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A stochastic security constrained unit commitment model for reconfigurable networks with high wind power penetration

Ehsan Nasrolahpour*, Hassan Ghasemi

School of Electrical and Computer Engineering, University of Tehran, Iran

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ABSTRACT

Wind power generation continues to grow at a high rate around the world. Variability and uncertainty are inherent characteristics of wind power generation resulting in technical and economical challenges for power system operators. In order to maintain security of the system, significant amount of wind generation resources may be curtailed. Also large amount of reserve is required to compensate for the uncertainty associated wind generation in real-time operation. To ensure the security of the system, these reserves must be distributed with a careful consideration of existing transmission constraints. In this paper, a stochastic security constrained unit commitment (SCUC) model for reconfigurable transmission networks is introduced and utilized to facilitate wind power integration. The proposed model benefits from network reconfiguration to minimize energy, spinning reserve, wind curtailment and load shedding costs while accommodating transmission constraints. The corresponding optimization problem is formulated and solved based on Benders decomposition method. The performance of the proposed model is investigated in details using a 6-bus and IEEE 118-bus test systems.

1. Introduction

The installed wind power is growing worldwide with a fairly good pace. Although wind generation integration is accompanied by numerous benefits, their energy output is characterized by variability and uncertainty. Therefore, its high penetration poses a risk to secure and economic operation of power systems [1].

In order to accommodate sudden load-generation mismatches in daily operation, spinning/non-spinning/operating reserves are required. As the level of wind power generation increases, the required spinning reserve would increase to maintain system security [2]. With high amount of variable and uncertain wind power, traditional unit commitment with deterministic spinning reserve requirements is inadequate. Therefore, alternative power system scheduling methods, which are capable of taking stochastic nature of wind power into account, are required [3].

In order to provide a more realistic evaluation of spinning reserve requirement, different methods have been presented considering uncertainty caused by non-dispatchable units. In [4,5], probabilistic reliability indices are used as constraints to limit risk at a predefined risk level. Further extension of [5] is presented in [6] to consider wind in operation planning. Determining a predefined risk level is a difficult problem, which is the main drawback of these references.

In [7], reliability indices are used to determine optimal spinning reserve, which is then employed in the unit commitment problem. The wind generation uncertainty is considered later in [8]. However, the network constraints are not considered in the formulation of these references. In [9], a method is presented for joint energy and reserve allocation considering wind generation uncertainty. In [3], error forecast in wind generation is modeled as normal distribution and then divided into discrete amounts, which are then used to calculate optimal spinning reserve requirement and expected energy not supplied. Ref. [10] provides a comprehensive review about modeling and issues of joint energy and reserve market.

Wind resources are usually located far away from load centers. Therefore, this may cause congestion in transmission lines. Also, it seems plausible to expect that transmission line congestion may be exacerbated due to variability and uncertainty of wind power generation [11]. This condition can be worsened particularly when the wind penetration in the power systems is such that it accounts for a major portion of total generation [12].

In the long run, high wind penetration in power system can create a greater focus on new transmission needs, thus leading to transmission expansion [12] or employment of FACTS devices to facilitate wind power integration [13]. Since transmission expansion usually takes longer time compared to building wind power

* Corresponding author.
E-mail address: e.nasrolahpour@ece.ut.ac.ir (E. Nasrolahpour).

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i, j	index of bus
g	index of generator unit
d	index of load consumer
w	index of wind unit
k	index of line
c	index of wind generation scenario
t	index of time
$\hat{}$	index of given variables

Sets

n_g, n_w	set of conventional generators and wind plants, respectively
n_d	set of loads
n_{op}, n_{cl}	set of lines that are open/closed, respectively
n_t	set of scheduling hours
n_c	set of scenarios
Q_g	mapping of the set of generator units into the set of buses
Q_w	mapping of the set of wind units into the set of buses
Q_d	mapping of the set of loads into the set of buses

Variables

u_{gt}	status of Unit g at time t
PG_{gt}	active power generation of conventional generator g at time t
δ_{it}	phase angle of Bus i at time t
PL_{kt}	active power flow of Line k at time t
$SRup_{gt}, SRdn_{gt}$	system up and down-spinning reserve of Unit g at time t
$\Delta P^{up}_{gtc}, \Delta P^{dn}_{gtc}$	spinning reserve activated of Unit g in real-time at time t for scenario c
$X^{on}_{gt}, X^{off}_{gt}$	on- and off-time of Unit g at time t
PW_{wt}	wind power generation of Unit w at time t
WS_{wt}	wind curtailment of Unit w at time t
LS_{dtc}	load shedding of consumer d at time t for scenario c
z_{kt}	binary variable which represents the status of Line k (0: open, 1: closed) at time t
α	mismatch at each iteration of sub problem in Benders decomposition method
$\varphi_{gt}, \mu_{gt}, \zeta_{gt}, \varrho_{gt}, \pi_{kt}$	marginal values associated with u_{gt}, PG_{gt}, $SRup_{gt}$, $SRdn_{gt}$ and z_{kt}

Parameters

$Supc_{gt}, Sdnc_{gt}$	start up and shut down cost of Unit g at time t
$PG^{\max}_g, PG^{\min}_g$	upper and lower limits for active power generation of Unit g
$\delta^{\max}_i, \delta^{\min}_i$	upper and lower limits for phase angle at Bus i
$PL^{\max}_k$	maximum capacity for active power flow at Line k
T^{on}_g, T^{off}_g	on- and off-time limits for Unit g
PD_{dt}	active power demand of consumer d at time t
P_{tc}	probability of wind power at time t for scenario c
R^{up}_g, R^{dn}_g	ramp up and down limits of Unit g
MSR^{up}_g, MSR^{dn}_g	maximum up and down-spinning reserve limits of Unit g
F_{max}	maximum number of allowed switching actions
$\rho^{PG}_{gt}, \rho^{SRup}_{gt}, \rho^{SRdn}_{gt}$	supply offer price for energy, up and down-spinning reserve of Unit g at time t
ρ_w, ρ^{rtp}_{gt}	cost of curtailed wind power of Unit w and real-time energy price of Unit g at time t
$VOLL_d$	value of lost load for consumer d
$SPA^{\max}_l$	maximum standing phase angle difference of Line l
M	big positive multiplier
m	number of iterations
n	number of all buses
ϵ	convergence tolerance
B	susceptance matrix

plants [1,14], temporary solutions are required in day-ahead operations to avoid frequent congestion [15].

In [16], compressed air energy storage as a solution to store energy is proposed and its effects on transmission congestion management, wind curtailment and other operational issues are studied. In [17], storage capability of plug-in electric vehicles is utilized to mitigate the variability of wind power resources and to reduce grid operation costs in the context of stochastic security constrained unit commitment (SCUC). In [18], demand response program has been implemented to cover transmission limit violations caused by wind generation uncertainty.

In [19], a stochastic unit commitment is presented, which considers wind power integration in power systems. It shows how generation schedule will be changed with wind generation uncertainty. However, required reserve to cover wind uncertainty is assumed to be fixed percentage of total wind power generation.

In [20,21], in order to deal with stochastic characteristics of wind generation in unit commitment problem, a chance constrained programming is applied. This method is a class of stochastic optimization, which requires that a constraint should hold with a specied probability, rather than all possible realization.

In [22], the stochastic security constrained unit commitment problem with a high penetration of wind energy is solved by constrained ordinal optimization method. The basic idea is to sample a large number of candidate unit commitment solutions and then use an accurate model on a small selected subset to find good enough unit commitment solutions.

The operation coordination of hydro and wind power opens up new possibilities to both producers [23]. In [24], coordination of pumped-storage hydro and wind units is presented based on the application of stochastic SCUC. Fast response of pumped-storage hydro units provide system reserves by switching between generation, pumping, and idling modes as well as changing their dispatches in corresponding modes. In [25], coordination of wind and nuclear power plant in the context of a hydrogen economy has been studied. When transmission line congestion limits the sale of electricity produced in the electricity market, the electricity can be converted in hydrogen and sold to the hydrogen market.

Among various system security constraints, transmission limits are of paramount importance and hence are carefully respected in power system operation.

Higher wind penetration into power systems are increasingly putting stress on transmission systems. While the wind power forecast may not show any violation in transmission systems, actual wind power generation may deviate from the forcasted value due to forecast errors that may lead to congestion in real-time. This challenge resulting in wind curtailment and/or deviation from optimal dispatch which would lead to higher costs; when the system is congested, expensive generation units instead of units that were determined by market scheduler will be dispatched in real-time operation. These underscore the importance of considering wind generation uncertainty in transmission congestion studies. Therefore, one should be aware that a system with enough spinning reserve to cover power mismatches in the case of suffering contingencies and/or wind forecast errors, may not be able to utilize the available reserve due to bottlenecks in the transmission system. In other words, for a system with high wind penetration, beside large spinning reserve, the system operator has to ensure that the reserve resources are distributed in the system such that they can be