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Multi-period stochastic security-constrained OPF considering the uncertainty sources of wind power, load demand and equipment unavailability

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ABSTRACT

The uncertainty sources of the intermittent generation and load demand as well as transmission line unavailability threaten the security of power systems. In this paper, to treat these uncertainties, a new stochastic optimal power flow considering the security constraints is proposed. A scenario generation method is also presented to model the uncertainties of wind generations and load demands considering their correlations. In the proposed model, the uncertainties are coped with through combination of optimal here-and-now and wait-and-see decisions. The effectiveness of the proposed model is shown on the well-known IEEE 24-bus test system. Higher effectiveness of the proposed model compared with four deterministic methods and one other stochastic method to determine procured reserve and 'after-the-fact' conditions is numerically illustrated. Additionally, the impact of the number of scenarios on the performance of the proposed model is evaluated by means of a sensitivity analysis. It has also been shown that the scenarios generated considering correlations have more smooth variations and can more effectively capture the uncertain behavior of load.

1. Introduction

Continuously increasing fossil fuel prices and atmosphere pollution as well as depletion of fossil fuel energy sources causes that renewable green energy sources have a growing share in supplying human's energy demands. Wind power is the most widely used renewable energy source in today's electricity generation. However, the uncertain and variable nature of wind generation together with traditional load forecasting error dramatically add the uncertainty sources and seriously challenge the optimal and secure operation of power systems [1]. Moreover, load growth, change of generation pattern caused by renewable resources, and increased energy transactions in the environment of competitive electricity markets increase the probability of overload in the electric network, which in turn jeopardize the system security [2]. Therefore, power system operators should make secure their systems against different unexpected generation/load patterns and network configurations. However, the uncertainty sources seriously challenge the applicability of traditional optimal power flow (OPF), which usually determines the operating state of power system assuming only its most likely operating conditions [3].

A few approaches have been presented in the literature to handle wind/load uncertainties in OPF models. The most important methods include probabilistic techniques [4], chance constrained programming [5], robust optimization [6], and stochastic programming [7]. Probabilistic methods tend to present the probability density function characteristics of desired outputs instead of one aggregated optimal solution. In chance constrained programming, constraints are satisfied with some predetermined probabilities. Chance constrained programming leads to nonlinear problems, which are not easy to handle. While robust optimization (RO) is a professional uncertainty handling method for non-deterministic optimization problems involving low-frequency and non-random uncertain variables, setting the appropriate uncertainty sets for RO may be a challenging task. Moreover, when the uncertainty sources of non-deterministic optimization problem are in the form of high-frequency uncertain variables, RO may not necessarily be able to effectively employ the whole statistical information of these variables. Apart from the foregoing problems, none of the mentioned research works considers the required preventive/corrective actions together with their associated costs, e.g., when the so-called N − 1 criterion is employed.

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Nomenclature

Sets and indices

B Set of network buses
Bg Bus-generator incidence matrix
Bt Bus-branch incidence matrix
C_N Set of non-islanding branch contingencies
c Branch contingency index
G Set of conventional generating units
g Index of conventional generating units
(i, j) Network bus indices
N_t The set of scenarios including the same realizations of the uncertain variables from hour 1 to hour
S Set of wind generation and load demand (W&L) scenarios
S' Set of trial scenarios
s, s_1, s_2 W&L scenario indexes
s' Trial scenario index
T Number of time steps in the scheduling horizon
t Index of time steps in the scheduling horizon
w Index of wind generating units

Parameters

$C^U_{t,g}, C^D_{t,g}$ Offer cost for up and down spinning reserve capacity by conventional unit g for hour t, respectively
F^{max}_{ij} Maximum flow limit of the branch connecting bus i and bus j
P^{min}_g, P^{max}_g Minimum and maximum generation limits of conventional unit g
$Pd^s_{t,i}$ Specified load demand of bus i in hour t and W&L scenario s, obtained through the scenario generation method
$PPw^s_{t,w}$ Specified generation for wind unit w in hour t and W&L scenario s, obtained through the scenario generation method
$R^{D,max}_{t,g}, R^{U,max}_{t,g}$ Maximum available down/up spinning reserve capacity of conventional unit g in hour t
UR_g, DR_g Up and down ramp rate limit, respectively
$V_{t,i}$ Load shedding cost for load i in hour t
x_{ij} Branch reactance between buses i and j
$\rho^E_{t,g}, \rho^U_{t,g}, \rho^D_{t,g}$ Offer cost for energy and deployed up and down spinning reserve by conventional unit g for hour t, respectively
$\lambda^U_{t,g}, \lambda^D_{t,g}$ Offer cost of conventional unit g for up and down generation shift in hour t, respectively
$\pi_c, \pi_s, \pi_{s'}$ Probability of contingency c, W&L scenario s, and trial scenario s', respectively

Variables

$F^s_{ij,t}, F^{s,c}_{ij,t}$ Power flow of the branch connecting bus i and bus j in hour t and W&L scenario s, in normal state and post-contingent state c, respectively
$P_{t,g}$ Scheduled generation of conventional unit g for hour t in normal state
$Pc^{s,c}_{t,g}$ Generation of conventional unit g in hour t, W&L scenario s, and post-contingent state c
$Pn^s_{t,g}$ Generation of conventional unit g in hour t, W&L scenario s, and normal state
$Ps^{s,c}_{t,i}$ Load shed of bus i in hour t, W&L scenario s, and post-contingent state c
$Pw^s_{t,w}$ Scheduled generation of wind unit w in hour t, W&L scenario s and normal state
$Pw^{s,c}_{t,w}$ Scheduled generation of wind unit w in hour t, W&L scenario s and post-contingent state c
$R^U_{t,g}, R^D_{t,g}$ Scheduled up and down reserve capacity of conventional unit g for hour t, respectively
$rc^{U,s,c}_{t,g}, rc^{D,s,c}_{t,g}$ Up and down reserve of conventional unit g in hour t, W&L scenario s, and post-contingent state c, deployed in addition to $rn^{U,s}_{t,g}, rn^{D,s}_{t,g}$, respectively, to cope with the contingency
$rn^{U,s}_{t,g}, rn^{D,s}_{t,g}$ Deployed up and down reserve of conventional unit g in hour t, W&L scenario s, and normal state, respectively, to cope with the W&L uncertainty
$gmr^{U,s'}_{t,g}, r^{D,s'}_{t,g}$ Total deployed up and down reserve of conventional unit g in hour t of trial scenario s'
$\Delta^{U,s'}_{t,g}, \Delta^{D,s'}_{t,g}$ Up and down generation shift of conventional unit g in hour t of trial scenario s', respectively
$Ps^{s'}_{t,i}$ Load shed of bus i in hour t of trial scenario s'
$Po^{s'}_{t,g}$ Generation of conventional unit g in hour t of trial scenario s'
$SPw^s_{t,w}$ Wind spillage of wind unit w in hour t, W&L scenario s and normal state to cope with the W&L uncertainty
$SPw^{s,c}_{t,w}$ Wind spillage of wind unit w in hour t, W&L scenario s and post-contingent state c, deployed in addition to $SPw^s_{t,w}$ to cope with the contingency
$\theta^s_{i,t}, \theta^{s,c}_{i,t}$ Voltage angle of bus i in hour t and W&L scenario s, in normal state and post-contingent state c, respectively

Inclusion of security constraints in the OPF problem leads to a more effective operation tool, usually known as the security constrained OPF (SCOPF). However, SCOPF is a more computationally complex optimization problem than OPF as it includes significantly more constraints. Different numerical optimization approaches, such as iterative-based solution methods [8], Benders decomposition [9], and parallelism techniques [10], have been proposed to handle the high dimensional SCOPF problem. Although various evolutionary algorithms have also been presented for solving SCOPF [11], these methods usually suffer from high computation burden to solve SCOPF for practical power systems. Moreover, the effectiveness of evolutionary algorithms depends on the initial population and selected values for their settings, while usually there is no analytical method to fine-tune these settings for solving SCOPF.

The main contributions of this paper can be summarized as:

1) A new multi-period security-constrained stochastic optimal power flow (MPSC-SOPF) model taking into account load and wind generation uncertainties as well as uncertainties associated with equipment unavailability is presented. The proposed model, based on two-stage stochastic programming, determines the optimal operating point and required corrective actions considering probability of different load/wind generation scenarios and contingency states. By simultaneously handling the corrective actions required for coping with different uncertainty sources (including the uncertainties of load and wind as well as the uncertainties of equipment unavailability), a more effective reserve procurement strategy is achieved. This is the key issue which distinguishes the proposed MPSC-SOPF model from the previous stochastic OPF models which determine the corrective actions required for handling different uncertainty sources separately.
2) A new scenario generation method composed of Latin hypercube sampling (LHS) and rank correlation is proposed. The proposed method can model the correlations between wind generations