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Spinning reserve quantification by a stochastic–probabilistic scheme for smart power systems with high wind penetration

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ABSTRACT

This paper introduces a novel spinning reserve quantification scheme based on a hybrid stochastic–probabilistic approach for smart power systems including high penetration of wind generation. In this research the required spinning reserve is detached into two main parts. The first part of the reserve is procured to overcome imbalances between load and generation in the system. The second part of the required spinning reserve is scheduled according to the probability of unit outages. In order to overcome uncertainties caused by wind generation and load forecasting errors different scenarios of wind generation and load uncertainties are generated. For each scenario the reserve deployed by different components are taken account as the first part of the required reserve which is used to overcome imbalances. The second part of the required reserve is based on reliability constraints. The total expected energy not supplied (TEENS) is the reliability criterion which determines the second part of the required spinning reserve to overcome unit outage possibilities. This formulation permits the independent system operator to purchase the two different types of reserve with different prices. The introduced formulation for reserve quantification is also capable of managing and detaching the reserve provided by responsive loads and energy storage devices. The problem is formulated as a mixed integer linear programming (MILP) problem including linearized formulations for reliability metrics. Obtained results show the efficiency of the proposed approach compared with the conventional stochastic and deterministic approach.

1. Introduction

Environmental concerns and increasing costs of fossil fuels have lead to the increase of using wind generation in power systems in the last decade. According to [1] the contribution of wind generation will reach 20% of the total energy of the U.S in 2030. This penetration of wind generation can even increase due to the low operation cost of these sources and reduced amount of environmental pollution [2,3]. However considering the intermittent and volatile operation of wind sources and the errors for wind generation and demand forecasting, imbalances can be caused between generation and demand. Therefore additional reserves have to be predicted to provide an acceptable level of reliability for the customers for smart power systems.

On the other hand sudden unit outages can also jeopardize the reliability and lead to load curtailments. Many system operators use deterministic criteria to determine the required amount of spinning reserve which is usually based on the capacity of the largest unit or a coefficient of the total load. Although this approach provides a high level of reliability for the system however it increases the costs of spinning reserve [4]. In order to obtain a compromising solution for the level of reliability and reserve costs the random behavior of system components have to be considered [5]. Hence the traditional unit commitment using deterministic reserves is not suitable anymore and new approaches have to be developed regarding stochastic characteristics of generation, demand, and units.

Unit commitment with reserve optimization was first presented in [6] by a Lagrangian relaxation method. However wind generation was not accounted in this work. In [7] probabilistic reserve criteria such as loss of load probability (LOLP) and expected load not served (ELNS) are used to specify the required amount of spinning reserve formulated as a MILP problem. Reference [8] commits more reserve in order to overcome wind uncertainties. In [9] a framework is presented for spinning reserve estimation for a microgrid. A cost/benefit analysis is used is [10,11] which uses spinning reserve levels as constraints for the unit commitment problem. In [12,13] according to a set of contingencies and involuntary load curtailment the objective function is calculated for contingencies and normal operations. However, only a set of contingencies holding higher probabilities are studied. In [14]

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Nomenclature

i	thermal generation unit index
w	wind generating unit index
k	energy storage devices index
sg	production mode of energy storage system
sc	charging mode of energy storage system
e	energy responsive load index
r	reserve responsive load index
t	hour
s	scenario
NG	set of total generation units
NW	set of total wind producers
NK	set of total energy storage devices
NE	set of total energy responsive loads
NR	set of total reserve responsive loads
NL	set of total buses
NS	set of total scenarios
NT	set of total hours
$v_k^{sg(sc)}$	binary variable specifying production (storage) mode for energy storage device
$P_k^{sg}(t)$	generated power by energy storage device (MW)
$P_k^{sc}(t)$	storing power by energy storage device (MW)
$A_k(t)$	energy remained in the energy storage device (MW h)
$RU(RD)$	ramp up (down) limit (MW)
$DRRU$	reserve demand response for load and generation imbalances (MW)
$DRRO$	reserve demand response for unit outages (MW)
$Ar_k(t,s)$	price of reserve up deployment by energy storage devices for unit outages imbalances ($/MW h)
$LS_l(t,s)$	amount of load curtailed (MW)
$WS_w(t,s)$	amount of wind power curtailed (MW)
$P_w(t)$	generation of wind units (MW)
cu_r	price of reserve provided by responsive loads for load and generation imbalances ($/MW h)
co_r	price of reserve provided by responsive loads for unit outages ($/MW h)
v	wind speed (m/s)
v_{ci}	cut in speed (m/s)
c	scaling factor
v_r	rated speed (m/s)
v_{co}	cut of speed (m/s)
L	mean value of load forecasting errors
σ	standard deviation of load forecasting errors
b_i, c_i	cost coefficients of generators
$u_i(t)$	commitment status of thermal units
$P_i(t)$ (MW)	generation of thermal units (MW)
γ_k^{sg}	production cost of energy storage device ($/MW h)
γ_k^{sc} ($/MW h)	storage cost of energy storage device ($/MW h)
π_s	probability of each scenario
γ_i^{ruw}	price of reserve up deployment by thermal units for load and generation imbalances ($/MW h)
γ_i^{rdw}	price of reserve down deployment by thermal units for load and generation imbalances ($/MW h)
$ruw_i(t,s)$	up reserve deployed for thermal units for load and generation imbalances (MW)
$rdw_i(t,s)$	down reserve deployed for thermal units for load and generation imbalances (MW)
γ_i^{rudc}	price of reserve up deployment by thermal units for unit outages ($/MW)
$ruc_i(t,s)$	up reserve deployed for thermal units for unit outages (MW)
γ_k^{ruw}	price of reserve up deployment by energy storage devices for load and generation imbalances
γ_k^{rdw}	price of reserve down deployment by energy storage devices for load and generation imbalances
γ_k^{rudc}	production cost of energy storage device
$VOLL_l(t)$	value of loss of load ($/MWh)
$WSC_w(t)$	price of wind curtailment ($/MWh)
D	total load (MW)
$A_k(t,s)$	remained energy in the storage device for the reserve market dedicated to unit outages (MW h)

simulated annealing (SA) was used to assess the required spinning reserve according to LOLP and expected unserved energy (EUE). In [15] IPSO algorithm is used to solve the unit commitment problem considering probabilistic reserve but in this work a certain level for the reliability index is not specified. In [16] a stochastic optimization framework is presented for scheduling energy and reserve in a smart distribution systems. But this work does not consider unit outages and their probability. Hence the required reserve is only calculated to eliminate unbalances in the system caused by renewable sources and demand forecasting errors.

In the recent years responsive loads and energy storage systems have been integrated into power systems in order to enhance the economic and secure operation of these systems. The literature of using responsive loads and energy storage devices in smart power systems continue to grow [17–20]. Energy and reserve demand response programs have been developed in many countries in the recent years [21–23]. In [23,24] demand response models are introduced for energy and reserve markets however reliability constraints are not used in these works to determine the required amount of reserve. In Ref. [25] a portion of spinning reserve is provided by demand response programs. But in this work renewable sources are not included in the day ahead scheduling. Ref. [26] only uses demand response programs in energy markets. Electrical vehicles are used in [27–29] as a source of providing the required reserve with a performance similar to responsive loads.

On the other hand energy storage units can provide the required level of reliability with lower costs by storing energy when the total energy is more than the required amount and produce energy at the required time. Also the stored amount of energy can be a reliable source to be deployed in the case of unit outages [30]. Ref. [31] presents a security constrained unit commitment scheme with compressed air energy storage systems. But in this work wind power uncertainty and unit outages are neglected.

In this research a novel spinning reserve quantification approach is presented for a smart power system including demand response providers, energy storage devices and high penetration of renewable energy according to the required amount of reliability. The proposed formulation indicates that how much reserve has to be dedicated to imbalances caused by wind generation and load forecasting errors and how much reserve has to be bought by the system operator for unit outages according to their outage replacement rates. The problem is formulated in the form of a two stage stochastic programming which is solved by a MILP method which assures obtaining near global solutions. For each scenario the expected energy not supplied (EENS) is calculated and the expected amount of 24 h EENS (TEENS) for all scenarios has to be beneath a determined amount. In this paper two types of reserves are defined. (1) Reserves predicted for eliminating imbalances of energy in the system (imbalance reserve). (2) Reserves specified to overcome energy shortages caused by unit outages (reliability reserve). For each of these reserves different prices are set.