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Stochastic multi-objective security-constrained market-clearing considering static frequency of power system

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A B S T R A C T

This paper deals with frequency control following the occurrence of a contingency. The frequency is considered by modelling the generators' governor performance during pre- and post-contingency intervals, load frequency dependency, rate of change of frequency (Rocof) of generators and Rocof of the system and frequency-based reserve scheduling. The time intervals following the occurrence of a contingency are formulated in detail to analyze the influential factors in static frequency. A novel index besides the frequency dependent social welfare function and frequency excursion index has been proposed to control the frequency and the Rocof during post-contingency intervals. The proposed stochastic multi-objective model incorporates the precise scheduling of reference power setting of generators based on participants' bids for energy and reserve services. The eventual goal of the proposed approach is to help the ISOs to make a trade-off concurrently between system frequency profile, Rocof and total operating cost to operate the power system securely in an economically efficient manner. This multi-objective programming formulation is simulated through two case studies; a three-bus system scheduled over 1 h and the IEEE Reliability Test System over 24 h, solved by means of lexicographic optimization and ε-constraint method.

1. Introduction

In competitive electricity markets worldwide, maintaining security constitute the first precedence ahead of economic issues similar to the traditional power systems. Security involves a series of control actions designed to keep the system operating at standard frequency and voltage when contingencies occur. These control actions, with the aim of covering contingencies, are implemented by ancillary services; therefore such services are essential for ensuring the secure operation of the power system [1–5]. One of the applications of reserve services to system security preservation is frequency control. The frequency control following the occurrence of an outage is especially important in small isolated power systems because the ratio of the power produced by the lost generator to the total remaining generation may be high. Balancing and frequency control are performed by using different resources available in related interval [6,7]. After the outage of a dispatched generator, the output power of remaining synchronous dispatched generators increase instantaneously by releasing their kinetic energy to establish the balance between generation and demand. The transformation of kinetic energy into electrical energy results in deceleration of the involved generators and finally, a system frequency drop. In a system with less synchronous inertia, the system frequency falls faster after an outage which means higher rate of change of frequency (Rocof) [8]. Obviously, a comprehensive frequency dependent model of power system is required to keep the safe range of frequency excursion and Rocof. It should be noted that in the event of any contingency, enough generation and demand flexibility relative to the predisturbance levels should be made available, therefore, considering the effects of frequency and Rocof on reserve services scheduling, frequency must be considered during short-term (day ahead) security-constrained market clearing to control system frequency and limit the Rocof in an economically efficient manner [6,7,9].

Different approaches have been developed to consider power system security and reserve scheduling, but a few researchers have studied the static frequency following the occurrence of a contingency. In [10], the authors have proposed an economic dispatch methodology which allows the cost of providing enough reserve to avoid load shedding following the outage of any given unit to be calculated and assessed against the cost of load shedding. In [11], the optimal energy and reserve dispatch problem as a mixed integer linear program has been outlined. In [12], a joint energy and reserve market model that incorporates demand-side reserve offers has been proposed. Ref. [13] has addressed a reliability-constraint market clearing algorithm that incorporates the scheduling of spinning reserve according to a hybrid deterministic/probabilistic reliability

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Nomenclature

Indices

i, j indexes of buses running from 1 to N_{bus}
h, h' indexes of hours running from 1 to N_h
blk index of bid blocks for energy running from 1 to N_{blk}
g index of generators running from 1 to N_g
d index of demands running from 1 to N_d
int index of intervals, could be equal to *pre* (pre-contingency interval), *pri* (primary interval), *ter* (tertiary interval)
ud index used to show up ($ud = up$) or down ($ud = dn$) states
s index of scenarios running from 1 to N_s

Parameters

$p^{(s)}$ probability of scenario s
$\alpha_{Eg}^{(i,g,blk,h)}$ bid price of generator g located at bus i for block blk at hour h
$\alpha_{Ed}^{(i,d,h)}$ bid price of demand d located at bus $i$during hour h
$p_{g\min}^{(i,g)}$ lower limit of real power of generator g located at bus i
$p_{g\max}^{(i,g)}$ upper limit of real power of generator g located at bus i
$p_r^{(i,g)}$ rated power of generator g located at bus i
$\alpha_{Rg}^{(i,g,ud,\text{int},h)}/\alpha_{Rd}^{(i,d,ud,\text{int},h)}$ up or down Bid price of generator/demand g/d located at bus i for reserve during interval int at hour h
$voll^{(i,d,h)}$ value of lost load of demand d located at bus i
t_b base value of time.
f_{ref} reference frequency of power system
$f_{\min}^{(\text{int})}/f_{\max}^{(\text{int})}$ minimum/maximum allowable frequency during interval *int*
$k^{(s,i,g,h)}$ binary parameter defining the availability of generator g located at bus i if equals 1 or unavailability if equals 0 at hour h under scenario s
$b^{(i,j)}$ susceptance of line located between buses i and j
$p_{l\max}^{(i,j)}$ upper real power limit of line located between buses i and j
$p_{d\max}^{(i,d,\text{int},h)}/p_{d\min}^{(i,d,\text{int},h)}$ upper/lower real power limit of demand d located at bus i during interval *int* at hour h
$blk\max^{(i,g)}$ upper MW limit of each offered block of generator g located at bus i for energy
$r^{(i,g)}$ droop (regulation) parameter of generator g located at bus i
$H^{(i,g)}$ inertia constant of generator g located at bus i
$p_{0g}^{(i,g)}$ power output of generator g located at bus i at hour 0
$u_0^{(i,g)}$ commitment state of generator g located at bus i at hour 0
$ramp_{up-h}^{(i,g)}/ramp_{dn-h}^{(i,g)}$ ramp-up/down limit of generator g located at bus i between consecutive hours
$ramp_{st-h}^{(i,g)}/ramp_{sh-h}^{(i,g)}$ startup/shutdown ramp limit of generator g located at bus i between consecutive hours
$ramp_{up-tp}^{(i,g)}/ramp_{dn-tp}^{(i,g)}$ ramp-up/down limit of generator g located at bus i between primary and tertiary intervals
$ramp_{st-tp}^{(i,g)}/ramp_{sh-tp}^{(i,g)}$ startup/shutdown ramp limit of generator g located at bus i between primary and tertiary intervals
$ramp_{up-pp}^{(i,g)}/ramp_{dn-pp}^{(i,g)}$ ramp-up/down limit of generator g located at bus i between pre-contingency and primary intervals
$D^{(i,d)}$ frequency dependency of demand d located at bus i
$\Delta f_{\max}^{(\text{int})}$ maximum allowable frequency excursion of the power system during interval *int*
$Maxrocof_g^{(i,g)}$ maximum allowable Rocof of generator g located at bus i
$Maxrocof_{sys}$ maximum allowable Rocof of system

Variables

$p_{gb}^{(s,i,g,\text{int},blk,h)}$ the power block blk of generator g located at bus i during interval *int* at hour h under scenario s
$u^{(s,i,g,\text{int},h)}$ binary variable shows the commitment state of generator g located at bus i during interval *int* at hour h. it equals 1 if the generator is committed; equals 0 otherwise
$R_g^{(i,g,ud,\text{int},h)}/R_d^{(i,d,ud,\text{int},h)}$ up/down reserve of generator/demand g/d located at bus i during interval *int* at hour h
$ELNS^{(i,d,h)}$ expected load not served of demand d located at bus i during hour h
$f^{(s,\text{int},h)}$ system frequency during interval *int* at hour h under scenario s
$Rocof_{g,\max}^{(s,i,g,h)}$ maximum rate of change of frequency of generator g located at bus i under scenario s at hour h
$Rocof_{sys,\max}^{(s,h)}$ maximum rate of change of frequency of system at hour h under scenario s
$p_g^{(s,i,g,\text{int},h)}/p_m^{(s,i,g,\text{int},h)}$ electrical/mechanical output/input power of generator g located at bus i during interval *int*at hour h under scenario s
$p_{gov}^{(s,i,g,\text{int},h)}$ governor output command of generator g located at bus i during interval *int*at hour h under scenario s
$p_d^{(s,i,d,\text{int},h)}/p_{d-f}^{(s,i,d,\text{int},h)}$ frequency independent/dependent demand of customer d located at bus i during interval *int* at hour h under scenario s
$\theta^{(s,i,\text{int},h)}$ voltage angle of bus i during interval *int* at hour h under scenario s
$LSH^{(s,i,d,\text{int},h)}$ involuntarily shed load of demand d at bus i during interval *int* at hour h under scenario s
$p_l^{(s,i,j,\text{int},h)}$ power flow of the line located between buses i and j during interval *int* at hour h under scenario s
$p_{ref}^{(s,i,g,\text{int},h)}$ the reference power setting of generator g located at bus i during interval *int* at hour h under scenario s
s_l the LaPlace variable
t time variable

Functions

F_1 total operation cost index
F_2 frequency excursion index
F_3 Rocof index
$C_E^{(i,g,h)}$ energy cost function offered by generator g located at bus i for hour h
$C_{Rg}^{(i,g,h)}/C_{Rd}^{(i,d,h)}$ reserve cost function offered by generator/demand g/d located at bus i for hour h
$B^{(i,d,h)}$ benefit function bid by demand d located at bus i for hour h
F_{gov}/F_{tur} governor/prime mover transfer function

Sets

G_i set of generators located at bus i
C_{ij} set of lines which are connected to bus i by the susceptance $b^{(i,j)}$

Definitions

$\Delta_1 x^{(\text{int})} = x^{(pri)} - x^{(pre)}$, $\Delta_2 x^{(\text{int})} = x^{(ter)} - x^{(pri)}$, $\Delta_3 x^{(\text{int})} = x^{(ter)} - x^{(pre)}$ where x is any of the described variables
Δx deviation of variable x from its previous value
x^* the optimal value of the variable x