SIMULATION TOOL FOR TECHNO-ECONOMIC ANALYSIS OF HYBRID AC/DC LOW VOLTAGE DISTRIBUTION GRIDS

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Abstract

Partial operation of the distribution grid in DC instead of AC has been identified as a possible strategy for cost-effective management of future grid scenarios driven by international decarbonisation goals. By applying a simulation tool for techno-economic analysis on synthetic test grid models, it has been shown that the conversion of AC low-voltage grid feeders to DC is a suitable solution to mitigate overloading and decrease voltage fluctuations caused by, inter alia, integration of electric vehicles (EVs), photovoltaic systems (PV) or increased energy demand. Cost models were applied to the simulation results. The economical findings indicate that the implementation of DC in low-voltage grids can be financially beneficial, especially when future developments and learning curves of DC technologies are considered.

1 Introduction

Direct current (DC) transformation was only made possible by the introduction of semiconductors, therefore alternating current (AC) had won the War of Currents in the late 19th century. Nowadays, DC can be efficiently transformed using converters; the advantages of DC stay, while the biggest disadvantage disappeared.

The benefits of DC distribution have been investigated in many industries. Following the development of high voltage direct current (HVDC) for transmission networks, there are efforts to use DC at lower voltage levels. Significant developments can be observed in the field of hybrid electric propulsion [1], marine systems [2], data centres [3] and DC-based medium-voltage distribution networks [4]. Furthermore, DC enables a more efficient way of integrating the loads and renewable energy sources (RES) of the future in low-voltage distribution grids due to the reduction of conversion stages [5]–[8]. In [9], hybrid AC/DC low voltage (LV) grid simulations focusing on system efficiency using Modelica Electric Power System Library (EPSL) are presented. The simulation tool proposed in this paper is designed for techno-economic analysis of hybrid AC/DC LV networks from a grid planning perspective by the means of quasi-stationary simulations in Power Factory.

2 Methodology

The presented simulation tool enables automated conversion of low voltage alternating current (LVAC) lines and feeders to DC and the subsequent simulation of the hybridised grid using Power Factory, controlled through its integrated Python API. A web interface provides an input mask to parameterize and start the simulations. For direct comparison, both pure AC and hybrid AC/DC systems are simulated under identical conditions. Moreover, different EV and PV penetrations can be added to the grid. If this is the case, two additional simulations are performed including the supplemented loads. An economic analysis can be applied on the simulation results through the same interface, whereas parameters are set by the user. The implemented DC configurations and scenarios as well as the grid and economic models are explained in detail in the following sections.

2.1. LVDC configuration and voltage levels

DC distribution lines and feeder must be configured as either unipolar or bipolar systems. Based on 4-conductor LVAC lines, the configurations shown in Figure 1 are applied in the simulation tool. For parallel AC lines, three instead of one conductor are used for both plus and minus conductor in bipolar DC operation.
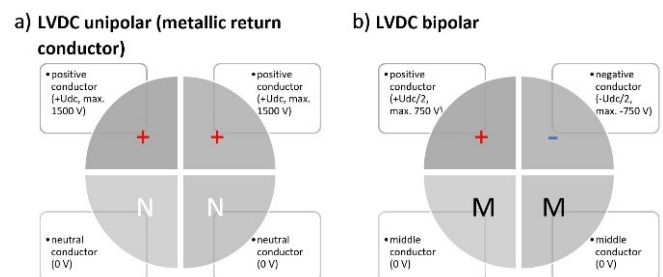

Figure 1: a) LVDC unipolar line configuration (with metallic return conductor to prevent corrosion) and b) LVDC bipolar configuration for 4-conductor LV line.

2.1.1 LVDC voltage levels: No standards are defined yet for the operating voltage levels of LVDC grids. Nevertheless,

there are ongoing efforts to reach international standardization. The recommended operation voltages for LVDC distribution grids <1500 V_{DC} according to the technical report IEC TR 63282:2020 [10] are listed in Table 1. All presented results were simulated for the max. recommended nominal voltage level of 1400 V_{DC} (±700 V_{DC}).

Table 1: Recommended LVDC voltage levels [10].

Configuration	U_{nom}	U_{min}	U_{max}
unipolar	350 V_{DC}	320 V	380 V
unipolar	700 V_{DC}	640 V	760 V
bipolar	±350/700 V_{DC}	640 V	760 V
bipolar	±700/1400 V_{DC}	1280 V	1500 V

2.2. Synthetic grid model

The utilized synthetic grid model (presented in [11], available at [12]) covers all elements between the transmission level (220 kV), distribution level (110 kV and 20 kV, urban and rural) and the LV connection points. Ten LV feeders (Table 2) with a total of 190 loads are modelled in detail, representing typical rural and urban LV feeders in the European distribution grid. Beside a radial LV grid scenario, the model is available with meshed LV topology.

Table 2: Detailed LV feeders in synthetic grid model.

Feeder	Max Length [m]	Nr of lines	Nr of loads
LV rural 1	1056	26	16
LV rural 2	430	22	14
LV rural 3	549	30	17
LV rural 4	610	34	22
LV rural 5	220	2	1
LV urban 1	430	28	25
LV urban 2	370	22	19
LV urban 3	360	30	26
LV urban 4	400	34	31
LV urban 5	450	21	19

Furthermore, equivalent loads (operated in AC) at all network levels are available, modelling the part of the grid which is not directly under investigation. The yearly load and PV profiles in 15-minutes resolution are based on measured European data [12]. EV profiles are modelled with realistic static charging profiles [13].

2.2.1 Line types: The simulation tool offers automatized evaluation of maximum power transmission capacity vs line length for AC and DC operation of any given line type, taking simulated line losses into account. Within the applied synthetic grid model, the rural LV grid mainly consists of typical European overhead line types, whereas the urban grid is modelled using typical LV cables, such as evaluated in Figure 3. By applying recommended DC voltage levels (Table 1), it was confirmed that the transmission capacity for the given line

type XAY2Y 4x150 can be doubled at 1400 V_{DC} bipolar compared to the operation at 400 V_{AC}. If voltage fluctuation dV of ±25% are considered, the transmission power for long (>2000m) LV feeder is increased significantly by factors >10 for DC operated systems at 1400 V_{DC}.
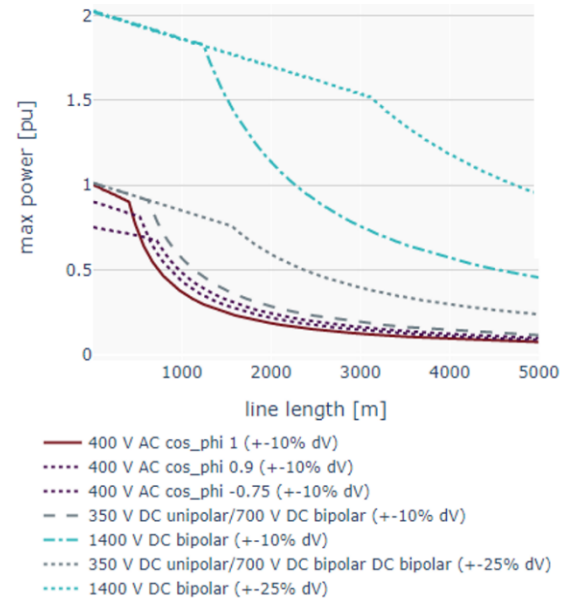

Figure 2: Maximum transmission power vs line length cable type XAY2Y 4x150; max 1400 V_{DC} bipolar; p.u. of max. power at 1m line length 400 V_{AC} cos(φ) = 1.

2.3. AC/DC hybrid LV grid scenarios

Defined scenarios are considered within the simulation tool, listed in Table 3, to convert LV lines and feeders from AC to DC, resulting in hybrid LV distribution grids.

Table 3: AC/DC hybrid LV grid scenarios.

Scenario	Description
0	lossless conversion to DC
1a	LVDC lines, AC customers
1b	LVDC lines, AC customers, PV and EV connected to LVDC grid
2	LVDC lines, DC customers

Scenario 2 was selected for the presented results, since it is the most promising scenario for LVDC grid applications.

2.4. Simulation Parameters

In Table 4 the available simulation parameters are listed. The values in column "Simu Params" are applied in the later presented simulation results.

Efficiency gains are specified for loads, PV and EV if connected to DC. Studies have shown, that (depending on a multitude of parameters) efficiency advantages of 1% to 20% can be achieved for different household loads if connected directly to DC [5]–[8]. For the presented scenario, an average

2

value of 10% was used. The efficiency gain for EV charger and PV converter is estimated to be significantly smaller (i.e. 1%), since for both applications converters are being optimized in terms of efficiency, and development in this direction will most likely continue. Nevertheless, if future development in DC technology is considered, an increased efficiency can be expected for renewable energy sources (RES) and DC loads connected to DC grids due to the reduction of conversion stages.

Table 4: Simulation parameter.

Parameter	unit	Simu Params	Range	Description
Grid model	-	w/	w/ or w/o	Synthetic grid model w/ or w/o equiv. loads
LV feeder	-	1-5 rur. 1-5 urb.	1-5 rur. 1-5 urb.	LV feeder selection (rural and urban) for conversion to DC
DC voltage	V	1400	100-1500	LVDC voltage level
DC config	-	bipolar	unipolar bipolar	DC system configuration
Load scaling factor	-	1,3	0.1-5	Model heat pumps or additional customers
Load eff. gain	%	10	0-30	Household load efficiency gain if connected to LVDC
PV	%	30	0-100	PV penetration (Fn. of nr. of loads)
PV eff. gain	%	1	0-30	PV efficiency gain if connected to LVDC
EV	%	80	0-100	EV penetration (Fn. of nr. of households)
EV eff. gain	%	1	0-30	EV efficiency gain if connected to LVDC
AC topology	-	radial	radial meshed	Topology for AC LV grid
DC scenario	-	2	1a/1b/2	AC/DC hybrid scenario
VSC1 eff	-	0.98	0.6-1	VSC 1 efficiency
VSC2 eff	-	-	0.6-1	VSC 2 efficiency (only applies to scenario 1)
VSC rated power ratio	-	0.9	0.5-1.2	VSC rated power (ratio of max. feeder S_{in_max} / max. household load S_{load_max} for VSC2)

The maximum feeder input apparent power S_{in_max} only occurs for short time periods within all DC feeders, therefore the voltage source converter (VSC) rated power is selected to be $0.9 * S_{in\_max}$ considering dynamic overload capability of AC/DC converters. An in-depth analysis of the load profiles per feeder would be necessary to determine most economic rated power factors for each converter. Optimal sizing of the converter allows operation at higher efficiency, since weak utilization

can be limited. Although not considered in this analysis, the possibilities of peak shaving or storage within LV feeders would most likely allow the VSCs to be dimensioned smaller, which would have a positive impact on the costs for conversion to DC due to reduced losses and capital expenditure (CAPEX).

EV and PV penetration as well as load scaling were chosen to represent possible future scenarios in which the existing grid reaches its capacity limits.

2.5. Economic analysis

Changing LV feeders from AC to DC requires considerable efforts and investments. The driving force of such significant structural changes must be the potential of economic benefit. For the purposes of this techno-economic analysis, the costs for AC reinforcement versus conversion to DC for the presented LV feeders are modelled considering the parameters listed in Table 5.

Table 5: Economic analysis parameter

Parameter	unit	Default value	Range	Description
CAPEX VSC	€/kW	150	100-500	Installation costs of converter per Watt
CAPEX rural line reinforcement	€/m	50	30-120	Installation costs for rural AC line reinforcement
CAPEX urban line reinforcement	€/m	100	30-120	Installation costs for urban AC line reinforcement
VSC life cycle	A	20	10-50	Expected lifetime of converter in LVDG installation
System life cycle	A	40	10-100	Expected system life cycle
OPEX VSC	%	2	0-5	Operation costs of VSC per year in % CAPEX
OPEX line reinforcement	%	1	0-5	Operation costs of line per year in % CAPEX
Energy price	Ct/kWh	4.44	0-10	Energy price for industry customers

Interest rates and inflation are not considered, reducing the complexity of such long-term investments. The values in column "Default values" are applied in the results presented and are chosen according to current industry standards, taking into account expected price reduction for LVDC components due to growing markets. Furthermore, VSC life expectancy is likely to increase and operational expenditure (OPEX) to decrease with more reliable devices available. Additional parameters, dependent on the feeder properties (Table 2) and simulation results, which are incorporated into the cost calculation are feeder length [m], installed converter power [kW] and yearly losses [kWh].

3   Results

In the following, the simulation results implementing the previously explained variables in the synthetic grid model are presented.
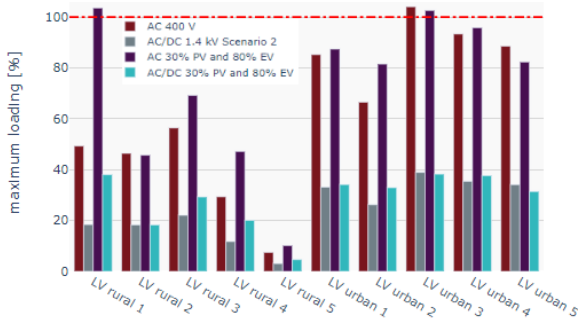

Figure 3: Maximum Loading of LV feeder yearly simulation (parameters in Table 4).

Figure 3 shows an overall reduction of maximum loading for all simulated feeder using 1400 V_{DC} instead of 400 V_{AC}. Additional PV and EV loads affect the loading of LV rural 1 severely, whereas max. loading could even be reduced in other feeders by adding future loads. Evaluating the max. loading throughout the simulated year, feeder LV rural 1 and LV urban 3 experience overloading violations.
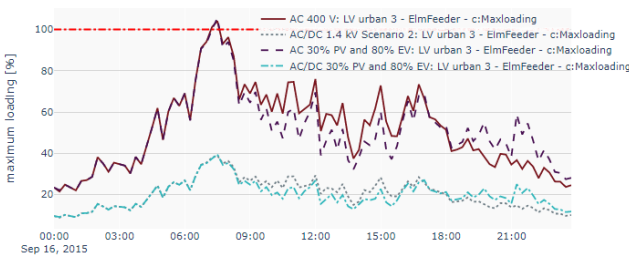

Figure 4: LV urban 3 daily max. loading profile, Sept 16.

Max. loading as well as min. and max. voltage profiles for LV urban 3 are shown in Figures 4 and 5 for one day, Sept 16, where the max. loading occurs. Although overloading is only

a short-time peak, the voltage profile (Figure 5) shows that the allowed min. voltage of 0.9 p.u. (according to EN 50160) is violated multiple times throughout the day, which can be prevented by conversion of the feeder to 1400 V_{DC}.
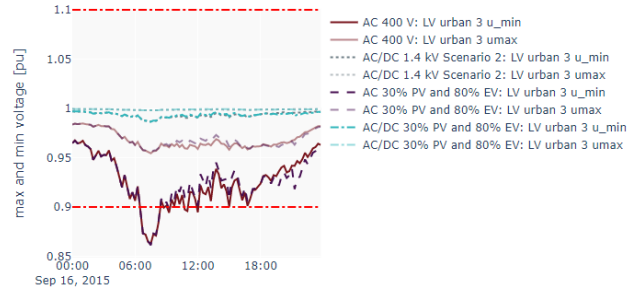

Figure 5: LV urban 3 daily min/max voltage, Sept 16.

Similarly, the voltage profile for feeder LV rural 1 on 23 June (Figure 6) shows that the allowed voltage band cannot be adhered using 400 V_{AC} in the investigated scenario. Voltage fluctuations are reduced remarkably in the 1400 V_{DC} system.
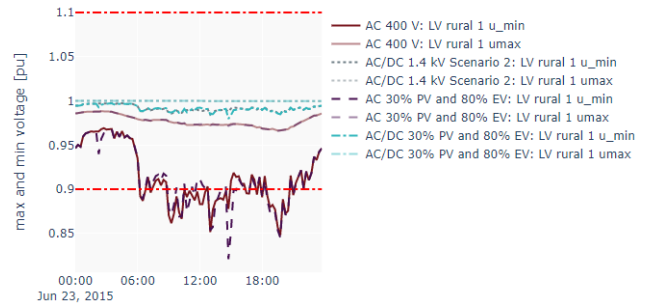

Figure 6: LV rural 1 daily min/max voltage profile, Jun 23.

The cost model was applied to the yearly simulation results. Figure 7 shows that the conversion of any LV feeder to DC would be economically beneficial in comparison to reinforcing the AC lines under the given circumstances. For feeder LV Rural 1, which is one of the feeders where the AC network reached its limits, it is clearly economically beneficial to
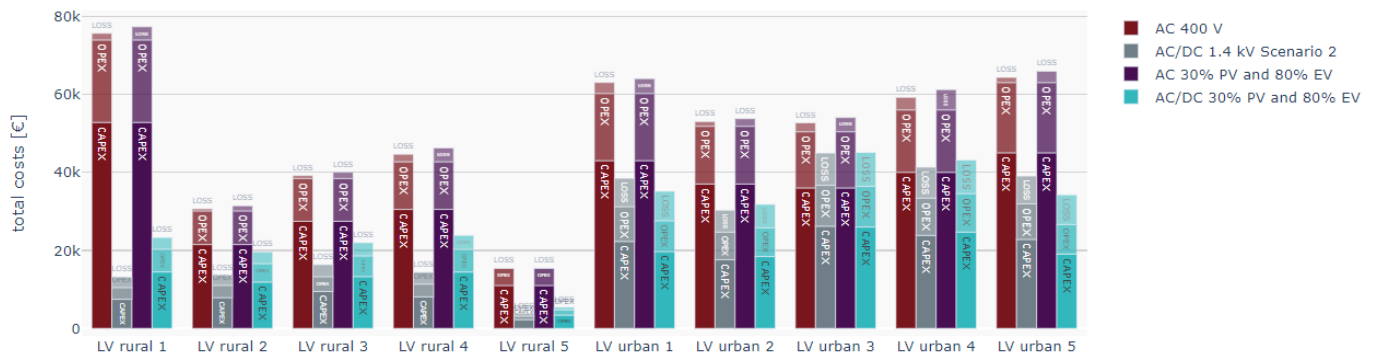

Figure 7: Comparison of TOTEX costs for AC grid reinforcement and conversion to DC for all LV feeders in test grid, TOTEX divided in CAPEX and OPEX (losses costs (LOSS) are indicated separately from the rest of OPEX costs) using default values from Table 5 and yearly simulation results.

implement DC, even if scenarios 1a or 1b are considered. As already demonstrated in [14], it was confirmed that long rural feeders such as LV rural 1 are important use-cases for LVDC. Moreover, it was shown that even for urban LV feeder such as LV urban 3, if the current AC grid is reaching its capacity limitations, the conversion to DC is an option worth considering from a techno-economic perspective.
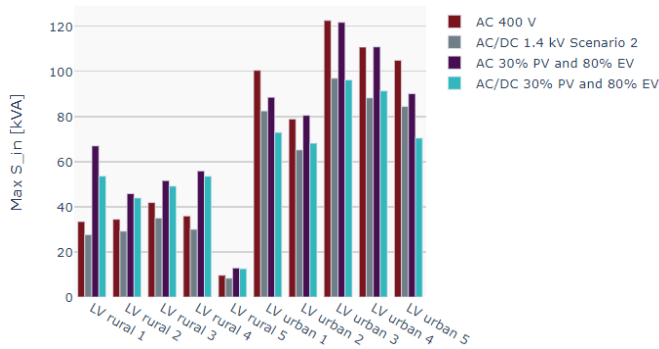

Figure 8: Maximum LV feeder input apparent power S_{in_max} (yearly simulation, parameters in Table 4)

Overall yearly feeder losses in the given scenario could only be reduced for feeder LV rural 1 and 4 in case EVs and PVs are included in the test grid (comparison of LOSS costs in Figure 7). In general, DC system losses resulted to be higher mainly due to the high VSC no-load losses and frequent low load operation of the converter. Nevertheless, beside potential cost reduction of DC equipment, VSC losses and CAPEX costs can be further reduced by minimizing the converter size. Moreover, Figure 8 shows that the efficiency gains applied to loads, EVs and PVs if connected to DC resulted in a notable reduction of maximum feeder input apparent power S_{in_max}.

4 Conclusion

The presented simulation tool enables flexible and fast hybridisation of complex grid models in Power Factory. An economic model helps identifying cost sensitivities and facilitates the high-level evaluation of the implementation of LVDC from a grid planning perspective.

Selected simulation results underline the potential benefits of DC in LV grids. In case capacity limits of an LVAC system are reached, it is shown that a conversion of the LV feeder to DC instead of reinforcing the existing lines can be economically beneficial, for both rural and urban LV feeders, especially considering future technological development of DC equipment.

Further investigations are planned in the optimal sizing of the converters as well as the inclusion of more complex converter control strategies. This will allow the investigation of possible effects of the hybridization on the overlaying AC grid, as well as the identification of synergies to tackle future challenges such as low inertia grids or management of decentralized energy communities.

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