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A COMPARATIVE STUDY OF OPTIMAL PLANNING OF DISTRIBUTION SYSTEMS: AC/DC ARCHITECTURE VS. CONVENTIONAL STRATEGIES

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ABSTRACT

As the integration of DC distributed energy resources increases in recent years, hybrid AC/DC topology appears as a promising alternative in the planning of distribution systems. This paper aims to compare conventional planning strategies with conversion of AC lines into DC through the formulation of optimal planning models. Both operational and reinforcement solutions are considered in the conventional planning. The results indicate that line reinforcement is more cost-effective from a DSO point-of-view for the case study considered.

INTRODUCTION

Distribution systems are facing an increasing integration of highly variable distributed energy resources (DERs) in recent years. This tends to raise the risks of security constraints violations and accelerates the need to upgrade these systems. Historically, Distribution System Operators (DSOs) rely on conventional network development solutions such as conductor reinforcement and operational/ non-wire alternatives (e.g. DER reactive power support and setting of transformers tap) to deal with aforementioned risks.

Nevertheless, because the majority of DERs is DC native, converting AC systems into hybrid AC/DC emerges as a solution to alleviate overloaded networks and keep voltage into safe limits while facilitating the connection of DC DERs. The benefits of such a conversion are an increase of maximum transfer capacities as well as reduction of losses and voltage drop in the feeders [1]. Indeed, [2] and [3] present concrete projects where converting existing AC cables into DC provided a cost-effective solution.

This solution can be especially worthwhile in Medium Voltage (MV) systems with a significant increase of high-power DC DERs integration. In these cases, a local MVDC network can avoid network developments that would be otherwise required if the network remained operated full AC.

Although AC/DC expansion planning strategies have been developed in the literature [4], a comparison between this strategy and conventional solutions is rarely found. Therefore, this paper aims to compare current solutions with AC/DC topology in order to identify most suitable strategies and propose a systematic optimization tool to aid in DSO planning decision-making process.

PROBLEM DESCRIPTION

To deal with DERs connections over long-term horizon, DSOs typically carry out planning studies to determine best solutions to host these resources without jeopardizing system security [5]. In this work, optimal planning models are developed to study DERs integration into MV distribution systems ensuring grid code compliance. Different solutions developed to respect voltage and current limits are presented in the next paragraphs.

First, an optimal operational planning considering non-wire alternatives is developed and tested. This strategy considers reactive power support from DERs according to an optimal set of power factor following the French DSO grid code [6]. Moreover, optimal system configuration (choice of normally open points) and on-load tap changer (OLTC) voltage control are also considered.

For weak grids with high integration of DERs, non-wire alternatives are sometimes unable to ensure a secure operation. In this case, two strategies are further tested, namely AC/DC and reinforcement planning.

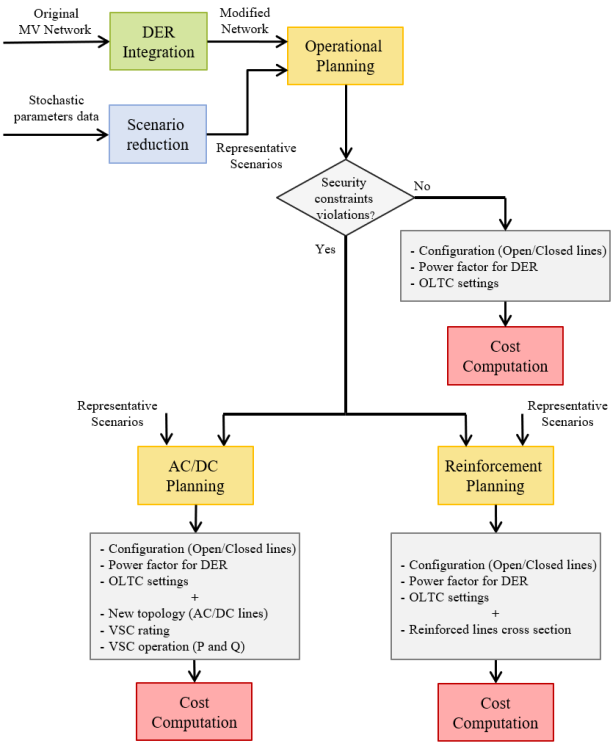
The first strategy studies the optimal conversion of a part of the system into DC to create a link between AC feeders, improving feeder balance and avoiding constraints violation. At the same time, DC resources can be connected to the MVDC systems, providing a less costly and more efficient connection of DC resources to the network from a DERs holder point-of-view.

The second strategy models the conventional solution used by DSOs to propose replacement of a conductor by another, i.e. line reinforcement. In this way, network developments are determined to minimize the costs while keeping current and voltage within the limits by changing line capacity and impedance.

Both AC/DC and reinforcement planning include also operational solutions applied for operational planning (Volt-VAR control, new configuration and OLTC). All models are formulated as Mixed Integer Quadratic Programming (MIQP) optimization problems, guaranteeing optimality within a reasonable computation

time with off-the-shelf solvers. Figure 1 summarizes flowchart of methodology used to compare developed planning models for a given case study.

Figure 1 – Flowchart of planning model



OPTIMAL PLANNING MODELLING

The Distribution System Planning (DSP) strategies defined in the next subsections aim to optimize economic expenditures from a DSO point-of-view over a set of illustrating relevant operating points for a given planning horizon. The costs for the DERs holders are not modelled here.

Representative Scenarios

A Wasserstein distance minimization-based scenario reduction technique [7] is used to determine representative scenarios for stochastic parameters, i.e. level of load demand, electric vehicle charging station demand, wind turbine power and photovoltaic power. Hence, each scenario is defined by a modulation index that multiplies nominal power and by a weight coefficient (w^s) representing the probability of occurrence of the scenario.

Objective function

The proposed models minimize the Net Present Cost (NPC) presented in (1) over a planning horizon y considering a discount rate d. Capital Expenditures ($CAPEX$) consider the capital cost of AC/DC Voltage Source Converters (VSC) used to connect AC and DC networks (CC_{vsc}) or the capital cost of lines reinforcement (CC_{reinf}), as presented in (2)-(4). Operational Expenditures ($OPEX$) consider the losses cost of the converters (LC_{vsc}) and lines (LC_{lines}) in (5)-(7) taking into account losses unit cost (lc) and a weight coefficient (w^s). The line losses computation is done by an approximation of current for nominal voltage operation in (8)-(9) to obtain a quadratic objective function. Note also that indices s, i, ij and k are used to refer respectively to the variables for each scenario, node, line and conductor type.

$$\min \sum_{t=0}^{y} \frac{1}{(1+d)^t}(CAPEX_t + OPEX_t) \quad (1)$$

$$CAPEX_t = CC_{vsc} \;\; or \;\; CC_{reinf} \quad (2)$$

$$CC_{vsc} = cc_{vsc} \sum_{nodes} S_{vsc,i}^{rated} \quad (3)$$

$$CC_{reinf} = \sum_{\substack{conductor\\type}} \left(cc_{reinf,k} \sum_{lines} length_{ij} \right) \quad (4)$$

$$OPEX_t = LC_{vsc} + LC_{lines} \quad (5)$$

$$LC_{vsc} = lc \sum_{scen} w^s \sum_{nodes} P_{vsc,l,i}^s \quad (6)$$

$$LC_{lines} = lc \sum_{scen} w^s \sum_{lines} \left(r_{ac,ij}^s l_{ac,ij}^s + r_{dc,ij}^s l_{dc,ij}^s \right) \quad (7)$$

$$l_{ac,ij}^s = \frac{\left(p_{ac,ij}^s\right)^2 + \left(q_{ac,ij}^s\right)^2}{V_0^2} \quad (8)$$

$$l_{dc,ij}^s = \frac{\left(p_{dc,ij}^s\right)^2}{V_0^2} \quad (9)$$

Operational constraints

Power flow constraints are formulated through a *LinDistFlow* model [8], which solves the power flow for squared nodal voltage (v_i) and branch power (p_{ij} and q_{ij}), neglecting line losses in power balance nodal constraints (10)-(11) as well as in voltage drop equation (12). Line security limit is modelled through apparent power limitation presented by a piecewise linearization of (13) [9]. Voltage security constraint is defined in (14).

$$\sum_{lines} p_{ac,ij}^s + P_{ac,i}^s + P_{vsc,ac,i}^s = 0 \quad (10)$$

$$\sum_{lines} q_{ac,ij}^s + Q_{ac,i}^s + Q_{vsc,ac,i}^s = 0 \quad (11)$$

$$v_{ac,i}^s - v_{ac,j}^s = 2\left(r_{ac,ij} p_{ac,ij}^s + x_{ac,ij} q_{ac,ij}^s\right) \quad (12)$$

$$\sqrt{\left(p_{ac,ij}^s\right)^2 + \left(q_{ac,ij}^s\right)^2} \le \overline{s_{ac,ij}} \quad (13)$$

$$\underline{v_{ac}} \le v_{ac,i}^s \le \overline{v_{ac}} \quad (14)$$

These approximations yield to a linear formulation of the problem that is piecewise convex, reducing computational burden with good accuracy, as later discussed in the Results section.

AC/DC Architecture

DC operational constraints

Analogously to AC power flow constraints, (15)-(18) represent the DC power flow constraints valid whenever a line is converted into DC.

$$\sum_{lines} p^s_{dc,ij} + P^s_{dc,i} + P^s_{vsc,dc,i} = 0 \quad (15)$$

$$v^s_{dc,i} - v^s_{dc,j} = 2r_{dc,ij}p^s_{dc,ij} \quad (16)$$

$$p^s_{dc,ij} \leq \overline{p_{dc,ij}} \quad (17)$$

$$\underline{v_{dc}} \leq v^s_{dc,i} \leq \overline{v_{dc}} \quad (18)$$

Double circuit feeders were considered in this system. Since isolation of three-phase AC conductors is roughly designed to withstand peak phase-to-phase voltage, it is assumed here a conversion factor of $k_v = 2\sqrt{2}/\sqrt{3}$ between phase-to-phase AC voltage and pole-to-pole DC voltage. This results in a conversion factor of $k_r = 0.5$ for resistance and $k_p = \sqrt{2}$ between AC and DC lines power capacity in per unit [1]. This conversion is further illustrated by Table 1 and (19)-(21).

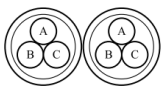
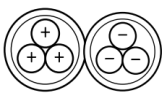
$$U_{dc} \cong k_v U_{ac} \quad (19)$$

$$r_{dc,ij} = k_r r_{ac,ij} \quad (20)$$

$$\overline{p_{dc,ij}} = k_p \overline{s_{ac,ij}} \quad (21)$$

These conversions define base values for the models and allow the coupling of per unit power constraints of AC and DC systems. The values considered ($k_p > 1$ and $k_r < 1$) result therefore in an increase of maximum transfer capacities and in the reduction of losses and voltage drop in feeders converted into DC.

Table 1 – Double circuit feeder conversion of AC 3-phase into DC symmetrical without neutral wire (based on [1])

Configuration			$\overline{P_{dc}}$ or $\overline{S_{ac}}$
AC		or	$\sqrt{3}U_{ac} \times 2\overline{I}$
DC		or	$U_{dc} \times 3\overline{I}$

VSC constraints

The VSC constraints ensure balance between AC and DC active power and losses in (22)-(23). Losses are assumed to be proportional to VSC rated and operating apparent power in (24), producing 5% losses at nominal power. Operating apparent power of the VSC is computed by a piecewise linearization of (25), which is a relaxation of exact constraint for each scenario. Finally, VSC operating apparent power is limited by its rated power in (26).

$$P^s_{dc,i} + P^s_{vsc,dc,i} = 0 \quad (22)$$

$$P^s_{vsc,dc,i} + P^s_{vsc,ac,i} + P^s_{vsc,l,i} = 0 \quad (23)$$

$$P^s_{vsc,l,i} = c_0 S^{rated}_{vsc,i} + c_1 S^s_{vsc,i} \quad (24)$$

$$\sqrt{\left(P^s_{vsc,ac,i}\right)^2 + \left(Q^s_{vsc,ac,i}\right)^2} \leq S^s_{vsc,i} \quad (25)$$

$$S^s_{vsc,i} \leq S^{rated}_{vsc,i} \quad (26)$$

Reinforcement constraints

The reinforcement planning determines the replacement or not of a conductor by selecting between the conductor sections typically used by a French DSO (Table 2). This planning strategy is defined through same constraints of operational planning, but considering different cross sections options for each network feeder in power flow constraints. Thus, constraints (10) – (12) are written as (27) – (29) when a line is reinforced.

$$\sum_{\substack{conductor\\type}} \left(\sum_{lines} p^s_{ac,ij,k} \right) + P^s_{ac,i} + P^s_{vsc,ac,i} = 0 \quad (27)$$

$$\sum_{\substack{conductor\\type}} \left(\sum_{lines} q^s_{ac,ij,k} \right) + Q^s_{ac,i} + Q^s_{vsc,ac,i} = 0 \quad (28)$$

$$v^s_{ac,i} - v^s_{ac,j} = 2\left(r_{ac,ij,k}p^s_{ac,ij,k} + x_{ac,ij,k}q^s_{ac,ij,k}\right) \quad (29)$$

Table 2 – Reinforcement parameters

Conductor type	R (ohm/km)	X (ohm/km)	Cost (k$/km)
Al 95 mm²	0.320	0.100	109
Al 150 mm²	0.206	0.100	110
Al 240 mm²	0.125	0.100	112
Cu 240 mm²	0.075	0.100	150
2x Al 240 mm²	0.062	0.050	224

Topological modelling

Aforementioned constraints actually depend on the topology of the network, i.e. they are activated as a function of the choice between AC or DC, open or closed and conductor type, for instance. This selection between constraints and radiality constraints are modelled by using binary variables in this work.

RESULTS

The goal of this planning is to determine the most economical topology of a distribution system from a DSO point-of-view considering the integration of DC distributed resources. To evaluate planning models, a case study based on part of a French rural MV distribution

system presented next is considered.

The proposed formulations are implemented in the YALMIP optimization toolbox [10] with MATLAB R2020b, solved by Gurobi [11], on a laptop equipped with a 1.70GHz Intel® CoreTM i5-10310U CPU and 16 GB RAM.

Case Study

The case study considered has 18 nodes and 18 lines (2 Normally Open Points) and includes 14 large MV loads. The integration of DC DERs is considered by adding to the grid a photovoltaic power plant (PV), a wind turbine power plant (WT), a DC load and 2 electric vehicle charging stations according to Table 3.

Table 3 – DER integration data

Node	Type	Nominal Power (MW)
5	PV power plant	2.00
6	EV charging station	1.00
11	DC MV load	0.50
12	WT power plant	3.00
16	EV charging station	0.75

3 scenarios are considered to represent the probability distribution function of each stochastic resource. Then, under the hypothesis that resources availability and load demand are independent [12], the scenarios are combined to generate $3^4 = 81$ representative scenarios.

A 30 years planning is performed considering a 55% load growth, equivalent approximately to a 1.5%/year rate. This value is chosen to emulate a high load growth scenario. The converters cost took into consideration the replacement of the VSCs at the end of their service life. Other planning parameters are provided in Table 4.

Table 4 – Planning parameters

Parameter	Value
Base values ($\boldsymbol{S}$, $\boldsymbol{U_{ac}}$ and $\boldsymbol{U_{dc}}$)	10MVA, 20kV and 32kV
Voltage magnitudes limits	±5%
Discount rate	7.5%/year
VSC service life	15 years
Line service life	30 years
VSC unit capital cost	170$/kVA
Losses cost	0.08$/kWh

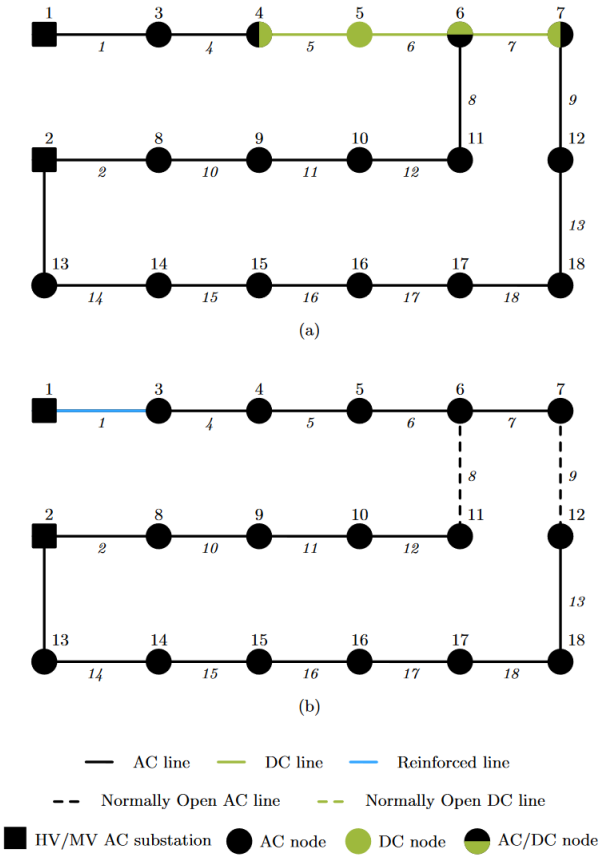
Planning results

The operational planning considering non-wire alternatives did not converge, i.e. it is an infeasible optimization problem, because security constraints cannot be ensured. The AC/DC and reinforcement planning results and optimal topology obtained are shown respectively in Table 5 and Figure 2.

Table 5 – Planning results

Planning model	NPC (M$)	CAPEX (M$)	OPEX (M$)
Operational		*Infeasible*	
AC/DC	1.307	0.380	0.927
Reinforcement	0.497	0.008	0.489

Figure 2 – Optimal topology planning of case study: (a) AC/DC and (b) Line reinforcement



The reinforcement requires a changing in configuration and replacement of line 1 by a Cu 240 mm^2 cross section conductor. The reinforced line is quite short (less than 50m), which represents a very low capital cost to ensure system operation under security constraints. In contrast, optimal AC/DC topology converts lines 5, 6 and 7 into a DC, creating a MVDC link between MVAC feeders improving balance between them by active power transfer. However, power converter high installation costs and losses expenditures required to implement this topology greatly increase both capital and operational expenditures. Accordingly, reinforcement solution significantly outperforms economically AC/DC planning.

This result applies for the given case study, where reinforcement needs are very limited, but it shows that AC/DC topology tends to be less cost-effective from the DSO point-of-view at the current conditions, i.e. VSC cost and performance. Notwithstanding, AC/DC topology

presents advantages not considered in the performed economic analysis, such as improving network DERs hosting capacity and facilitating DC connection to the grid through DC/DC converters instead of AC/DC ones. This could also have an impact on DERs holders' costs because DC/DC converters are as a general rule less costly and more efficient than VSCs.

CONCLUSION

Proposed models represent an advance towards systematic integration of DC into long-term distribution system planning studies. Although preliminary results show an advantage to conventional planning strategies from a point-of-view of a DSO, cost modelling did not consider cost reduction from DERs holder side related to the connection to a DC system instead of an AC one. Other case studies with larger and more overloaded distribution systems where more reinforcement is required might also highlight the interest of an AC/DC distribution planning.

Therefore, costs sharing between DSO and DER holders as well as scalability issues could be the subject of further investigation to find case studies where DC conversion is a cost-effective solution. In addition, future research should also focus on protection and reliability analysis of hybrid AC/DC systems to better evaluate cost-effectiveness of considered planning strategies.

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