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A convex chance-constrained model for reactive power planning

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ABSTRACT

This paper presents a new approach for long-term reactive power investment planning and operation using a multiperiod mixed-integer stochastic convex model, where load uncertainty is also included. The risk of not meeting the load with a certain level of confidence due to a reactive power deficit is represented by chance constraints. Tap settings of under-load tap-changing transformers are modeled as a set of mixed-integer linear equations. Existing and new discrete and continuous reactive power sources are modeled. These type of problem is challenging and have never been studied before. The proposed model is applied to the CIGRE-32 electric power system.

The notation used throughout the text is described in Nomenclature. Operators $\mathbb{E}$ and $\mathbb{P}$ are used as expectation and probability measures, respectively.

Introduction

Reactive power planning (RPP) is considered as one of the most complex problems for researchers, transmission system operators (TSOs) and transmission planners. RPP, which is essential to maintain the voltage profile and stability of the system, affects the active power transmission capability of a network significantly and can be modeled as a large-scale optimization problem with many uncertainties. Currently, most power system problems are not simply economic but imply a coordination between economic and security requirements. In a market environment, installing, sizing and commissioning new power plants, as well as the closure of old power plants and maintenance tasks, are basically made at the discretion of the power companies. These and other uncertainties such as future load, policy regulation and regional energy exchanges are considered uncertainties of RPP and are very difficult to manage. Therefore, all these uncertainties bring new challenges to the RPP problem.

Electric power systems, regardless of whether they are regulated or deregulated, are exposed to uncertainty due to a number of variations and random events. Uncertainty can be introduced by means of random variables using stochastic programming. The need to consider uncertainty has led to different types of stochastic programming models, which have been developed over time to serve different applications. One kind of stochastic programming is called chance-constrained programming (CCP), where randomness is incorporated into the model by means of a probabilistic measure [1]. CCP has also been applied to different types of problems with uncertainty in power systems planning and operation. In CCP some of the constraints are required to have specified levels of probability.

Literature review

The RPP problem can be cast as a large-scale mixed-integer nonlinear programming problem, which has been solved by several optimization, heuristic and meta-heuristic techniques.

One of the most widely used optimization techniques for the solution of the deterministic reactive power planning problem has been successive linear programming [2].The problem has been solved using a combination of successive linear programming with

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Nomenclature

Indexes
k, k' index for buses of the system
e index for buses containing existing discrete and continuous reactive power sources
i index for candidate buses to install new discrete and continuous reactive power sources
l index for **PQ** buses, also known as load buses
p index for **PV** buses, also known as generation buses
sl index for the **Slack** bus
j index for $\{\mathbf{PV} \cup Slack\}$ buses
n index for transmission lines
m index of branches containing under-load tap-changing transformers
h index for steps of under-load tap-changing transformers
t index for periods
ω index for scenarios

Sets
$\mathbf{\Omega_K}$ set of buses of the system
$\mathbf{\Omega_E}$ set of buses containing existing discrete and continuous reactive power sources
$\mathbf{\Omega_C}$ set of candidate buses to install new continuous reactive power sources
$\mathbf{\Omega_D}$ set of candidate buses to install new discrete reactive power sources
$\mathbf{\Omega_{PQ}}$ set of **PQ** buses
$\mathbf{\Omega_{PV}}$ set of **PV** buses
$\mathbf{\Omega_{SL}}$ *Slack* bus
$\mathbf{\Omega_N}$ set of branches containing transmission lines
$\mathbf{\Omega_M}$ set of branches containing under-load tap-changing transformers
$\mathbf{\Omega_H}$ set of steps of under-load tap-changing transformers
$\mathbf{\Omega_T}$ set of periods
$\mathbf{\Omega_\omega}$ set of scenarios

Constants
$K^c_{FC_{i,t}}, K^c_{FR_{i,t}}$ investment costs of capacitive and inductive continuous reactive power sources in bus i and period t
$K^d_{FC_{i,t}}, K^d_{FR_{i,t}}$ investment costs of capacitive and inductive discrete reactive power sources in bus i and period t
$K^c_{VC_{i,t}}, K^c_{VR_{i,t}}$ operating costs of capacitive and inductive continuous reactive power sources in bus i and period t
$K^d_{VC_{i,t}}, K^d_{VR_{i,t}}$ operating costs of capacitive and inductive discrete reactive power sources in bus i and period t
$K^{ELNS}_{l,t}$ cost of the expected load not served (ELNS) because of a reactive power deficit in bus l and period t
$NB^{\max}_{C_i}, NB^{\max}_{R_i}$ maximum number of new discrete capacitive and inductive reactive power sources in bus i
$NB^{\max}_{CE_e}, NB^{\max}_{RE_e}$ maximum number of existing discrete capacitive and inductive reactive power sources in bus e
NS_m number of steps of the under-load tap-changing transformer in branch m
$P_{G_{p,t}}$ active power produced by generation unit p in period t
$P_{Dl,t}(\omega), Q_{Dl,t}(\omega)$ active and reactive load in bus l, period t and scenario ω
$Q^{\min}_{G_j}, Q^{\max}_{G_j}$ lower and upper capacity limits of generator j
$Q^{\max}_{C_i}, Q^{\max}_{R_i}$ upper capacity limits of new continuous capacitive and inductive reactive power sources in bus i
$Q^{\max}_{CE_e}, Q^{\max}_{RE_e}$ upper capacity limits of existing continuous capacitive and inductive reactive power sources in bus e
REG_m regulating transformation of the under-load tap-changing transformers in branch m
r_t annual interest rate in period t
$SBCE_e, SBRE_e$ size of existing discrete capacitive and inductive reactive power sources in bus e
SBC_i, SBR_i size of new discrete capacitive and inductive reactive power sources in bus i
$S^{\max}_n$ complex total power capacity limit of line in branch n
$V^{\min}_k, V^{\max}_k$ upper and lower voltage magnitude in bus k
α level of confidence used in the calculation of ELNS
$\beta_{l,t}$ ELNS limit in bus l and period t
$\pi(\omega)$ probability of scenario ω
$\epsilon_\delta(\omega)$ allowable error in the voltage angle constraint
Tap^{min}_m, Tap^{max}_m minimum and maximum tap settings of the under-load tap-changing transformer in branch m

First-stage variables
$p_{Gsl,t}$ active power generation in the *slack* bus in period t
$q_{Gj,t}$ reactive power generation of existing generation units in bus j and period t
$uc_{i,t}, ur_{i,t}$ binary decision variables for continuous reactive power sources: 1 if they are built in bus i and period t, 0 otherwise
$udc_{i,t}, udc_{i,t}$ binary decision variables for discrete reactive power sources: 1 if they are built in bus i and period t, 0 otherwise

Second-stage variables
$d_{k,t}(\omega)$ auxiliary variable related with the convex formulation of the AC power flow equations in bus k, period t and scenario ω
$ntap_{m,t}(\omega)$ tap position of the under-load tap-changing transformer in branch m, period t and scenario ω
$nbc_{i,t}(\omega), nbr_{i,t}(\omega)$ number of new discrete capacitive and inductive reactive power sources in bus i, period t and scenario ω
$nbce_{e,t}(\omega), nbre_{e,t}(\omega)$ number of existing discrete capacitive and inductive reactive power sources in bus e, period t and scenario ω
$p_{k,t}(\omega), q_{k,t}(\omega)$ active and reactive power injections in bus k, period t and scenario ω
$qc_{e,t}, qr_{e,t}$ capacitive and inductive reactive power generation of existing continuous power sources in bus e and period t
$qc_{i,t}(\omega), qr_{i,t}(\omega)$ capacitive and inductive reactive power generation of new continuous reactive power sources in bus i, period t and scenario ω
$s_{n,t}$ complex power flow through transmission line n and period t
$v_{k,t}(\omega), \delta_{k,t}(\omega)$ voltage magnitude and angle in bus k in period t
$\eta(\omega)$ auxiliary variable related to scenario ω used to calculate ELNS

heuristic, meta-heuristic, and decomposition techniques. Examples of these are: binary search algorithms, special heuristics and branch and bound [3], genetic algorithms [4], sensitivity analysis [5] and branch and bound and genetic algorithms [6]. A dynamic model considering multiple load levels is solved using successive linear programming and Benders decomposition in [7]. Sequential quadratic programming is proposed in [8], minimizing active power losses.