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Optimal transmission network expansion planning in real-sized power systems with high renewable penetration

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ABSTRACT

The deregulation of power markets and the high amount of renewable energy expected in the coming decades have originated new needs for the expansion of the transmission network. Transmission expansion planning (TEP), the problem that deals with identifying the optimal grid reinforcements, is therefore becoming increasingly relevant. TEP, notoriously difficult to solve, is also deeply affected by uncertainty in factors such as renewable generation. Approaches for TEP based on optimization have not been widely used given that their high computational requirements mean that they could not be efficient for large-scale, real systems.

We present a model that performs optimal TEP efficiently in a Stochastic Optimization context. The model uses a modified version of Benders' decomposition that benefits from several improvements that are described. It deals with the incorporation of contingencies by using a double architecture for Benders cuts and a progressive contingency incorporation algorithm. In addition, it is able to identify the potentially interesting candidate transmission lines automatically, which is especially interesting in large-scale problems. Finally, it incorporates some other enhancements to the decomposition, which enable a faster problem resolution.

This paper describes the optimization model in detail as well as its implementation. This is completed with a realistic case study that illustrates that optimal TEP can be applied to large systems with high renewable penetration as long as efficient models and implementations are used.

Notation

This section defines all the symbols used in this paper. Upper-case symbols denote parameters and sets. Lower-case symbols indicate variables and indices.

Indices

y	Year
p	Period
s	Sub-period
n	Load level
g	Thermal unit, hydro plant or intermittent generator
t	Thermal generator
h	Storage hydro or pumped-storage hydro plant
f	Type of technology
i, j	Node
a, a'	Area
z, z'	Zone
ij	Line
l	Segments of the piecewise linear approximation of the ohmic losses
E, C	Sets of existing and candidates lines respectively

Parameters

	Costs
$\alpha, \beta, \gamma, \delta$	Weights of the different components of the objective function: weight of the transmission investment cost, generation operation cost, generation contingency cost and network contingency cost respectively
	Demand
D_{ypsni}	Demand in each node
IG_{ypsni}	Intermittent generation in each node
DUR_{psn}	Duration
R_{ps}	Reserve

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$CENS$	Cost of not served energy. Value of lost load (VoLL)
$CPNS$	Cost of not served power
	Generation system
$\underline{GP}_g, \overline{GP}_g$	Minimum load and maximum output of generator
$\overline{GC}_h$	Maximum consumption of a pumped-storage hydro
FCG_t, VC_g	Fixed and variable cost of generator. Variable cost includes fuel, O&M and emission cost
SC_t	Startup cost of thermal unit
η_h	Efficiency of pumped-storage hydro plant
I_h	Inflows of hydro reservoir
$\underline{R}_h, \bar{R}_h$	Minimum and maximum reservoir levels
	Transmission system
FCT_{ij}	Annualized fixed cost of a transmission line
$\bar{F}_{ij}$	Transfer capacity of a transmission line. In the operation scenarios it is used the net transfer capacity (total transfer capacity reduced by the security coefficient). In the reliability scenarios it is used the total transfer capacity
$\bar{F}'_{ij}$	Upper bound of the constraint of a transmission line
$\bar{F}_{ypsnaa'}, \underline{F}_{ypsnaa'}, \bar{F}_{ypsnzz'}, \underline{F}_{ypsnzz'}$	Maximum and minimum net transfer capacity between areas or zones
$\underline{F}_{ypsnaf}, \bar{F}_{ypsnaf}$	Maximum and minimum generation by area and technology
R_{ij}, X_{ij}	Resistance and reactance of a transmission line
S_B	Base power

Variables

	Demand
ens_{ypsni}	Energy not served in each node
pns_{yps}	Power not served in each node
	Generation system
gp_{ypsng}, gc_{ypsng}	Generator output and pump consumption
$u_{ypst}, su_{ypst}, sd_{ypst}$	Commitment, startup and shutdown of thermal unit {0,1}
r_{yph}	Hydro reservoir level
s_{yph}	Water spillage
	Transmission system
ic_{yij}	Indicator of cumulative installed capacity of candidate line in each year {0,1}
f_{ypsnij}	Flow through a line
$daf_{ypsnaa'}, eaf_{ypsnaa'}$	Deficit of lower bound and surplus of upper bound of flow between areas
$dzf_{ypsnzz'}, ezf_{ypsnzz'}$	Deficit of lower bound and surplus of upper bound of flow between zones
l_{ypsnij}	Half of the ohmic losses of the line
θ_{ypsni}	Voltage angle of a node
$\Delta w^+_{ypsnijl}, \Delta w^-_{ypsnijl}$	Used width of a segment of the piecewise linear approximation

1. Introduction: the need for transmission

The transmission network has a deep impact on the power system as a whole: it constrains the power flows through the grid and, therefore, the market interactions among its participants. Transmission expansion planning (TEP), that is, the optimal selection of the transmission lines to be installed in order to meet the objectives of the system as efficiently as possible [1], is a key issue that has received considerable attention. One of the key drivers for transmission expansion is the integration of new generation. The European Union (EU) has set very aggressive emission reduction targets, establishing a 20% reduction in greenhouse gases with respect to 1990 levels by 2020 and target of 80% reductions and 100% clean electricity by 2050 [2]. Thus, large amounts of new generation are expected in the medium-term future, which will require additional network investments for its integration into the system. Moreover, this new generation capacity will be so large that it will affect the cross-border flows of the EU network. This need for transmission investments has been acknowledged by the EU, whose joint budget for transmission during the period 2012–2022 amounts to over EUR 100 bln [3].<

The problem that solves the optimal network expansion (reinforcements or new lines), that is, optimal transmission expansion planning is therefore key in this process and as such is receiving an increasing attention. This is manifest, for instance, in the EU project e-Highway, which aims to develop a consistent methodology for TEP in the EU for a long-term future (2030 up to 2050) [4]. This problem is stochastic by nature due to the uncertainty that characterizes variable renewable energy sources. Some other uncertain factors that affect the impact of new lines in the operation of the system are demand (and demand response), hydro inflows, fuel costs or carbon emission costs [5]. However, solving this problem (even simplified, deterministic versions) is considerably difficult. This is the case too in other network optimization problems such as gas pipeline design [6]. Optimal TEP has been extensively studied in the literature [7]. However, the computational and implementation complexity of applying Stochastic Optimization to real-sized systems mean that most Transmission System Operators (TSOs) rely (at least, partially) on their intuition when designing an expansion plan rather than on formal approaches.

TEPES (transmission expansion planning for an Electric System) is a model that has been developed to perform the optimal selection of new transmission lines incorporating detailed network considerations and uncertainty in a Stochastic Optimization approach. The proposed model uses a modified version of Benders' decomposition to solve this problem in large power systems, and has been applied in projects such as Desertec [8] and Beyond 2020 [9], which propose to install very large amounts of renewable power in North Africa or the Mediterranean, respectively, and export it partly using newly constructed lines. This paper describes the model and its implementation, and provides a real-size case study that illustrates its applicability to large systems with high renewable energy penetration.

As explained, given the complexity of the problem, TEP is not usually solved using optimization in practical settings. This model shows that it is possible to optimize real-sized systems with uncertainty in affordable times. This is particularly important in cases where transmission expansion needs are high, such as the high penetration of renewable energy that EU emission reduction targets imply.

The contributions of this paper are the following:

- We develop a full model for transmission expansion planning which includes investment and operation costs, as well as penalties for non-served energy in the case of contingencies. This is carried out from a stochastic point of view that minimizes the expected value of the sum of costs and penalties. This article presents the model with a high level of detail. The model is able to perform the transmission expansion planning of large systems in affordable times using a stochastic description of uncertainty, which as described above is of paramount importance when considering renewable generation. It incorporates state-of-the-art research in order to get an efficient and sufficiently accurate results. It should be noted that the model proposes not only network reinforcements but also large-scale investments: for instance, a large-scale grid overlay. This is especially interesting in the context of high renewable penetration, where far-located large power plants might call for long, high-power lines for their integration into the system.
- The proposed resolution is based on an enhanced version of Benders' decomposition that includes several improvements. In order to tackle the incorporation of contingencies, we propose a combination of mono and multicut schemes that is especially