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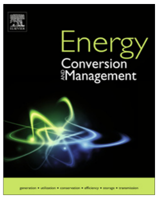

A stochastic framework for the grid integration of wind power using flexible load approach

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ABSTRACT

Wind power integration has always been a key research area due to the green future power system target. However, the intermittent nature of wind power may impose some technical and economic challenges to Independent System Operators (ISOs) and increase the need for additional flexibility. Motivated by this need, this paper focuses on the potential of Demand Response Programs (DRPs) as an option to contribute to the flexible operation of power systems. On this basis, in order to consider the uncertain nature of wind power and the reality of electricity market, a Stochastic Network Constrained Unit Commitment associated with DR (SNCUCDR) is presented to schedule both generation units and responsive loads in power systems with high penetration of wind power. Afterwards, the effects of both price-based and incentive-based DRPs are evaluated, as well as DR participation levels and electricity tariffs on providing a flexible load profile and facilitating grid integration of wind power. For this reason, novel quantitative indices for evaluating flexibility are defined to assess the success of DRPs in terms of wind integration. Sensitivity studies indicate that DR types and customer participation levels are the main factors to modify the system load profile to support wind power integration.

1. Introduction

The predominant share of conventional fossil fuel units in the electricity supply mix has increased concerns on climate change, energy security and price volatility. To address these concerns, many power systems have started changing their energy generation portfolios to include significant amounts of renewable energy resources [1]. Although most renewable energy resources have a dramatic installed capacity growth in the recent years, the development of wind power has enhanced much more, especially. The global installed wind generation capacity increased from 10 megawatts (MW) in 1980 to 282 gigawatts (GW) by the end of 2012 [2].

However, uncertain and non-dispatchable characteristics of wind power compared to other conventional plants may pose important challenges to power system operation. Highly intermittent nature of wind power may impair power system's balance between supply and demand and lead to system reliability endangerment as well as higher operation costs. Furthermore, ramping requirement of the system in the presence of wind generation is more than the case where no wind power is generated. In such situation, existing generation units must ramp up and down more frequently and operate in de-rated capacity. As a result, the average operating efficiency will be decreased [3].

On this basis, a challenge that system operators are facing with large-scale integration of wind power is how to cope with and mitigate the wind variability and forecast uncertainties. To address the mentioned challenges, several different studies have conducted on large-scale grid integration of wind power. In this regard, providing a more flexible power grid is a common aim that can be seen in all previous researches. To achieve that aim, several solutions are presented for power system operators in former publications which can be classified into three major categories:

(1) Utilizing energy storage technologies.
(2) Providing additional reserve capacity throughout electricity market and improving market mechanism, rules and structures.
(3) Using flexible demand side resources.

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Nomenclature

Indices

b	index of system buses
i	index of generating unit
l	index of transmission line
m	segment index for linearized fuel cost
n	segment index for linearized total incentive curve
s	index of scenarios
t, t'	index of hours
NSE_i, NSF_i	number of segments for the piecewise linearized emission and fuel cost curves of unit i
NS	number of segments for the piecewise linearized total incentive curve

Parameters

$AS_n(t)$	slope of segment n in linearized total incentive curve in hour t (MW h)
$C_i^e(m)$	slope of segment m in linearized fuel cost curve of unit i ($/MW h)
$d_0(t)$	initial electricity demand (MW)
C_{it}^{SR}	offered capacity cost of spinning reserve provision of unit i in hour t ($/MW)
C_{it}^{NSR}	offered capacity cost of non-spinning reserve provision of unit i in hour t ($/MW)
C_{it}^{re}	offered energy cost of spinning reserve provision of unit i in hour t ($/MW h)
C_{it}^{nre}	offered energy cost of non-spinning reserve provision of unit i in hour t ($/MW h)
$e_i(m)$	slope of segment m in linearized emission curve of unit i (kg/MW h)
ECC	environmental cost coefficient of pollutants ($/kg)
$E(t,t')$	elasticity of demand
$\underline{Em}_i$	lower limit on the emission cost of unit i ($/h)
$\underline{F}_i$	lower limit on the fuel cost of unit i ($/h)
LD_b	demand contribution of bus b (MW)
$P_i^{\min}/P_i^{\max}$	minimum/maximum output limit (MW)
RU_i/RD_i	ramp up/down (MW/h)
SU_i/SD_i	start-up/shutdown cost of unit i ($)
UT_i/DT_i	minimum up/down time (h)
$W_{st}^{\max}$	available wind power (MW h)
X_l	reactance of line l
η_d	customer participation level in DRPs
π_{FIT}	FIT incentive value ($/MW h)
π_{cur}	cost of wind power curtailment ($/MW h)
$\rho_0(t)$	initial electricity price ($/MW h)
ω_s	probability of wind power scenario s

Variables

$C_{EDRP}(t)$	cost of customer's participation in EDRP ($)
F_{lts}	power flow through line l in hour t of scenario s (MW)
I_{it}	binary status indicator of generating unit i in hour t
y_{it}/z_{it}	binary start-up/shutdown indicator of unit i in hour t
$P_{its}^e(m)$	generation of segment m in linearized fuel cost curve (MW h)
P_{bt}^{mod}	modified demand of bus b in hour t after implementing DR (MW)
P_{its}^{tot}	total scheduled power of unit i in hour t of scenario s (MW)
SR_{it}	scheduled spinning reserve of unit i in hour t (MW)
NSR_{it}	scheduled non-spinning reserve of unit i in hour t (MW)
sr_{its}	deployed spinning reserve of unit i in hour t of scenario s (MW h)
nsr_{its}	deployed non-spinning reserve of unit i in hour t of scenario s (MW h)
$q_{its}(m)$	generation of segment m in linearized emission curve (MW h)
$\upsilon_n(t)$	award of segment n in linearized total incentive curve in hour t ($/MW h)
W_{st}^{int}	integrated wind power in hour t of scenario s (MW h)
W_{st}^{curt}	curtailed wind power in hour t of scenario s (MW h)
δ_{bts}	voltage angle at bus b in hour t of scenario s (rad)

In a tremendous share of the previous researches utilization of a storage device alongside wind farms has been suggested. Rabiee et al. [4] review various storage systems for wind power applications. In addition, Jannati et al. [5] compare the ability of four different types of the energy storage systems to mitigate wind power fluctuations. Zafirakis and Kaldellis [6] propose an optimization model to determine the rated power and capacity of a Compressed Air Energy Storage (CAES) to accommodate high wind power penetration in remote island networks. A dynamic optimization model is presented by Loisel [7], which simulates the key role of CAES under two development scenarios for European Commission (EC) and French Transmission System Operator (RTE) by 2030.

Combined operation of wind-hydrogen based, wind-flywheel based, and wind-pumped based energy storage systems are discussed by [8–10], respectively. Also, applying a hydro power plant as a supplemental unit beside wind farms is another solution which is taken into consideration for reducing the intermittent impacts of wind generation [11].

Another set of papers have proposed new market structures to facilitate wind power integration. Weber [12] discusses some key feature of the short-term adjustments required by wind energy and the necessity of intraday markets. The obtained results of a realistic case related to Australian National Energy Market (NEM) have been outlined in [13] which investigate policy and market design to facilitate wind integration. Other studies such as [14–16] investigate additional reserve capacity requirements for reliable grid integration of wind power through electricity market environment, belonging to the second category. It is worthy to note that, application of deterministic approaches in wind-thermal scheduling problems is not effective due to the stochastic behavior of wind generation. Hence, many recent papers focused on stochastic programming approaches as it has exerted in [15,16].

The third group of researches includes flexible demand side resources such as Plug in Hybrid Electric Vehicles (PHEVs) and Demand Side Management (DSM) solutions, particularly Demand Response (DR). Electric Vehicles (EVs) have been proposed as an option to alleviate the diversity between the electricity supply and demand in systems with high penetration of wind power as emphasized in [17–19]. In addition to EVs, some papers investigated the major role of DR in compensating wind power uncertainties. The possible impacts of DR on power system operation with high penetration of wind power have been analyzed in [20,21]. Many researches have been investigated to detail the impacts of DR on wind integration. Sioshansi and Short [22] evaluate the effects of a price-based DR program on the usage of wind power. Precisely, the impacts of Real-Time Pricing (RTP) implementation on increasing both the percentage of load that is served by wind generation, and potential wind generation is examined. In the paper, DR is implemented under a RTP tariff considering own price elasticity, only. Demand side resources have been considered in the form of peak clipping and demand shifting units with application to wind integration [23,24]. Parvania and Fotuhi-Firuzabad [25]