HYBRID AC AND DC DISTRIBUTION NETWORKS MODELLING AND PLANNING USING *EPSL* MODELICA LIBRARY: PRELIMINARY RESULTS

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ABSTRACT

With the development of power electronics in most customer appliances, DC grids may prove to be an interesting alternative to the usual AC grids in a near future. This paper provides a first set of results for various settings of LV grids in the prospect of investigating new architectures for grid planning: full-AC, hybrid AC/DC and full-DC variations are considered for a same LV grid with solar panels, decentralized storage units and electric vehicles connected. Each grid architecture is compared on the basis of technical aspects, especially losses and voltage drops, for different operation points. Usual electric planning tools are currently quite limited in regards to such hybrid networks, making it difficult to assess non-conventional planning strategies. We use here the Modelica Electric Power System Library (EPSL) developed by Dassault Systèmes and extended in a joint work with EDF in order to tackle this issue and perform an evaluation of the grid architectures.

INTRODUCTION

Direct Current (DC) powered appliances connected to distribution grids, such as distributed generation, electric mobility and static storage units, are rapidly spreading worldwide. This fast evolution raises the question of the sustainability of our present-day Alternative Current (AC) distribution network architecture, established decades ago. It is envisioned that hybrid AC and DC distribution grids could help avoid conversion and distribution losses, facilitate the integration of Distributed Energy Resources (DER) and reduce overall costs of systems ([1], [2]). Various Low Voltage (LV) network architectures could thus be envisioned to meet these expectations.

The simulation of hybrid AC and DC distribution grids is essential in the context of network planning when assessing the value of such hybrid systems and comparing them to classic AC grids. The resulting reliability, safety and quality of the power supply should be considered in addition to infrastructure, maintenance and operation costs. Moreover, network planning is no longer limited to simple sizing strategies based on basic load and generation profiles. Modelling of DERs and Demand Response control mechanisms should be integrated, requiring complex interactions between these models and the electrical modelling of grid assets.

Simulation tools usually used by grid operators, such as EMTP-RV, PowerFactory… are well suited to simulate AC networks, and can also simulate standalone DC systems. But they are not able to simulate in one go hybrid AC and DC grid architectures, when the AC and DC parts and their control mechanisms are deeply interconnected. Initialization methods of such electric systems are complex and computationally demanding, making them unfit for planning purposes.

We present here the joint work carried out by EDF R&D and Dassault Systèmes teams on *EPSL* to apply it to quasi-static simulations of hybrid distribution grids. We explain first how this all-purpose Modelica electric library was extended for the distribution grid purposes with ready-to-use AC, DC and AC-DC distribution grid components. In a second part, we simulate several LV distribution grid architectures with a high share of photovoltaic (PV) generation, electric vehicles (EV) and storage. Various functioning points are considered. All these grids are modelled with *EPSL* using Dymola simulation tool, which is controlled by *DisNetSimPl*, a simulation platform developed by EDF R&D [3].

AC/DC NETWORK MODELING

Needs for network planning and tool selection

Network planning consists of a technical and economic trade-off that aims at designing the most efficient network architecture while keeping both investment and operation costs to a minimum. To do that, grid operators compute specific functioning points of a grid structure and assess the resulting voltage and current constraints, i.e. the nodes where the voltage is over or lower than the Un±10% threshold defined by the EN 50160 standard [4], and the line segments and transformers where the current is exceeding their rating to ensure asset reliability as seen in [5] and [6]. Losses are also part of the decision process leading to investments in the grid.
The tools currently used to perform these simulations are well suited to simulate AC networks, capitalizing on the

accumulated experience and knowledge gained over the past decades. They can also simulate standalone DC systems. But they are not able to simulate in one go hybrid AC and DC grid architectures when AC and DC parts are deeply interconnected by their control mechanisms. Several processes, such as [7], [8] and [9], have been used to initialize the simulation of such electric systems, mostly relying on temporal simulations. But all of them are complex and computationally demanding, making them unfit for planning purposes where fast steady-state calculations are required.

Extending *EPSL* Modelica library

To answer this challenge, EDF R&D has selected the Modelica *Electric Power Systems Library* (*EPSL*) developed by Dassault Systèmes. *EPSL* is the most complete Electric Modelica library available: it offers many interesting features such as steady-state and transient calculations of both DC and AC systems, variable frequencies and harmonics simulation, dynamic phasor modelling, etc. A large number of components already existed modelling the generation, the distribution, the conversion and the consumption of electric power. Yet the library was not directly applicable for distribution grid planning calculations as several key models were missing. To address this issue, EDF R&D has collaborated with Dassault Systèmes to extend *EPSL* with models specific to public electric distribution grids. Several new models have been developed or completed in this regard. Some of them are presented in Table 1.

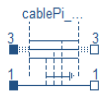
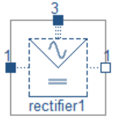
	Voltage sources with an internal impedance: • either with an internal voltage set by the user, • or an internal voltage adapted to match the outer voltage set by the user
	AC and DC line or cable segments with wires numbering from 2 to 4 described with symmetric or per wire representations depending on the use case considered.
	AC and DC loads / generators with delta or star connections and voltage sensitivity modelled: $P_{load} = P_{ref}\ \mathrm{abs}\left(\frac{V_{load}}{V_{ref}}\right)^{\alpha}$ and $Q_{load} = Q_{ref}\ \mathrm{abs}\left(\frac{V_{load}}{V_{ref}}\right)^{\beta}$ Where: P_{ref}, Q_{ref} are the active and reactive power references, V_{ref} the voltage reference and α, β the dependency to the measured voltage V_{load}. Reactive parameters are only applicable to AC components.
	Rectifiers ensuring the conversion from AC to DC or vice-versa depending on the control mode. The main control modes implemented in *EPSL* are: $V_{DC} - Q_{AC}, PQ_{AC}, V_{AC} - P$.

Table 1 – Examples of ESPL components developed/extended

It is also to be noted that EDF has developed other Modelica libraries such as BuildSysPro[1] for building thermics modelling. Using a Modelica library such as *EPSL* facilitates the coupling of electric models of the grid with these models, allowing an easier tuning of the planning hypotheses such as load dispersion.

Extending *DisNetSimPl* platform

EDF teams rely on the *Distribution Network Simulation Platform* (*DisNetSimPl*) to define and run the scenarios applied to the tested grid. This platform developed by EDF R&D [3] allows the graphical representation and edition of grid topology and component characteristics, interfaces itself to several simulation tools such as *OpenDSS*[2] (EPRI) and EMTP-RV, and provides result representations such as voltage profiles and constraint maps.

DisNetSimPl was historically conceived as an AC centric platform like most electrotechnical tools. For the purpose of assessing both AC and DC grids, it has been extended with new DC and AC/DC components. A new interface has also been developed in order to automatically generate the *EPSL* models of distribution grids whether full AC, full DC, or hybrid AC and DC ones, and to import the simulation results.

The framework formed by *DisNetSimPl* and *EPSL* helped to easily simulate and compare the grid configurations and scenarios considered in the following section.

EXPERIMENT DESCRIPTION

Configurations of the Low Voltage grid

With the increasing number of power electronic equipment connected to LV grids such as household appliances, electric vehicles, solar panels… new challenges and opportunities arise. One of them consists in the integration of DC grids in the existing AC framework. If several improvements are envisioned thanks to such hybridization regarding losses and cost savings in certain settings, they have to be confronted to the real life of distribution grids.

Consumption	Customer number Overall average power	82 40 kW
Generation	Number of solar panels Peak power of a solar unit	11 PV 3 kVA
Electric vehicles	Maximum number connected Maximum power of an EV	13 3.6/7.2kVA
Decentralized storage units	Number of storage units Maximum (dis) charge power	8 5 kVA
Transformer	Rated power	250 kVA
Lines	Total length of the feeder Furthest point of the feeder Minimum existing section Maximum existing sections	1095 m 516 m 54+35mm^2 240+95mm^2

Table 2 – Main characteristics of the LV feeder considered

We consider a typical French AC LV feeder (Figure 1) to get some first highlights regarding usual planning aspects

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[1] https://github.com/edf-enerbat/BuildSysPro

[2] http://smartgrid.epri.com/SimulationTool.aspx

that are the voltage and current constraints, and the losses. Its characteristics that remain constant over all the grid configurations and scenarios are summarized in Table 2.

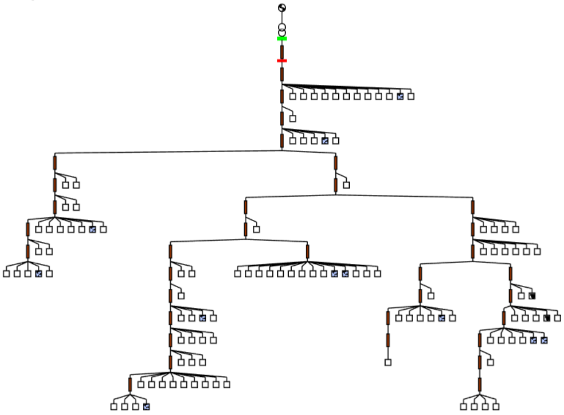

Figure 1 – AC version of the LV feeder considered

Two variations of this initially AC network are considered: a full DC equivalent fed by a 250 kVA AC/DC converter, and a hybrid version where all the large DC loads (electric vehicles, solar panels and decentralized storage units) are connected to a second DC feeder fed by a 100 kVA AC/DC converter (Figure 2). Voltage on the DC side is controlled by the AC/DC converter in both cases.

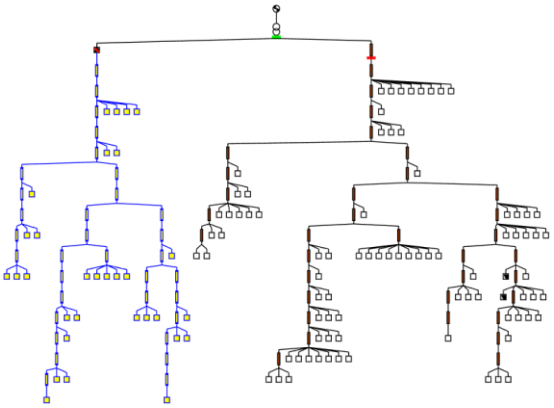

Figure 2 – Hybrid version of the LV feeder considered

The line-to-line nominal voltage for the AC grid is 400 V, while, for the DC parts of the grid, the nominal voltage between the Positive to Negative poles (PN) is set at 750 VDC. Figure 3 illustrates the gain obtained regarding the voltage drop observed for the DC feeder in a hybrid configuration when using a 750 VDC nominal voltage rather than 380 VDC in the same conditions. It is to be noted that a voltage nominal of 380 VDC was initially considered. But too large voltage drops were observed in regards to the power drawn by the appliances considered in the different scenarios, in particular for the full DC grid where variations over 10% of the reference voltage were observed.

There are several other aspects not discussed here, that should be considered when making investment decisions, such as the protection scheme, the reliability and power quality of the supply, and all the related economics, each aspect being linked to the other.

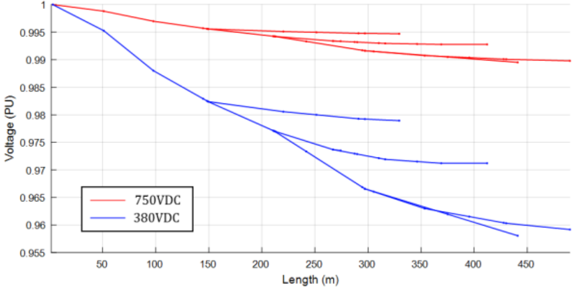

Figure 3 – Voltage drop on the DC feeder in the hybrid configuration for one of the winter settings

Use cases description

Fourteen different consumption, generation, EV charging, and storage operating points are used to compare the three grid architectures previously presented. Different seasonal settings are considered: a sunny day in summer with PV functioning near their maximum capacity or an evening during winter with no PV generation. For EV, the following states are considered: no charge, 3.6 kW normal charge and 7.2 kW fast charge. We also consider combinations with storage units in their charging, discharging and neutral states. Table 3 summarizes the set of situations considered in this paper.

All these functioning points are not designed to be representative of the usual operation of the grid. They are more like extreme cases illustrating different sizing situations, involving EV chargers, battery units and solar panels, as well as their environment. Depending on the case, they represent self-consumption within an area of the grid, maximum transit from the upstream network, or even maximum transfer between AC and DC parts of the grid. For example, the storage unit output is either scheduled to optimize energy usage by compensating locally PV generation and EV charge, or creating a significant transit between two network parts. This allows us to quantify the performance of each grid architecture regarding these functioning points, and better grasp their pros and cons.

Day type	EV state	Storage	ID
Sunny day	Fast	Neutral	#0
	Normal	Charge	#1
		Discharge	#2
		Neutral	#3
	Off	Charge	#4
		Discharge	#5
		Neutral	#6
Winter evening	Fast	Charge	#7
		Neutral	#8
	Normal	Charge	#9
		Discharge	#10
		Neutral	#11
	Off	Charge	#12
		Discharge	#13
		Neutral	#14

Table 3 – Scenarios considered for the 3 grid configurations

Evaluation protocol

Different quantities are considered to assess the performance of the three grid architectures:

- The total losses on the grid in kW and relative to the overall transit in the grid. They include those in the transformers, line segments as well as AD/DC converters. Different converters are considered in this computation: the converter of the feeder located at the secondary substation, and all the AC/DC converters of the DC appliances. When going DC, only the DC/DC converter is retained.
- The maximum voltage drop at each node observed over the whole network. It is expressed in regards to the relevant nominal voltage.

RESULTS

The analysis of the simulation results displayed in Figure 4 for each scenario shows that several trends emerge regarding the network losses.

- The hybrid AC/DC architecture displays the least volume of losses in most of the scenarios considered. However for several of them, it ranks last and displays large amount of losses. It is especially the case for scenario where the consumption and generation within the DC feeder is largely unbalanced; leading to important transit within the 100kW AC/DC converter. The losses saved thanks to the suppression of each individual AC/DC converters are lost with penalties (network losses) when going through the central 100kW converter.
- The losses of the full LVDC grid version are the most consistent and stable when compared to the best configuration of each scenario. And in the least favourable scenario (winter evening and fast EV charging), the volume of losses displayed is still smaller than those calculated for the full AC.
- The AC grid emerges as the least favourable solution in nearly all the scenarios considered. This can however be linked to the difference between the nominal voltages chosen for the AC (230 V) and the DC parts (750 V) of the network.

Regarding voltage variations (Figure 5), the full-DC configuration displays the smallest amount of variations within the grid. The full-DC architecture is helped by the choice of a 750 VDC nominal voltage, while the hybrid architecture can only take advantage of this for the DC loads connected to DC feeder, the other loads being connected to the usual AC grid. The full-AC grid is subject to the largest voltage variations since it has to host more power with a smaller nominal voltage.

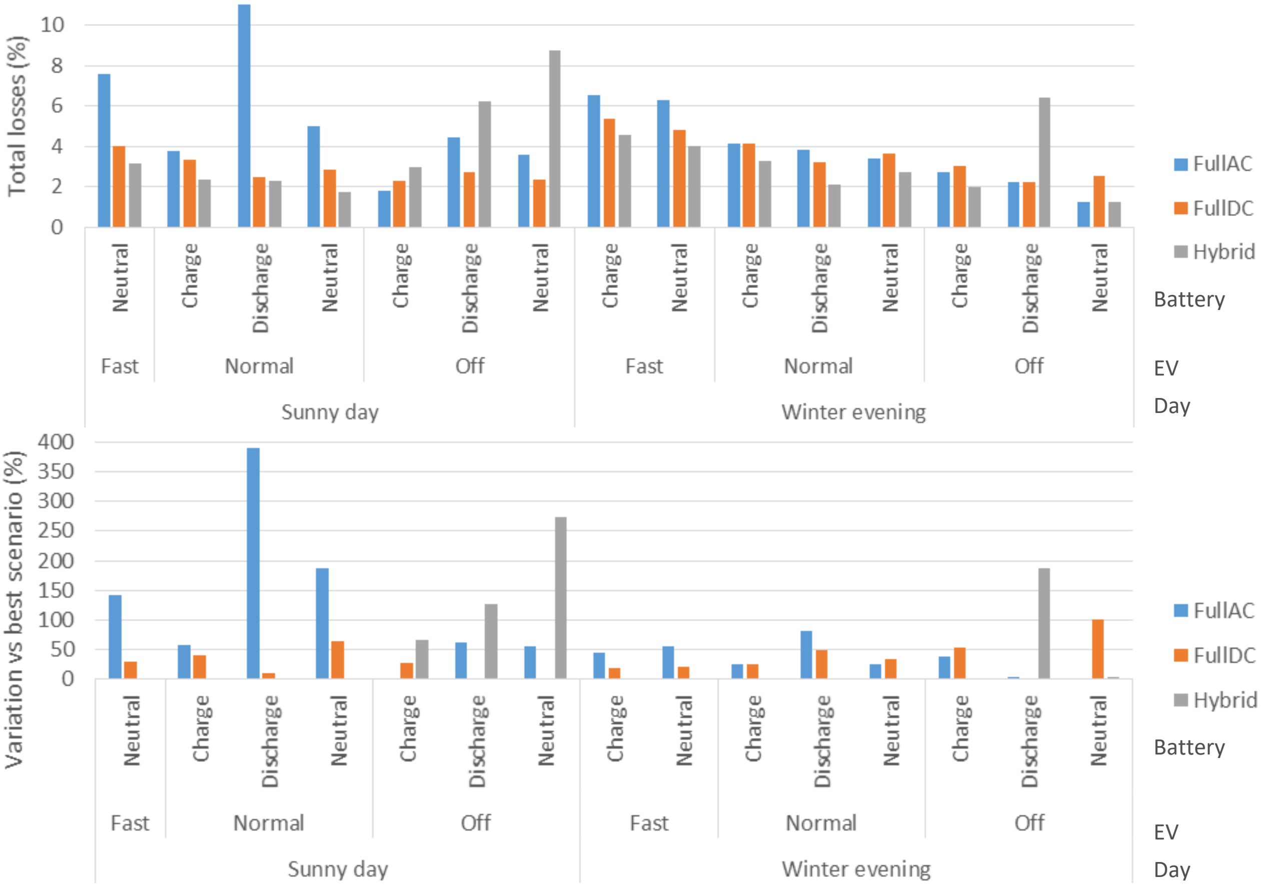

Figure 4 – Overall network losses calculated for each scenario (atop: losses expressed in percent to the overall transit; bottom: variation of the losses regarding the most favorable scenario)

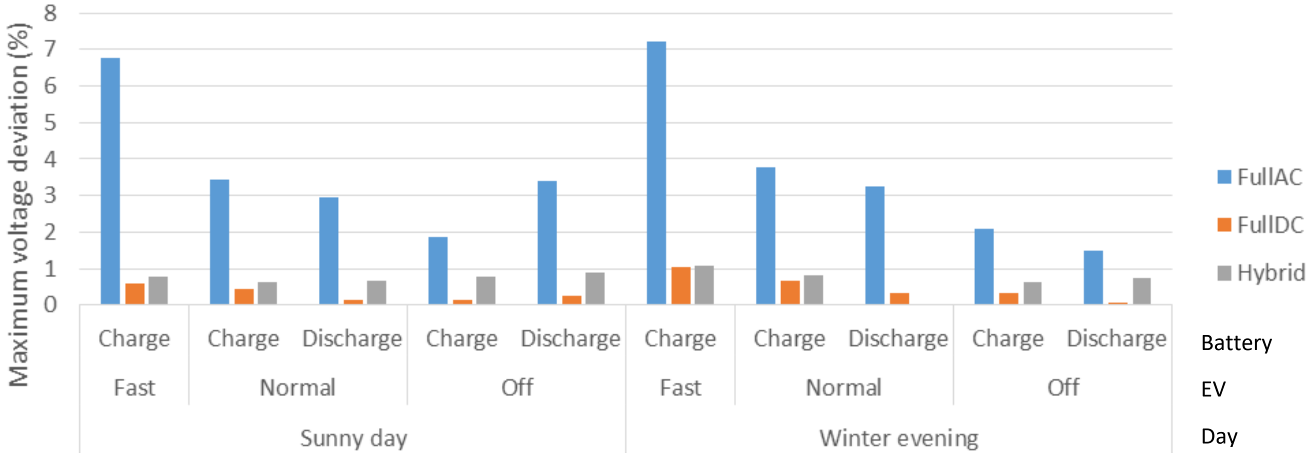

Figure 5 – Maximum voltage deviation calculated for each scenario

PERSPECTIVES

Thanks to EPSL Modelica library we were able to easily compare three grid architectures involving AC and DC parts in regards to their losses and voltage variations for different scenarios. It allowed us to model all the studied use cases within a unified tool framework.

The results presented in this paper show that hybrid AC / DC grids show the least amount of losses in most of the scenarios. However they clearly perform worse when the powers consumed and injected on the DC side are unbalanced, i.e. when the flow at the interface between the upstream AC network and the downstream DC feeder becomes quite large.

The results presented here are part of ongoing research within EDF lab. They will be supplemented by:

- Taking into account other grid topologies, such as connecting equipment between PE, NE and PN conductors depending on their power, or multi-terminal DC feeders for a better reliability.
- Considering other planning related aspects, and in particular the protection scheme.
- Integrating economical information in the assessment of the solutions.
- Increasing the number of grids considered, both in rural and urban areas.

This will compel us, for example, to investigate nominal voltages other than 750 V, since higher voltage means fewer losses but a more expensive protection scheme.

EPSL library will also be further improved, by integrating new models and new regulations in order to cover all the envisioned use cases, but also by reducing the time required for the compilation and computation of the Modelica models of the grids.

REFERENCES

[1] R. Weiss, L. Ott and U. Boeke, "Energy Efficient Low-Voltage DC-Grids for Commercial Buildings," *IEEE International Conference on DC Microgrids (ICDCM)*, 2015.

[2] E. Rodriguez-Diaz, J. Vasquez and J. Guerrero, "Potential energy savings by using direct current for residential applications: A Danish household study case," *IEEE Conference on DC Microgrids (ICDCM)*, pp. 547-552, 2017.

[3] J. Horta, D. Kofman, D. Menga and M. Caujolle, "Augmenting DER hosting capacity of distribution grids through local energy markets and dynamic phase switching," *Conference ACM e-Energy*, 2018.

[4] EN 50160, Voltage characteristics of electricity supplied by public distribution systems, 2011.

[5] W. E. Featheringill, "Power transformer loading," *IEEE Transaction on Industry Applications*, vol. 19, no. 1, pp. 21-27, 1983.

[6] W. J. McNutt, "Risk assessment for loading transformer beyond nameplate rating," *Proceeding of American Power Conference*, vol. 41, pp. 710-715, 1979.

[7] P. Rault, Dynamic Modeling and Control of Multi-Terminal HVDC Grids, PhD manuscript, 2014.

[8] J. Beerten, S. Cole and R. Belmans, "A sequential AC/DC power flow algorithm for networks containing Multi-terminal VSC HVDC systems," *IEEE Power and Energy Society General Meeting*, 2010.

[9] N. Murray, J. Arrillaga, N. Watson and Y. Liu, "Improved Simulation of an HVDC Test Case through Power-flow Initialization," *IPST*, 4-7 June 2007.