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Enabling EV Charging by introducing LVDC Backbones in Low-Voltage Distribution Networks

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Executive Summary

Within this paper, the conventional method of charging electric vehicles on AC low-voltage distribution network is compared to a novel approach by means of a low-voltage DC backbone. For this purpose, the study uses an actual low-voltage distribution network where several scenarios regarding the penetration levels of electric vehicles are studied. Furthermore, the combination of electric vehicles with distributed energy resources is assessed. Results from the power flow analysis indicate that the application of a low-voltage DC backbone provides many benefits. Not only by reducing losses in the network, but also through avoiding phenomena such as voltage imbalance occurring in the AC distribution network.

Keywords: EV-integration, LVDC backbone, Power Quality, Converter efficiency

1 Introduction

Interest in electric vehicles (EVs) keeps growing, which from a distribution system operator's perspective raises the questions *'How will low-voltage distribution networks cope with the increase of electric vehicles charging?'*, and *'Do alternatives exist to enable the charging while maintaining the power quality within the limits?'*. Conventional methods to charge EVs on a low-voltage (LV) distribution system involve the use of AC/DC converters. However, these conversion stages lead to considerable energy losses, as depicted in [1, 2]. Moreover, it is expected that as more EVs are connected to the grid, distribution networks will be confronted more frequently with power quality related issues [3]. Therefore, this study presents a novel approach to enable large-scale EV charging in residential contexts. Instead of connecting each individual EV-charging station to the distribution grid, the proposed method introduces a low-voltage DC (LVDC) network, further called as LVDC backbone. To this end, a LVDC backbone is described within this article as an extension of the already existing low-voltage grid to which all stochastic distributed grid exchangers (SDGE) are connected (i.e., EVs, photovoltaic (PV) systems and battery storage systems (BESS)).

Since the studied network includes house-units featuring PV solar panels, the analysis is carried out for different PV penetration levels as well. Thereby, identifying the synergy between both, EVs and PV systems. In this respect, an assessment of electric vehicle charging for a residential distribution network is compared to a hybrid AC/DC distribution system. Based on a probabilistic approach different power quality parameters (i.e., voltage limit violations and voltage unbalance factor) are examined. Furthermore, a loss comparison will be presented between the proposed LVDC backbone and the conventional distribution system.

2 Methodology

For this study, a representative LV distribution network of a semi-urban area with a balanced mix between detached and semi-detached house-units is utilised. The start of the studied distribution network is considered at the point of common coupling (PCC), i.e., LV-side of the distribution transformer, as depicted in Fig. 1 (a). Here (a) represents the topology for the power flow simulations in AC, while (b) illustrates the DC backbone. Note that the LVDC backbone is connected through a single point of connection (SPoC) to the transformer's LV-side, as Fig. 1 (b) shows.

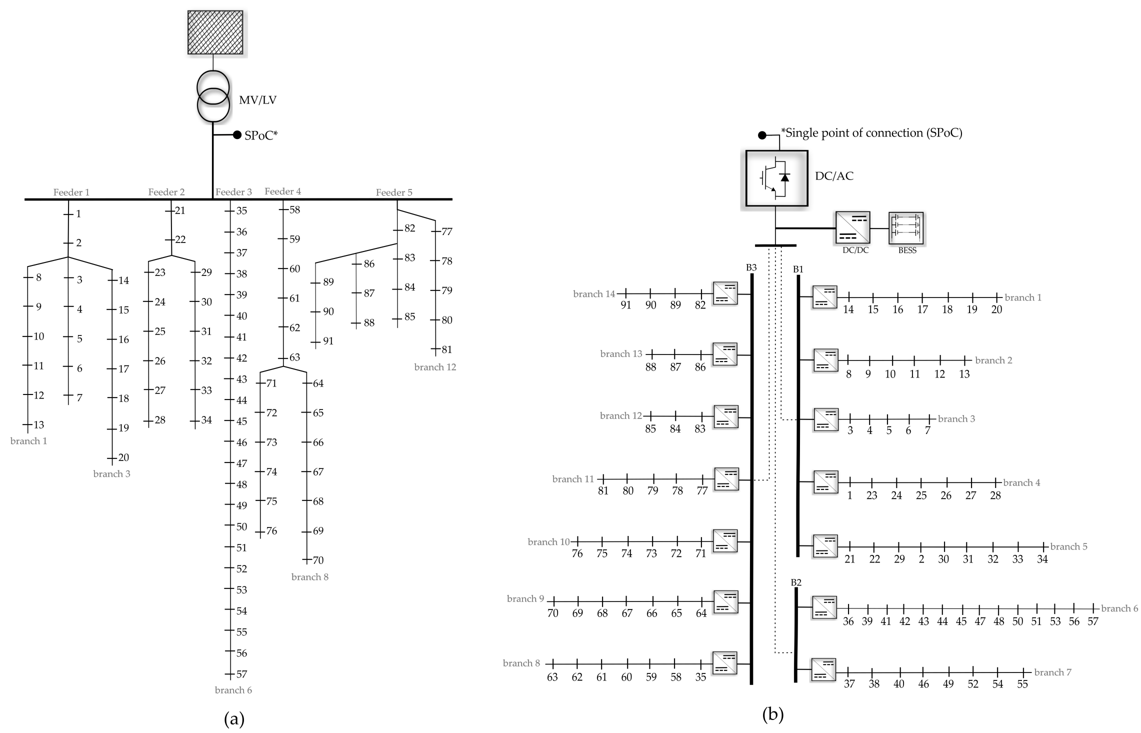
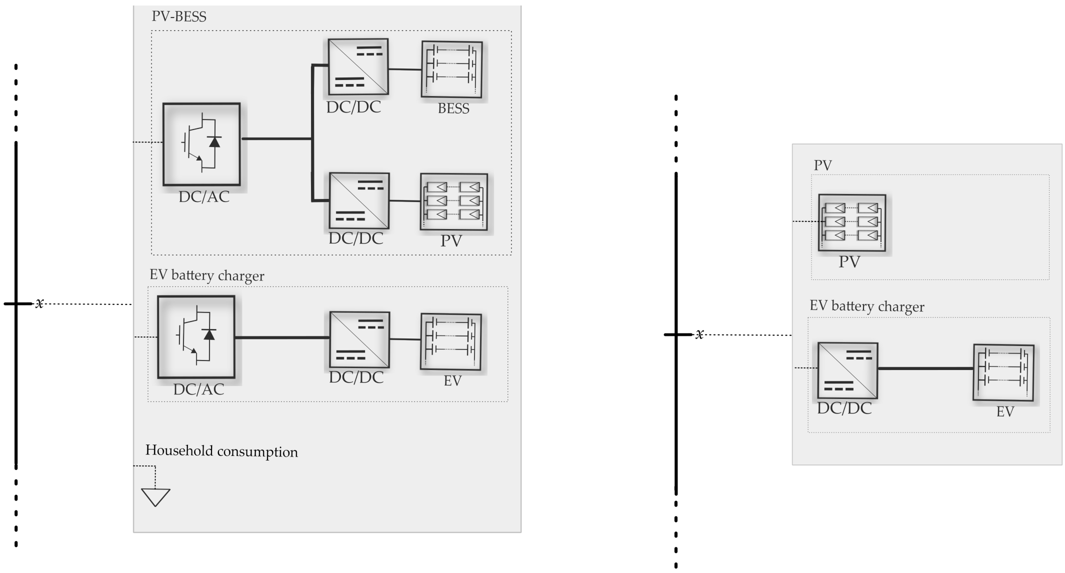


Figure 1: Line diagram of the studied LV distribution network, with (a) the conventional approach and (b) the proposed LVDC backbone.

In contrast to the conventional AC method where multiple feeders depart from the LV busbar of the transformer (i.e., PCC), the proposed LVDC backbone is consisting of three common DC-buses. At each of these buses multiple DC/DC converters are connected, consisting of a cluster of PV systems and EV chargers distributed on a DC-branch. Both, the DC-buses and DC-branches are unipolar but are operating on a different voltage level. The DC-branch is operating on the maximum power point tracking voltage (MPPT) which is varying between 180 V and 325 V while the DC-bus is operating at 700 V in order to avoid extensive cable losses.

House-units in the conventional case are individually provided with an EV charging station, a PV system and a battery energy storage systems (BESS), Fig. 2 (a). The EV charging station and PV-BESS are each provided by a seperated DC/AC converter. The PV system and BESS are connected on the same DC/AC inverter via an individual DC/DC converter. A maximum power point tracking is included in every DC/DC converter of the PV system.

Whereas the suggested approach (Fig. 2 (b)) considers distributed PV systems to be directly connected on the DC-branch via a centralized MPPT to the DC-bus. A community BESS is introduced in the LVDC backbone in order to achieve an adequate comparison between the two cases while reducing the number of converters.



(a) (b)

Figure 2: Detailed view of the connection of the load and SDGEs for (a) the conventional approach and (b) the proposed LVDC backbone.

The analysis is limited to a residential area with single-phase connected house-units. Consequently, the maximum charging rates are set to 7.4 kW [4] and the installed capacity of PV systems is limited to 5 kVA [5]. In order to observe the consequences of both (i) EVs and (ii) PV systems, simulations are subject to penetration levels in increments of 25%, up to a penetration level of 100%.

2.1 Datasets

Several datasets were used for the study. For instance, consumption profiles were taken from a dataset of 1422 consumers provided by the distribution system operator Fluvius cvba. The pre-processing of the dataset is part of previous research carried out by Claeys et al. [6]. However, the 91 selected consumption profiles are subject to a random selection in which the annual consumption ranges between 1000 kWh and 5000 kWh. Thus ensuring the inclusion of small- and medium-sized consumers as specified in [7]. EV profiles are generated from the density distributions of real-world arrival and departure times, obtained from ElaadNL [8]. The dynamic power charging curves are derived from [9]. A summary of the networks' specifications is given in Table 1. Lastly, climate data provided by the Belgian Royal Meteorological Institute (RMI) is used as input for modelling the PV system. This data consists of wind speed, global irradiance and temperature, all having a resolution of 15 min.

Table 1: Summary of the grid specifications.

Description	Values
Transformer rating	250 kVA
Grid voltage	3x400 V + N
DC Backbone voltage	700 V
Distribution cable	EAXeVB 4x 150 mm^2
Connection cable	EXVB 4x 16 mm^2
No. of house-units	91
Max. feeder length	400 m
Distance to junction	[8,..., 15] m
Yearly consumption	[1000,..., 5000]* kWh

* The selection criteria is subject to random sampling.

2.2 PV-BESS modelling

It is of importance that the PV model is accurate in estimating the operating point, especially when the voltage level V_{pv} deviates from the MPPT voltage V_{mppt}. Therefore, the generated power of the PV system is estimated by a single-diode cell model [10] and the parametrization is based on the SAM module database [11]. The used module for the analysis is the Yingli YL-230P-29b. Further, a tilt angle of 35° and an azimuth of 180° are considered. The in-plane irradiance is calculated following the methodology described in [12]. At last, the amount of solar panels in series and parallel is configured as a function of the total annual consumption as presented in Table 2.

Table 2: PV sizing as a function of the total load demand

Total annual load demand $\mathbf{E_{load}}$ [kWh]	Modules in parallel $\mathbf{N_p}$	Modules in series $\mathbf{N_s}$	Total power of installed PV $\mathbf{P_{pv,tot}}$ [kWp]
$0 < E_{load} \leq 2435$	1	9	2.07
$E_{load} > 2435$	2	9	4.14

Furthermore, the battery losses and voltage variations as a function of the state of charge has been taken into account by method described in [13]. The battery management strategy consists of maximizing the self-consumption whereas, BESS specifications and sizing approach can be found in [2].

2.3 Power flow analysis

This research aims to obtain results for a set of diverse scenarios, therefore different modes of EV charging are considered: ranging from domestic charging (2.3 kW) to the max allowed single-phase charging (7.4 kW). It is assumed that the load distribution of the house-units is symmetrically connected to the distribution cable (i.e., house-unit 1 is connected to L1-N, 2 to L2-N, 3 to L3-N, 4 again to L1-N etc.). Hence, resulting in voltage unbalance [14]. Allocation of the charging stations takes place randomly, but in accordance with the allocation of PV systems. Further, as previously mentioned the behaviour pattern of charging hours is also assumed. Note that the EV charging process is uncoordinated. In order to include the seasonal effects of the PV yield and the load demand, the simulation is performed over one year.

Simulations are performed within a OpenDSS-Python environment, therefore the distribution network is modelled in OpenDSS [15] while the actual power flow analysis is performed in Python through the

OpenDSS COM interface, as presented in [16]. The method adopted for the modelling of the cables is described in [17]. Results for the conventional method are obtained through a steady-state power flow analysis performed for every 15 min-timestamp. Multiple scenarios are compared, by evaluating the various EVs and PV penetration degrees ranging from 0% to 100%. Table 3 presents a summary of the input variables for the algorithm.

In order to quantify the discrepancy between the conventional method and the proposed approach, simulations for the LVDC backbone are derived from the reference case of the conventional method (i.e., 0% penetration level for the EVs and PV systems). For this purpose, the reference scenario provides a quantification of the load losses incurred by each house-unit, while conversion and cable losses are obtained from a backward-forward sweep algorithm in Python. The implemented conversion loss models are based on previous work [2], where a distinction is made respectively for the conventional and proposed method. The DC/AC converter of the EV charging station is modelled as a full bridge active rectifier.

Table 3: Overview of the simulation variables.

Description	**Values**
EV penetration	$\daleth\{0;25;50;75;100\}^{*}$ %
PV penetration	$\daleth\{0;25;50;75;100\}^{*}$ %
Charging power	$\daleth\{2.3;3.7;5.8;7.4\}^{\dagger}$ kW

* $\daleth\{a,b\}$ denotes a discrete uniform distribution between a and b.
† Charging rates according to the Belgian DSO Fluvius cvba [4].

3 Results

This section describes results obtained for the respective criteria. Nevertheless, comparisons between both situations can not directly be made as the application differs for both, the conventional and proposed method. Results for voltage deviations are consequently divided into two parts, namely an AC part and a DC part.

3.1 Voltage profiles

3.1.1 Partim AC

Fig. 3 provides the probability density function of all voltage profiles from each individual bus of the LV distribution network. Voltages are expressed in per unit ()p.u.) on the x-axis, where the normalised 1 p.u. is equal to 230V, whereas the normalised density probabilities are reflected on the y-axis. These probabilities are represented in Gaussian distributions. Results are shown for the 85 combinations of penetration levels for EVs and PV systems. Herein, columns iterate the EV levels and rows iterate along the PV penetration degrees. Both iterations are performed in steps of 25%, starting at the reference case of 0%. This reference case is indicated in all subplots by a grey shaded histogram. Colours refer to the charging rate. The obtained outcome is representative for the conventional charging of electric vehicles on a LV distribution network. Hence, this is valid for both cases, where PV is present or omitted.

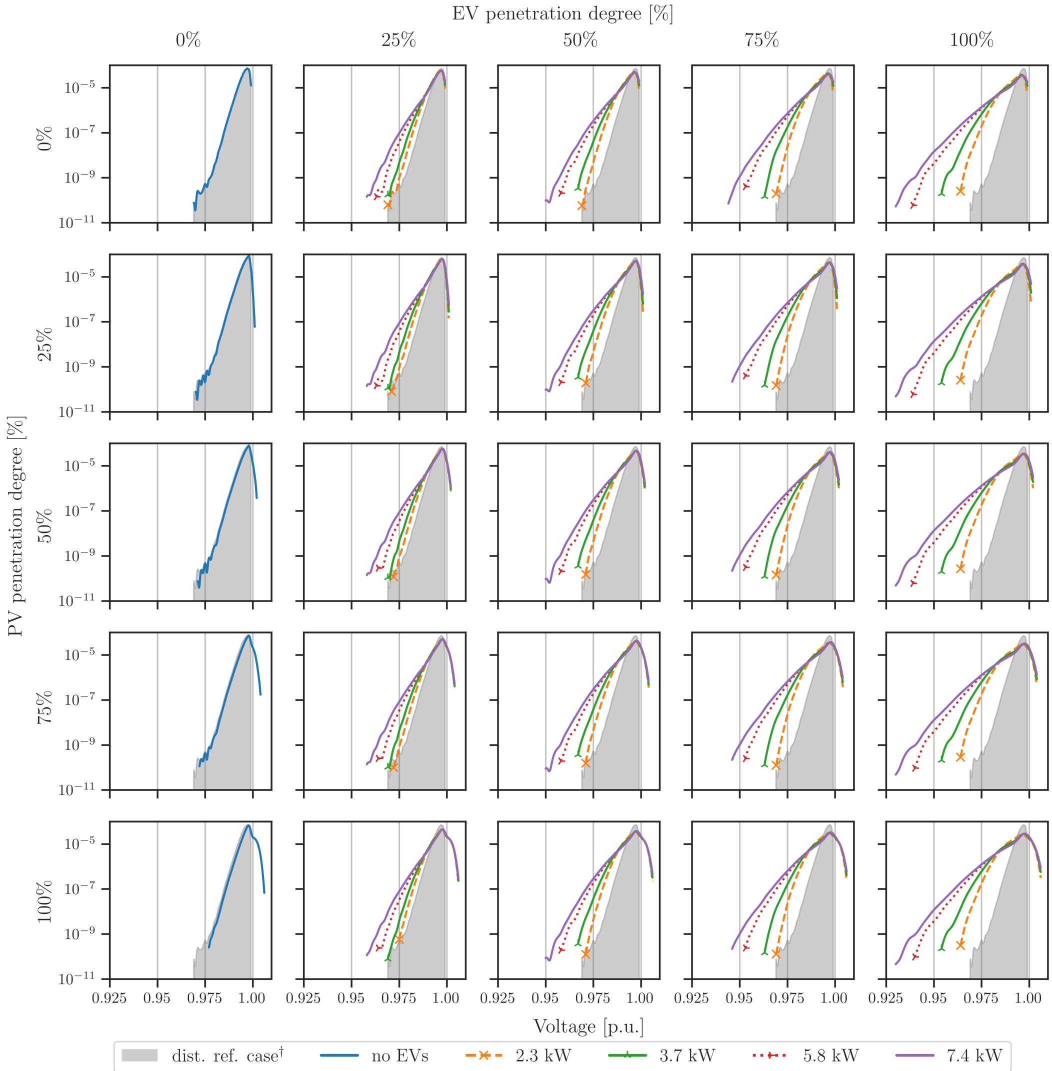


Figure 3: Gaussian distribution of the voltage profiles for different EV and PV levels at various charging rates. †Whereas, the grey shaded zone denotes the 0% EV and 0% PV case.

One can deduce from the figure that an increase in electric vehicles is accompanied by a decrease in the voltage across the nodes. Reflecting a voltage drop experienced by the cables due to increased consumption. In contrast, an increase in PV systems leads to a higher voltage level, exceeding 1 p.u. It should be noted, that this phenomenon is limited by the fact that the BESS is designed for self-consumption and therefore prevents this effect. It is important to notice that for the chosen network the voltage is still within the limits, despite the 7.4 kW charging rate. Although this needs to be nuanced as the individual annual consumption is limited to 5000 kWh and the cable cross-section of the network is 4x 150 mm^2. Consequently, it indicates that an EV rich scenario is likely to cause voltage issues, as demonstrated in [18]. Nevertheless, an assessment of this is not part of the intended scope of this study.

3.1.2 Partim DC

Given the fact that the MPPT is centralized in the LVDC backbone, distributed PV systems on the DC-branch will not operate on the same voltage operating point. Due to over- or undervoltage the power operating point will be shifted away from the MPPT, leading to a lower production. As shown in Fig. 4, this is especially noticeable for increasing cable lengths, where a power reduction of 5% is observed when having an overvoltage of 10%. However, due to the lower slope at the left side of the $P_{pv} = f(V_{pv})$ curve, the undervoltage has less impact on the production.

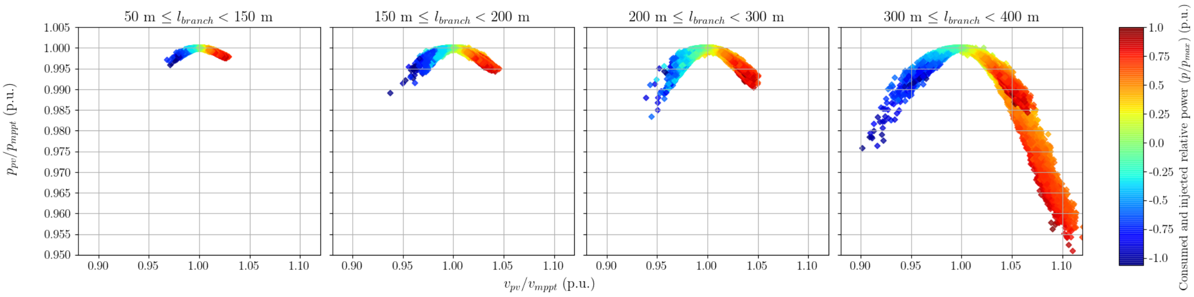


Figure 4: Voltage variation on the DC-branch and impact on the curtailed production as a function of the produced (positive) and consumed (negative) power.

3.2 Energy losses

The bar charts in Fig. 5 represents the different occuring losses in the two cases for the predefined scenarios. Results indicate that when having a combination of high EV and low PV penetration level, the benefits of an LVDC backbone decreases or even tends to be unfavourable. This becomes even more clear at higher charging rates. As the PV systems cannot cover sufficiently the EV charging demand on the same DC-branch, power is taken from other DC-branches, the BESS or the AC grid, leading to an increase of conversion losses in the DC/AC and DC/DC converters of the DC-branch.

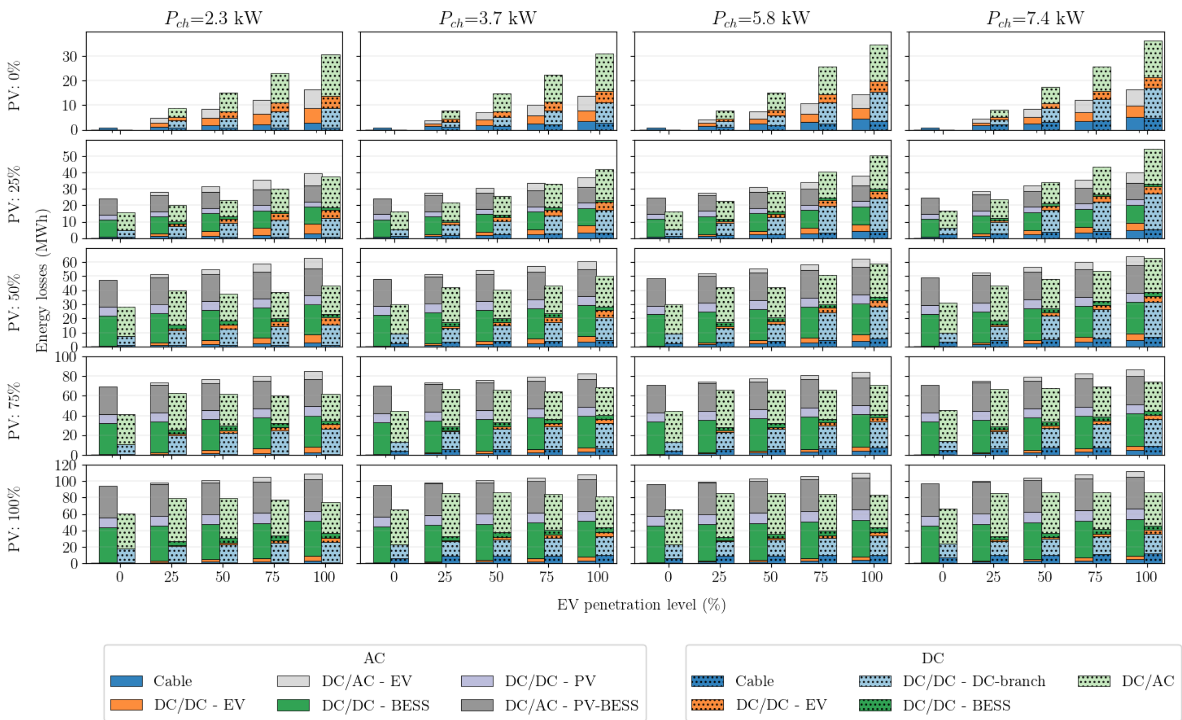


Figure 5: Conversion and cable losses for different charging powers EV and PV penetration levels for a conventional LVAC-grid and the proposed LVDC backbone.

The higher the PV penetration level, the smaller the increase rate of the losses for the LVDC backbone as a function of the EV penetration level. Although the conversion losses of the DC/DC at the DC-branch increases, the opposite trend is visible for the DC/AC conversion losses. This can be explained by the fact that a higher EV penetration level leads to a better self-consumption and simultaneously an increasing energy exchange between the several DC-branches and the BESS.

This consequently means that — *as the losses for the AC case still increases* — the benefit of an LVDC backbone increases in EV and PV rich scenarios. Fig. 6 represents the relative energy loss difference ($RELD$) given in Eq. (1), and clearly exhibits this behaviour.

$$RELD = \frac{E_{loss,dc} - E_{loss,ac}}{E_{loss,ac}} \quad (1)$$

$E_{loss,dc}$ and $E_{loss,ac}$ are representing the accumulated losses occurring in the AC and DC case. Similar behaviour can be observed at PV penetration levels: 50% and 75%. However, the $RELD$ stagnates at those levels, before it decreases again. A further increase of the EV penetration leads in this situation to an increase of the power extracted from the grid. Finally, the threshold in EV penetration level where the DC approach becomes unfavourable, decreases as a function of an increasing charging power.

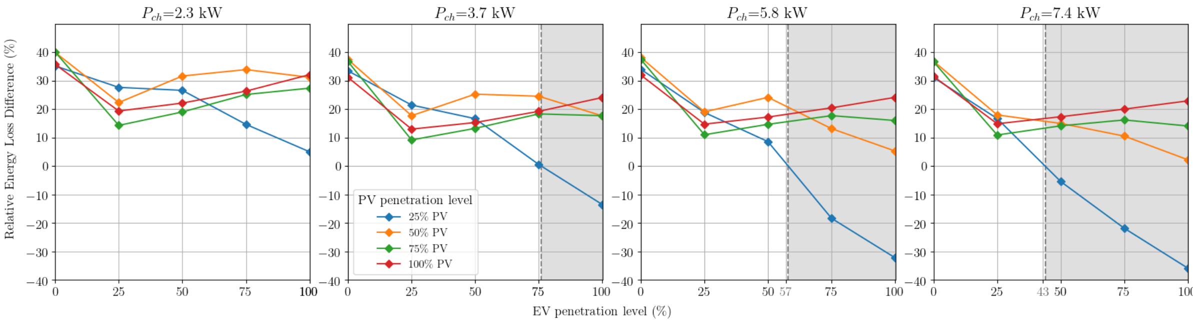


Figure 6: Comparison of the losses between the conventional approach and the proposed LVDC backbone for different charging rates, EV and PV penetration levels.

In Table 4 the feed-out energy from the grid is given for different charging powers for the case with 100% penetration of EV and PV. The relative feed-out energy difference ($RFOED$) denotes the difference in self-sufficiency between the conventional AC system and the proposed LVDC backbone. A substantial decrease of the $RFOED$ is observed with higher charging powers caused by the reduced self-consumption.

Table 4: Feed-out energy from the grid for the 100% EV and 100% PV case.

P_{ch} (kW)	**2.3**	**3.7**	**5.8**	**7.4**
AC (MWh)	374.448	374.184	376.151	377.885
DC (MWh)	329.347	331.617	335.574	338.808
RFOED %	12.04	11.38	10.79	10.34

3.3 Voltage unbalance

An important indicator for the power quality of a distribution system, is the voltage unbalance factor (VUF). This criterion describes the ratio between the negative sequence voltage V_{-} and positive sequence voltage V_{+}, see Eq. (2). In accordance with the IEC EN 50160 standard [19], voltage unbalance may not exceed the limit of 2%.

$$VUF = \frac{V_-}{V_+} \cdot 100, \; where \; VUF \leq 2\% \quad (2)$$

Results of the VUF are shown in Fig. 7, where the voltage unbalance of all the nodes is represented in relation to the losses each node experience. Here the figure is valid for the implementation of EVs (charged at 7.4 kW) into the grid without PV systems connected. Fig. 7 (a) represents the reference case without EVs, (b) the 50% EV penetration scenario and (c) a 100% case. A remarkable aspect in the figure is the correlation between the degree of voltage unbalance and the proportion of energy losses occurring on the distribution network. The same phenomenon is noticeable with lower EV penetration degrees, although the amplitude of VUF and node losses is more limited. Similarly, in case of even higher EV penetration, the limit will be reached more quickly.

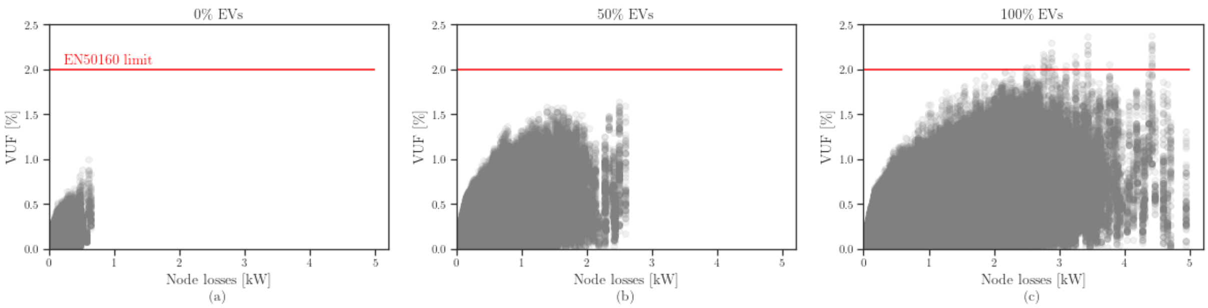


Figure 7: Voltage unbalance as a function of the node losses for various EV penetrations without PV systems.

Regarding the proposed LVDC backbone, it can be deduced from Fig. 7 that the reference case applies. Thus introducing a LVDC backbone involves as main advantage that the distribution network will not be affected by voltage unbalances for penetration reaching up to 100%.

4 Conclusions

As a result of the conducted analysis, several key observations have been identified:

- No violation of the voltage limit was observed in the AC partim. This was highly expected for the case with PV systems since the coupled BESS ensures that the injection is limited. However, when exclusively EVs are connected, the occuring voltage drop strongly depends on the load capacity on the one hand, and on the presence or absence of a PV system on the other hand. In case of a 100% penetration of EVs with a 7.4 kW charging rate, the minimum voltage level observed is 0.92 p.u., corresponding to 211 V.

- The directly connected PV systems on the DC-branches increases the self-consumption by the locally distributed EV chargers. However, a drawback of this architecture is that a voltage drop or rise leads to a reduction in power, going up to 5% for longer cable lengths. Nevertheless, an undervoltage caused by a high simultaneity of EV charging leads to a limited power reduction of 2.5%. This can be explained by the fact that during undervoltage, the PV systems are operating on the left side of the maximum power which has a lower slope than in the right side.

- Comparing the absence of electric vehicles with the systematic introduction of EVs (i.e. in steps of 25%), one notices that the energy losses associated with charging not only causes higher losses but reveals a linear relationship with the voltage imbalance within the distribution network. Furthermore, the study demonstrates that from integration levels of 75% and onwards, voltage unbalance violations of EN50160 standard are recorded. Consequently, a considerable advantage of unipolar

DC backbones manifests itself in the absence of voltage unbalance. Therefore, higher levels of EVs can be connected to the distribution network without causing predominant losses.

– The benefit of an LVDC backbone compared to a conventional AC system is especially observed when the stored BESS and PV energy can be consumed within the DC system. Hence, it is of importance that a high EV penetration is accompanied with a certain penetration level of PV systems and BESS. Results demonstrated also that the charging power is an important parameter. Whereas, the higher the charging power, the lower the EV penetration level threshold for which the LVDC backbone becomes unfavourable. The amount of energy withdrawn from the grid reduces with almost 12% when the proposed LVDC backbone is applied.

The authors are planning to perform further investigations on the impact of PV systems and BESS. Furthermore, the DC voltage levels and the dynamic voltage control is subject of further optimisation. Finally, the influence of a massive EV penetration on the zero sequence voltage unbalance will be assessed, since within current standards no limits are imposed.

Acknowledgments

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Presenter Biography

Rémy Cleenwerck holds a M.Sc. degree in Electrical Engineering from the KU Leuven, Belgium. He’s currently a Joint-Ph.D researcher at research groups EELab/Lemcko (Ghent University) and EVERGi (Vrije Universiteit Brussel). His research focuses on electric vehicles and their impact on low-voltage distribution networks as well as renewable energy sources and storage systems.

Hakim Azaioud graduated as a M.Sc. in Electrical Engineering at Ghent University in 2017. Currently he is pursuing a Ph.D at Ghent University on integration of PV in LVDC distribution networks. Other topics of interests are: voltage level optimization and efficiency optimisation of DC networks, integration of EV in DC networks, optimization of photovoltaic systems, sizing methodologies of renewable energy.