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Robust dynamic transmission and renewable generation expansion planning: Walking towards sustainable systems

C. Roldán[a], A.A. Sánchez de la Nieta[a], R. García-Bertrand[a], R. Mínguez[b,*]

[a] Department of Electrical Engineering, Universidad de Castilla-La Mancha, Ciudad Real, Spain
[b] Hidralab Ingeniería y Desarrollo, S.L., Spin-Off UCLM, Hydraulics Laboratory, Universidad de Castilla-La Mancha, Ciudad Real E-13071, Spain

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ABSTRACT

Recent breakthroughs in Dynamic Transmission Network Expansion Planning (DTNEP) have demonstrated that the use of robust optimization, while maintaining the full temporal dynamic complexity of the problem, renders the capacity expansion planning problem considering uncertainties computationally tractable for real systems. In this paper an adaptive robust formulation is proposed that considers, simultaneously: (i) a year-by-year integrated representation of uncertainties and investment decisions, (ii) the capacity expansion lines have and (iii) the construction and/or dismantling of renewable and conventional generation facilities as well. The Dynamic Transmission Network and Renewable Generation Expansion Planning (DTNRGEP) problem is formulated as a three-level adaptive robust optimization problem. The first level minimizes the investment costs for the transmission network and generation expansion planning, the second level maximizes the costs of operating the system with respect to uncertain parameters, while the third level minimizes those operational costs with respect to operational decisions. The method is tested on two cases: (i) an illustrative example based on the Garver IEEE system and (ii) a case study using the IEEE 118-bus system. Numerical results from these examples demonstrate that the proposed model enables optimal decisions to be made in order to reach a sustainable power system, while overcoming problem size limitations and computational intractability for realistic cases.

1. Introduction

1.1. Motivation

The new objective of the Kyoto Protocol for reducing Greenhouse Gases (GHG) encourages the development of renewable energy sources within electric systems [1]. The main reason for this is to combat the upward trend in worldwide average temperatures and climate change, and thus, it is expected that vast amounts of new generation facilities, especially renewable ones, will be built in the medium-term future.

Transmission network and renewable generation expansion planning analyze the issue of how to expand or reinforce an existing power transmission network, incorporate new renewable generation facilities and dismantle the old ones in order to adequately service system loads over a given time horizon while decreasing GHG emissions. This problem is challenging for several reasons [2]:

1. Transmission and generation investment decisions have a long-standing impact on the power system as a whole.
2. Transmission and generation investments, especially new generation sources, must be integrated appropriately into the existing system.
3. Consumption and renewable energy generation uncertainties, such as with wind and solar power plants, make resolution of the problem complicated. Note that wind power is the renewable technology that has most developed in the last decade, while the next renewable technology, in constant evolution, is photovoltaic power. The introduction of these types of renewable sources in the generation mix increases uncertainty about the feasibility of generation.
4. The expansion planning problem is by nature a multi-stage one that entails planning a horizon over several years. Keeping the dynamic complexity of the problem mostly results in computationally intractable problems.
5. Transmission expansion planning (TEP) and generation expansion planning (GEP) have usually been addressed independently, i.e. transmission planning is determined by considering that it is not possible to build new generation facilities and vice versa. However, transmission and generation expansion plans are clearly interrelated and treating them separately provides suboptimal solutions. The reason why these problems have been treated independently is that

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* Corresponding author.
E-mail address: roberto.minguez@hidralab.com (R. Mínguez).

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Nomenclature

Indices and sets

$\mathcal{D}$	set of demand indices
g	index for groups of generators built per phases
$\mathcal{G}$	set of indices of all generation units installed at the beginning of time horizon considered which cannot be removed from the system
$\mathcal{G}^{+}$	set of all prospective and independent new possible generators
$\mathcal{G}_{g}^{+}$	set of all prospective new generators which can be installed at different phases associated with group g
$\mathcal{G}^{-}$	set of all generators to be uninstalled or dismantled during the study period
i	index related to generators
j	index associated with loads
k	index referring to lines
l	counter index for each iteration
$\mathcal{L}$	set of all existing transmission lines
$\mathcal{L}^{+}$	set of prospective transmission lines
n	index related to buses
$\mathcal{N}$	set of networks buses
$n(i)$	bus index for the i-th generating unit
$n(j)$	bus index for the j-th demand
t	index related to time period
$\mathcal{T}$	set of indices of years
$\mathcal{U}^{(t)}$	set of indices of the uncertain variables for time period t
Ψ_{n}^{D}	set of indices of demand for bus n
Ψ_{n}^{G}	set of indices of generating units for bus n

Constants

b_k	line k susceptance (S)
c_i^{G}	generator i operational cost (€/MW h)
c_i^{GI}	generator i investment cost (€)
c_k^{LI}	line k investment cost (€)
c_j^{S}	consumer j load-shedding cost (€/MW h)
$e_j^{(t)}$	percentage of load shed by the j-th demand for year t
$f_k^{\max}$	line k capacity (MW)
$h_{\mu,j}^{(t)}$	nominal value evolution factor for demand j and period t
$h_{\sigma,j}^{(t)}$	dispersion value evolution factor for demand j and period t
I	discount rate
N_y	number of study periods
$o(k)$	line k sending-end bus
$r(k)$	line k receiving-end bus
$t_i^{G^{-}}$	time period when generator $i \in \mathcal{G}^{-}$ is uninstalled or dismantled
Π_{G}	generation expansion investment budget (€)
Π_{L}	transmission expansion investment budget (€)
σ	annual weighting factor (h)

Primal variables

$c_{\mathrm{o}}^{(t)}$	operating cost associated with given values of upper- and middle-level variables for year t (€)
$c_{\mathrm{op}}^{(t)}$	operating cost related to given values of upper-level variables for year t (€)
$c_{\mathrm{op},\nu}^{(t)}$	it corresponds to $c_{\mathrm{op}}^{(t)}$ at iteration ν
$f_k^{(t)}$	line k power flow for year t (MW)
$f_{k,\nu}^{(t)}$	line k power flow for year t (MW) at iteration ν
$g_i^{(t)}$	power production of generating unit i for year t (MW)
$g_{i,\nu}^{(t)}$	power production of generating unit i for year t (MW) at iteration ν
$p_j^{(t)}$	power consumption of demand j for year t (MW)
$p_{j,\nu}^{(t)}$	power consumption of demand j for year t (MW) at iteration ν
$r_j^{(t)}$	load shed of demand j for year t (MW)
$r_{j,\nu}^{(t)}$	load shed of demand j for year t (MW) at iteration ν
$\boldsymbol{u}^{(t)}$	vector of random or uncertain parameters ($u_i^{\mathrm{G}(t)}$,$u_j^{\mathrm{D}(t)}$) for year t, including maximum generation capacities and loads (MW)
$\boldsymbol{u}_{\nu}^{(t)}$	vector of random or uncertain parameters ($u_{i,\nu}^{\mathrm{G}(t)}$,$u_{j,\nu}^{\mathrm{D}(t)}$) for year t at iteration ν
$x_k^{(t)}$	binary variable representing new line k construction at the beginning of year t
$\widetilde{x}_k^{(t)}$	line k status (*existing* vs *no existing*) at the beginning of year t
$\widetilde{x}_{k,\nu}^{(t)}$	line k status at the beginning of year t and iteration ν
$y_i^{(t)}$	binary variable representing new generator i construction at the beginning of year t
$\widetilde{y}_i^{(t)}$	generator i status (*existing* vs *no existing*) at the beginning of year t
$\widetilde{y}_{i,\nu}^{(t)}$	generator i status at the beginning of year t and iteration ν
$\theta_n^{(t)}$	bus n voltage angle for year t (radians)
$\theta_{n,\nu}^{(t)}$	bus n voltage angle for year t (radians) at iteration ν

TEP pertains to a welfare-focused agent (ISO), while GEP relates to profit-focused producers.

1.2. Literature review

Transmission and generation expansion planning have been extensively studied areas from the time power systems began to operate [3]. In recent years, these problems have been widely researched and analyzed from different viewpoints, such as: solution method, reliability, electricity market, uncertainty, environmental impact, the modeling approach, from the time horizon viewpoint, time frames, among others [4]. State-of-the-art transmission planning is introduced in [5], where different contributions are classified by the solution method, treatment of the planning horizon, by considering the electrical sector restructuring, and the tools for developing planning models. A review of generation expansion planning techniques in the face of growing uncertainty is presented in [6]. In this document, the literature review is split into several categories: (a) the modeling approach, (b) algorithms, (c) time frames, (d) time scope, and (e) others, which makes it easier to discuss the contribution this paper has made.

The main difficulty of transmission and generation expansion planning problems is taking decisions with the great amount of uncertainty associated with different factors [7]. Moreover, the integration of renewable energy into the generation mix increases uncertainty on the generation side [8]. The stochastic programming techniques enable an optimal decision to be found in problems involving uncertainty data [9]. In order to incorporate (i) demand, (ii) the equivalent availability factor of the generating plants and (iii) the transmission capacity factor of the transmission lines as random events, stochastic programming and probabilistic constraints are used in [10] in a new model for generation and transmission expansion. Uncertainty associated with intentional attacks on the transmission network has been put forward in [11] by using a stochastic programming problem with recourse, while [12] utilizes the Monte Carlo simulation and scenario reduction technique to create scenarios that simulate random characteristics of system components and load growth. Chance-constrained optimization is a type of stochastic programming which handles the stochasticity of the problem by specifying a confidence level at