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Planning Future Electric Vehicle Central Charging Stations Connected to Low-Voltage Distribution Networks

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Abstract— A great interest is recently paid to Electric Vehicles (EV) and their integration into electricity grids. EV can potentially play an important role in power system operation, however, the EV charging infrastructures have been only partly defined, considering them as limited to individual charging points, randomly distributed into the networks. This paper addresses the planning of public central charging stations (CCS) that can be integrated in low-voltage (LV) networks for EV parallel charging. The concepts of AC and DC architectures of CCS are proposed and a comparison is given on their investment cost. Investigation on location and size of CCS is conducted, analyzing two LV grids of different capacity. The results enlighten that a public CCS should be preferably located in the range of 100 m from the transformer. The AC charging levels of 11 kW and 22 kW have the highest potential in LV grids. The option of DC fast-charging is only possible in the larger capacity grids, withstanding the parallel charge of one or two vehicles.

Keywords – electric vehicles, charging infrastructures, charging stations, low voltage grids

I. INTRODUCTION

IN 2008, the European Commission published the “20 20” by 2020 package. The aim is to reach reduced greenhouse gas emissions and to increase generation from renewable power sources [1]. A possible way for achieving the Commission targets is given by the combination of battery-powered vehicles, or simply EVs, and the charging infrastructures. In fact, in the process of electrification of transport sector, the infrastructure is going to play a major role. Until few years ago, EV infrastructures were seen as limited to single charging points in urban streets or parking lots, with little or no attention to their grid operation [2]. With more EVs coming on the market, the attention for infrastructures has increased, leading also to different charging concepts.

The standard way of charging an EV, originally known as slow charging option, has lately involved the opportunity of managing the charging process with communication technologies that enable a remote control [3]. This is possible by controlling a single charging spot, or the vehicle management system (VMS), if such intelligent equipment is available. The need for an EV range extension and the necessity of a short waiting time for charging pushed EV

manufacturers to implement the fast-charging option for EVs. Fast charging, or DC charging, is investigated in [4]. The third concept of EV charging is based on the battery switch station; in [5], the authors described the concept and possible solutions for the charging management of a cluster of batteries.

The gradual replacement of internal combustion engine (ICE) cars with EVs requires a more scrupulous planning of future charging infrastructures in LV distribution grids, not only limited to single charging points, but extended to the level of public central charging stations (CCS). With more EVs on the market, such CCS are expected to have automated functions that allow parallel charging and different charging power levels.

Furthermore, the planning of a CCS should take into account the different grid constraints in LV grids. In fact, such infrastructures, likewise gas stations, are likely to be located at strategic points of urban areas which are suitable to EV users. In the integration process, it should be ensured that the grid voltage and the components loading such as LV cables and transformers stay within their allowed range.

In this paper, different concepts of CCS to accommodate EV charging in LV distribution networks are proposed. The location and size for such infrastructures are identified for two LV grids of different capacity. Finally, a cost analysis for the different concepts of CCS is performed.

II. EV CHARGING

In the planning of a CCS, an important aspect to consider is the charging power defined in the common developed standards.

The actual status for EV conductive charging in Europe is defined in the IEC 61851-1 [6]. The standardization activity has focused on electric vehicle requirements for conductive charging with AC and DC supply. The different AC and DC charging options are depicted in Table I, for reference. The quick charging power levels of 22 kW and 43 kW will be accommodated gradually in three phases: the 22 kW, defined in IEC 61851 - Mode 2, will be deployed first; the second phase will involve the 43 kW charging power, defined in Mode 3, while the third phase will involve Mode 4 charging or DC charging, which entails next generation batteries requiring at least 60 kW ($400V_{dc}$ - 150A) charging power; with this case, a

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20 kWh battery pack can be charged up to 80% state-of-charge (SOC) in about 15 minutes [7].

From a CCS perspective, the main difference between Mode 3 and Mode 4 is that, with Mode 3, there is the option of charging an EV with AC power of up to 43 kW, if a vehicle on-board charger with same power is available; with Mode 4, the CCS should be capable of fast-charging using a stationary off-board DC charger.

One major requirement for CCS design is therefore the capability to provide AC or DC power for charging, depending on the desired charging time and based on the EV charging capabilities.

Table I
Charging power options

	Current	Voltage	Grid connection	Power
AC	16 A	230 V	single phase	3.7 kW
	32 A	230 V	single phase	7.4 kW
	16 A	400 V	three-phase	11 kW
	32 A	400 V	three-phase	22 kW
	63 A	400 V	three-phase	43 kW
DC	150 A	400 V	off-board charger	60 kW

A. Combo plug for AC and DC charging

The physical interface for transferring AC or DC power to the vehicle is defined in the Standard IEC 62196-3 [8]. This standard defines the contact coupler for DC charging, to be used under Mode 4 charging, according to IEC 61851-1. Though the publication of the standard is expected in

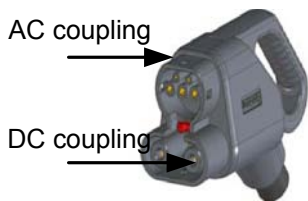


Fig. 1. “Combo” charging plug for EVs, based on IEC 62196-3 [9]

December 2013, the proposal from this standardization activity represents an important step towards the design of CCS architectures. The proposed coupler, Fig. 1, is also known as “combo” as it allows both AC and DC charging, embedded on the same charging cable [9].

Other ways of fast-charging or DC charging have been developed, where the AC inlet is completely decoupled from the DC inlet [10]. In this case, two different charging cables are required.

III. INTEGRATION OF EVS IN LV GRIDS

Urban grids have a high potential for CCS integration, due to the proximity to houses and parking lots. An optimal placement of public CCS shall minimize the distance driven for recharging the vehicles. However, depending on location and distance from the LV transformer, a CCS can have different

impacts on the grid voltage and on components loading. For this reasons, different grid constraints should be taken into account when dealing with CCS planning.

A. Voltage constraints for CCS planning

LV grids are mainly composed of radial feeders and cables with high R/X ratio. A typical residential LV grid with a 100 kVA secondary distribution transformer and two 95mm² main feeders rated at 230 kVA [12], is depicted in Fig. 2, and considered as case of study. The nomenclature used (e.g. A,2), indicates the electric cabinet ID and the number of connected households respectively. One of the issues limiting the load in LV grids is the voltage drop along the different feeders. The voltage in a LV grid is function of the following factors, among all:

- LV components characteristics: cables length, cross section and capacity, cable impedance etc.
- Operational characteristics: tap-changer position in secondary distribution transformers, voltage limits set by the local DNO etc.
- Load profiles: loads at each node in the grid etc.

Table II
Assumptions for maximum load calculation

Cases	Base grid voltage	Minimum allowed voltage
Case 1	1.00 p.u.	0.90 p.u.
Case 2	1.04 p.u.	0.90 p.u.
Case 3	1.00 p.u.	0.95 p.u.
Case 4	1.04 p.u.	0.95 p.u.

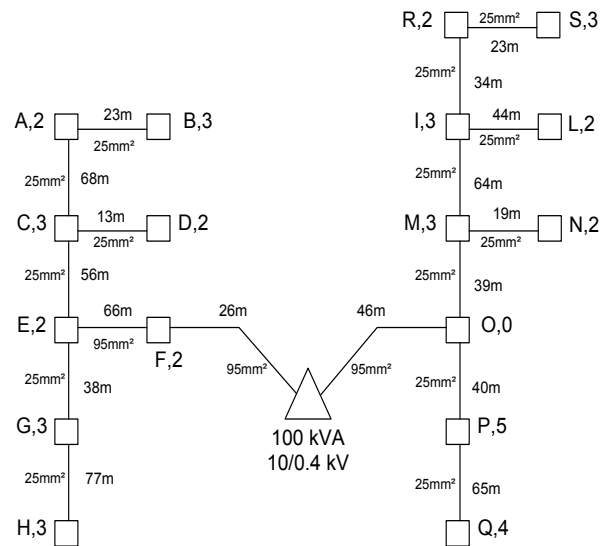


Fig. 2. Residential LV grid

For the LV in Fig. 2, it is possible to calculate the maximum load that does not exceed the minimum voltage level V_{min} required at the different terminals in the grid. The

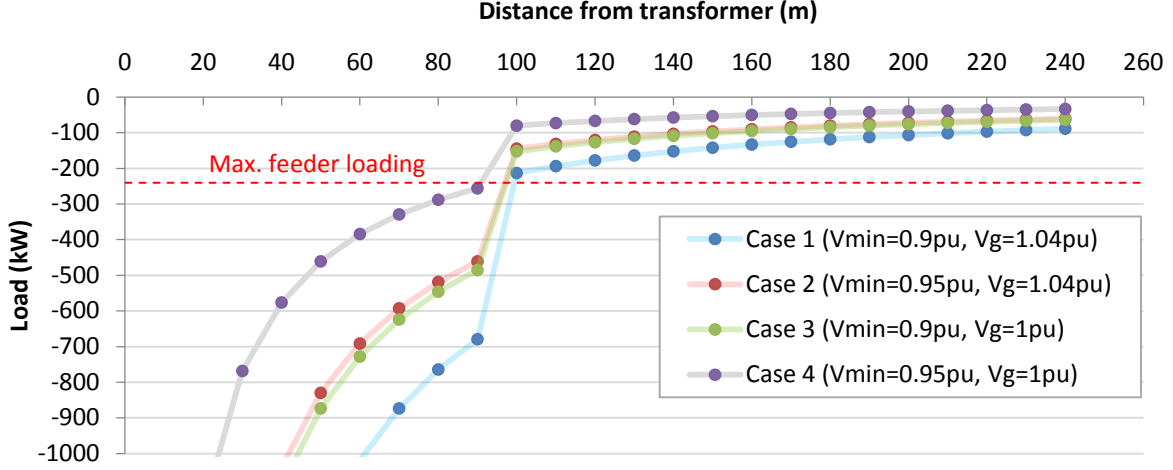


Fig. 3. Maximum load in relation to different operating conditions

calculation is performed according to the four cases of Table II, where two different values of base grid voltage V_g and minimum voltage V_{min} are considered.

The base grid voltage V_g is assumed 1.04 p.u. and 1.0 p.u. respectively, considering two possible operational set-points by the local DNO. As minimum voltage level V_{min} in the grid, 0.9 p.u. is assumed first, according to the voltage requirement by the standard EN 50160. Then, a minimum voltage of 0.95 p.u. is considered, taking as reference the design guidelines of a typical Danish LV grid [11].

Based on the assumptions made, the four power curves of Fig. 3 can be obtained according to [13], considering a three-phase load scenario using :

$$P \cdot l = 3 \frac{(V_{min} - V_g) \cdot V_{min}}{Z} \quad (1)$$

where Z is the cable impedance in Ω/m
 l is the distance from the transformer
 P is the power per unit length

In the range of 100 m from the transformer, Fig. 3, it is possible to observe that the network loading is mainly limited by the maximum 95mm² cable capacity, since a high load is possible without reaching the minimum voltage level V_{min} . The curve of Case 1 is the best case for loads, due to the highest base grid voltage and lowest voltage V_{min} of 0.9 p.u. Case 2 and Case 3 lead to very similar power curves, though they refer to quite different operational conditions. Case 4 depicts the most restrictive case for load power, due to a narrower operational voltage window, compared to the other cases. However, with an increasing distance from the transformer, the maximum load in the grid is limited by the voltage requirement, for all cases.

Considering that the load in the grid shall comprise the original residential load and the new CCS load, the voltage drop along the feeder cannot be entirely allocated to EV charging purposes. For this reason, the assumption of $V_{min}=0.95$ is taken, reserving the remaining voltage drop to the

existing loads. Furthermore, a base grid voltage V_g of 1.04 p.u. is considered at the transformer secondary side.

B. Components load constraints for CCS planning

The limit of feeder cable loading has been already considered in the CCS planning. The sizing aspects of CCS shall be also put in relation to the characteristics of typical LV distribution transformers. Two residential grids with transformer capacity of 100 kVA and 630 kVA respectively are taken into account for comparison.

For the grids, the loads were modeled considering real measurements for a 0.4 kV LV feeder. The simulation results of the study in [14] are taken as reference for estimating the transformer power allocation for a CCS. In [14], it was considered that the most critical situation of EV charging is the “dumb” charging scenario, where all vehicles can start or stop charging without coordination. This critical scenario was simulated during electricity peak-hours, i.e. from about 5 p.m. till 10-11 p.m. A definition of EV penetration was given, referring to the ratio between the total loading due to EV charging over the nominal transformer capacity and it was determined that an EV penetration of 20% is possible, without overloading the transformer. In support to this result, the findings of Clement-Nyns *et Al.* in [15] were considered. According to [15], 20-25% of EV penetration is possible in actual grids, without exceeding the voltage limits of Standard EN 50160 [16] and the transformer ratings.

A penetration level of 20% is therefore considered as design parameter for the power allocation of a CCS, in this paper. For the two analyzed grids, the CCS capacity is therefore indicated in Table III.

Table III
CCS size

Grid capacity	Allowed penetration level	Power allocated for CCS
100 kVA	20%	20 kVA
630 kVA	20%	126 kVA

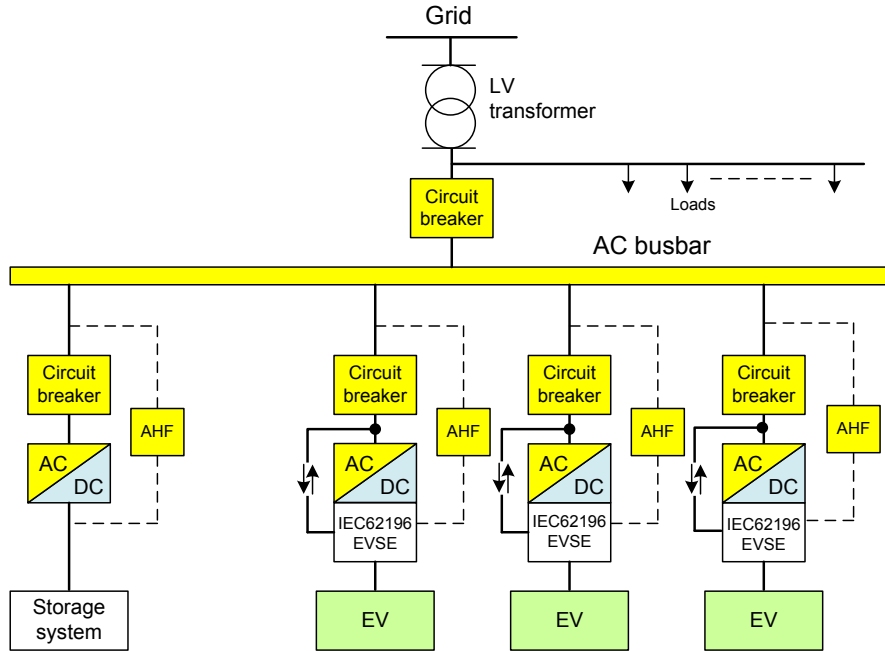


Fig. 4. AC-distribution CCS architecture

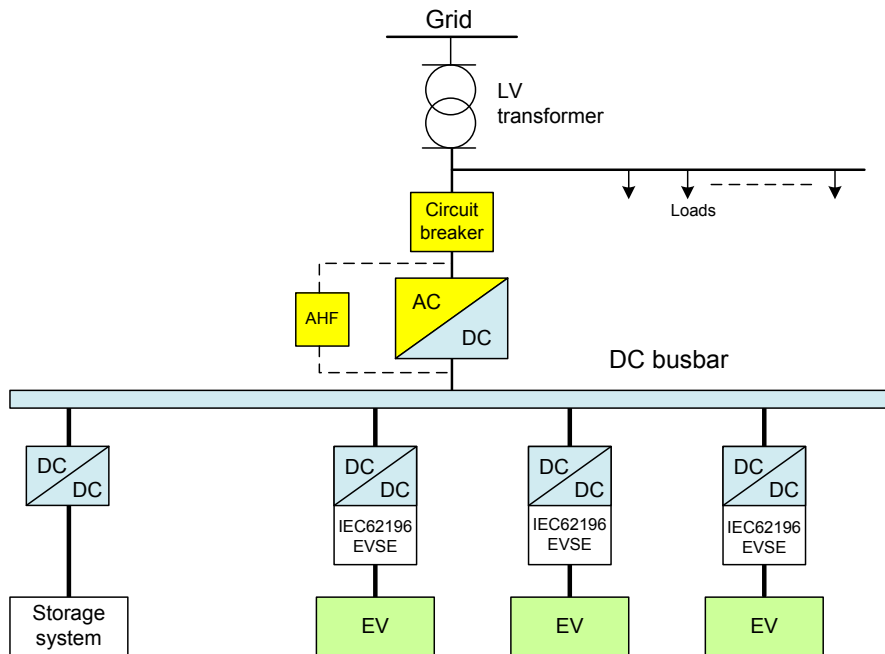


Fig. 5. DC-distribution CCS architecture

IV. CENTRAL CHARGING STATION CONCEPTS

The first defined concept is the *AC-distribution* CCS concept, Fig. 4. The CCS is connected to a 10/0.4 kV LV transformer, by means of a main AC circuit breaker. The CCS capacity is limited by the transformer capacity, which in this

paper is considered 100 kVA or 630 kVA. The second concept proposed is the *DC-distribution* CCS, Fig. 5. The possibility of fast-charging an EV battery using off-board DC chargers [7] and the reduced charging time are the main features of the second concept of CCS.

In both concepts, the CCS is energized by a 0.4 kV feeder, connected to the LV distribution transformer. A main circuit breaker ensures disconnection to the CCS whenever required.

After the AC breaker, each CCS is characterized of different electrical and power electronics components.

In the *AC-distribution* CCS, the power distribution is realized with AC busbar which supplies each terminal involved in the EV charging. Secondary circuit breakers are used for coupling between the busbar and the different charging terminals (EV supply equipment, EVSE). Since the power can follow two different paths, according to the architecture, both AC and DC charging are possible. The first one, indicated by arrows in Fig. 4, is the AC charging option: the power is derived after the AC breaker and conducted till the EVSE. The AC charging power options of Table I are valid under this use case and apply depending on the vehicle on-board charger capabilities. It is worthwhile noticing that under the AC charging case, the power path can be bidirectional, as inherently possible by the electrical CCS components. Of course, this requires a vehicle bidirectional charger. The case of reverse power flow, from EV to grid, is known as Vehicle-to-Grid mode [17], and for that, the same power levels described in Table I apply. Each EVSE is capable of AC and DC charging. Under DC mode, an AC/DC power converter rectifies the AC voltage/current and controls the charging current, by means of a DC/DC power converter; these two components can be seen as aggregated into a single charging unit. The interface with the vehicle is assumed to be realized through the EVSE, according to IEC 62196-3 [8].

Different power quality issues arise while charging an EV. Among all, harmonics and voltage variations are among the major issues. Orr *et Al.* in [18] presented results on harmonics due to EV charging; the main recommendation suggested is to filter harmonics and staying away from the limits emanated in the relative standard. At the scope, an active harmonic filter (AHF) is planned between the EVSE output and the point of common coupling with the AC busbar. Furthermore, a stationary energy storage system is added to the CCS hardware, to operate during transient events, e.g. switching on or off one or more power converters involved in DC charging [19].

In the *DC-distribution* CCS, Fig. 5, the architecture differs from the first one, after the main AC circuit breaker. In this case, a main AC/DC power converter is designed to supply power to the entire station. As this converter is not supposed to work continuously at its rated power, it should be accurately designed depending on the number of vehicles that can charge simultaneously. The power distribution to all charging terminals is realized with a DC busbar. On each terminal, a DC/DC converter is used for controlling the charging power level. Also in this case, an IEC62196-3 compatible EVSE is the required physical interface to the vehicle. With this CCS, harmonics problems are mitigated by a centralized AHF connecting between the LV feeder and the primary AC/DC converter.

A. CCS location and size

The location aspect for a CCS has enlightened that its installation in the proximity of the LV grid transformer, i.e. in the range of 100 m, can minimize voltage magnitude problems. The placement of a CCS in the grid is therefore assumed in the range of 100 m from the transformer.

The planning of the size should take into account the number of EVs that can potentially charge simultaneously in a CCS, for this we referred to the scenarios illustrated in Table II. The possible number of EVs charging simultaneously is estimated for both grids of 100 kVA and 630 kVA and the results are summarized in Table III. Considering the larger grid and the power allocation scenarios of Table II, it is possible to have 5 EVs charging with 22 kW or 2 EVs DC charging with 60 kW each. Therefore, both AC and DC charging are possible in the large grid. Within the 100 kVA grid, DC charging is not possible, while AC charging with a power a level of 11 kW is found to be an option.

Table III
Parallel charging options in the two LV grids

Power	Charging option	100 kVA grid	630 kVA grid
11 kW	AC	1	11
22 kW	AC	0	5
43 kW	AC	0	2
60 kW	DC	0	2

B. Cost estimation of CCS concepts

The power components cost for both CCS architectures is estimated and a comparison on the initial investment is performed for both the CCS. At the scope, the project report by Kristensen *et Al.* is considered as reference. The report is a deliverable of the Work Package 4, WP4, of the Danish Edison project [20].

In Table IV, the components cost is shown for both CCS. The grid connection cost is estimated at 5€/kW for both CCS and it is not indicated in Table IV.

To ensure flexibility of operation between AC and DC charging, the EVSE in the AC-distribution CCS are planned according to the IEC 61851-1 Mode 3 [6], which allows AC or DC charging with 400V_{dc}, 250A_{dc}, while only DC charging is possible in the second CCS.

In Table IV, results on investments estimation are shown. For the two different CCS, with equivalent power allocation, the additional flexibility offered by AC-distribution CCS shows a higher initial investment. This is due to more components than an equivalent size DC-distribution CCS. However, the flexibility offered by the AC-distribution CCS, for AC or DC charging, has itself an intrinsic economic impact that should be separately evaluated. With the actual EV on the market, having only few of them designed with DC charging capability, a best guess could be that an AC-distribution CCS

Table IV
Estimation of investment cost for the AC and DC distribution CCS

Component	AC-distribution CCS		DC-distribution CCS	
	Cost €	Q.ty	Cost €	Q.ty
AC Busbar	2851 (per terminal)	5	-	-
DC Busbar	-	-	2834 (per terminal)	2
Main AC/DC converter	-	-	12,000	1
AC/DC converter	6000 (per terminal)	5	-	-
EVSE	3000	5	3000	2
DC/DC converter	-	-	6000	2
Main AC breaker	2000	1	2000	1
Sec. AC breaker	2000	5	-	-
Tot.	71255 €		37668 €	

would have a higher utilization factor than a DC-distribution CCS.

VI. CONCLUSIONS

Two different CCS concepts were presented, namely the AC-distribution and DC-distribution CCS. The first one offers more flexibility as it permits both AC and DC charging to EV, though the investment cost results higher for the same installed power. In the DC-distribution CCS concept, charging is possible only if EVs are capable of DC charging.

The planning of public CCS in LV grids should take into account voltage and components loading requirements. To limit voltage variations, a CCS should be planned in the proximity of the LV transformer. The size of a CCS can be limited by transformer capacity and LV cables loading. The quick charging options of 11 and 22 kW are likely in urban LV grids within an AC-distribution CCS. DC charging up to 60 kW can be implemented in large LV grids in the proximity of LV transformers, allowing the simultaneous charging of up to 2 vehicles.

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