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The impact of energy storage modeling in coordination with wind farm and thermal units on security and reliability in a stochastic unit commitment

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ABSTRACT

The environmental concerns and restrictions of fossil fuel resources have led to the deployment of wind power installation. Due to the uncertain nature of wind speed, high penetration of wind power may threaten system reliability and security. Energy storage systems (ESSs) are considered to be a viable solution to this problem. In this study, a stochastic security constrained unit commitment (SCUC) problem is solved in the presence of wind and ESS units. The main concern of this paper is to study the impact of the proposed ESS model on the security and reliability of the system. To assess the reliability of a power system, the expected unserved energy (EUE) for line outage and demand underestimation contingencies is evaluated. The SCUC problem is solved by a scenario-based method incorporated with the Benders decomposition technique to mitigate congestions from power lines and provide feasibility and optimality of the solution in all the scenarios. The performance of the proposed approach has been evaluated using the 6-bus and 39-bus standard power systems. Simulation results demonstrated the economic advantages of the proposed model, while the security constraints are satisfied. Moreover, the impact of energy storage modeling on the EUE in post-contingency circumstances is discussed.

1. Introduction

The environmental emission caused by fossil-fuelled resources and their limited reserves have persuaded countries to design promotional policies for utilizing renewable energy resources and accelerate investments. In result, renewable energy resources are further involved in producing electrical energy [1]. Wind energy is one of the fastest-growing renewable energy sources (RESs) [2]. However, wind energy production may often swing by 20% of the wind farm capacity [5] because of its highly uncertain nature [3,4]. In an electric power system with a large amount of wind power (approximately more than 20% of total power generation), its inherent and significant uncertainty can potentially cause severe difficulties to power system operation [6]. For instant, the wind power forecast is an integral part of the electricity supply systems, and forecasting errors may cause power balance issues. The penalty factors method was proposed in Ref. [7] to diminish the risk of forecast error. Here, power shortage due to overestimation should be compensated by other alternate resources or load shedding should be executed. It is worth to note that excess power in underestimation conditions should be paid by the system operator (SO) to owner's DER. Many scholars have applied the demand response (DR) methodology using load control to balance total generation and demand in real time [8–11]. Price sensitivity in DR-based load forecasts with considerable wind penetration deteriorates forecasting accuracy, resulting in planning alternate backup generations [5]. Moreover, dynamic ramping is the potential capability of the power system which can be activated by applying stochastic programming for solving unit commitment (UC) problem. In a scenario-based stochastic programming, the reserved power capacity of a thermal unit which is determined according to the ramp up and down rates is programmed as a backup energy source for compensating power forecasting errors in the scenarios [12].

In state-of-the-art energy management strategies for RESs, energy storage systems (ESSs) are being increasingly used as beneficial technologies to improve power management of RESs [1,13,14]. ESSs cooperated with wind farms enhance both system reliability and maximum utilization of the available wind power in a real time

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Nomenclatures

Variables

$Es_{st,t}$	Stored energy in storage *st* at hour *t*
$I_{g,k}$	On/off status indicator (1 or 0) for thermal unit *g* at hour *k*
$Is_{st,k}$	Charge/discharge status indicator (1 or 0) of storage unit *st* at hour *k*
Fl_l	Power flow of transmission line *l*
$Fl_l^{\max}$	Maximum power capacity of transmission line *l*
$P_{g,k}$	Generation power of thermal unit *g* at hour *k*
$Psc_{st,k}$	Charging power of storage unit *st* at hour *k*
$Psd_{st,k}$	Discharging power of storage unit *st* at hour *k*
$Pw_{jw,k}$	Generation power of wind farm *jw* at hour *k*
st	Index of storage unit number
sn	Index of scenario number
$SU_{g,k}$	The Startup cost of gth thermal unit at hour *k*
$X_{g,k}^{on}$ and $X_{g,k}^{off}$	On/off counter of thermal unit *g* at hour *k*
μ, λ	Dual variables for thermal units
$\mu c, \lambda c, \mu d, \lambda d$	Dual variables for energy storage units
τ_{sn}^{k}	Transition cost from the main solution into scenario *sn*
b	Index of bus number
g	Index of thermal generation unit number
jw	Index of wind farm number
k	Index of periods of time (hour)
l	Index of transmission lines
q	Index of piecewise linearized segments
ψ	Index of contingency

Constants

$FL_l^{\max}$	Maximum power capacity of transmission line *l*
$KP_{b,g}$	Generation bus indicator matrix
KD_b	Load bus indicator matrix
$KST_{b,st}$	Storage bus indicator matrix
MU_g/MD_g	Minimum up/down time for thermal unit g
Nb	Number of buses
NG	Number of generation thermal units
NH	Number of time periods (hours)
NS	Number of scenarios
PD_k	Power demand at hour k
$Pw_{gw,k}^{f}$	Forecasted wind power for wind farm *jw* at hour *k*
$P_g^{\max}/P_g^{\min}$	Maximum/minimum power generation limits for thermal unit g
$Ps_{chrg}^{\max}/Ps_{chrg}^{\min}$	Maximum/minimum charging power limits for energy storage *st*
$Ps_{dis}^{\max}/Ps_{dis}^{\min}$	Maximum/minimum discharging power limits for energy storage *st*
$P_{b,k}^{net}$	Net power injected to bus *b* at hour *k*
Rup_g/Rdn_g	Ramp up/down rates for thermal unit *g*
$Rup_{st}^{chrg}/Rdn_{st}^{chrg}$	Ramp up/down rates for energy storage unit *st* in charging mode
$Rup_{st}^{dis}/Rdn_{st}^{dis}$	Ramp up/down rates for energy storage unit *st* in discharging mode
$SF_{l,b}$	Shift factor of bus *b* to line *l*
$\alpha_g, \beta_g, \gamma_g$	Coefficients of the cost function for *gth* thermal unit
η_{st}^{dis} and η_{st}^{chrg}	The efficiency of the storage unit in discharging and charging modes
ρ_{sn}	The probability of scenario *sn*
$(\bullet)^{sn}$	Variables statement in scenario *sn*

environment [15,16]. Therefore, ESSs are able to absorb the excess power and supply the power shortage in underestimation and overestimation conditions, respectively. A comprehensive study on the coordination of various ESS technologies with wind farms was carried out in Ref. [17]. In Refs. [18–22], a coordination between ESSs and wind farms was discussed subject to decrease wind curtailments.

From a practical point of view, contingencies such as line outages and power forecasting errors in real time may give rise to major power imbalances and interruptions in power delivery and, consequently, threaten power system reliability. The reliability of a power system is interpreted as the ability of the system to satisfy the peak demand and withstand changes or contingencies. It is really important for power system operators to assess power system reliability in any circumstances. Therefore, based on the probability of each contingency occurrence, the expected value of the unserved energy in all the busses (EUE) is calculated as a parameter for reliability assessment in UC problem [23].

Since the power grid is being driven to operate more and more close to its security margin, considering security-related transmission constraints in unit commitment problem; that is, security-constrained unit commitment (SCUC) becomes indispensable in the newly deregulated power market [24,25]. However, the security constraint should be modeled and relaxed throughout the network for all time periods, even though it is rarely violated for special lines. In the literature, there are three different frameworks for applying the security constraint to the UC problem: direct, indirect, and decomposition-based methods. In the direct method, the security constraint along with other constraints are formulated in a unified frame. The main drawback of this approach is that it adds $2 \times (\text{time periods}) \times (\text{line numbers})$ constraints to the UC problem and consequently may hamper convergence [26]. The indirect method splits the SCUC problem into two separate stages. In the first stage, the network security constraints are omitted from the optimization problem and a feasible solution is achieved in the second stage by performing optimal power flow or security-constrained economic dispatch. Reducing computational burden significantly and convergence time are among the positive features of this approach. However, this procedure does not provide a mechanism within the first stage to optimize the generation distribution, thus leading to starting from an inferior point for finding a final feasible solution. As the third strategy, in Ref. [27], the Benders decomposition method was applied to the SCUC problem. It introduces a recursive procedure that decouples the SCUC into a master problem and a security sub-problem. By using Benders decomposition to control power flow of the deviated lines, constraints of the master problem are adjusted according to the results of the security sub-problem. In Ref. [28], the Benders decomposition method considered the line power flow and bus voltages only for a system with thermal units. A stochastic SCUC in the presence of wind farms was proposed in Ref. [5]. Due to the stochastic nature of wind energy, feasibility and optimality cuts were added into the master problem formulation. In Ref. [25], AC security constraints in a hydrothermal scheduling problem were considered using the