVSE in the focus of further scientific research. For example, it should be analyzed whether a dynamic feed-in of reactive current during FRT is desirable for loads like EVSE.

The paper shows that the implementation of buffer storage inside the EVSE can have several benefits. Depending on the dimensions of the storage it can

- help to avoid peak loads
- enable FRT down to 0 % of the nominal grid voltage
- be used as balancing capacity.

The most economic sizing of any buffer storage needs to be evaluated project specifically.

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