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Transmission switching, demand response and energy storage systems in an innovative integrated scheme for managing the uncertainty of wind power generation

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ABSTRACT

This paper addresses the stochastic security constrained unit commitment (SSCUC) problem with flexibility resources for managing the uncertainty of wind power generation (WPG). Departing from the traditional flexibility resources such as the thermal units with fast up/down spinning reserves and transmission switching (TS), this paper explores also the use of demand response (DR) and energy storage (ES) systems in an innovative integrated scheme. The proposed scheme utilizes a stochastic optimization framework to coordinate the flexibility resources dealing with the uncertainty of WPGs and equipment failures. The stochastic optimization model is formulated as a mixed-integer linear programming (MIP), and this problem is large and computationally complex even for medium sized systems. Accordingly, we present a novel accelerating decomposition technique aimed at solving this problem and reducing the number of iterations and CPU time. Numerical simulation results on the modified 6-bus system and on large-scale power systems, i.e. IEEE 118 and 300-bus systems, clearly demonstrate the benefits of applying flexibility resources for uncertainty management and the efficacy of the proposed solution strategy for large-scale systems.

1. Introduction

1.1. Motivation and approach

One characteristic that sources of variable renewable generation such as wind, tidal, wave, solar, and run-of-river hydro have in common is having an output governed by atmospheric conditions. Especially, the wind power generation (WPG) may consequently be difficult to predict over some time scales [1]. Accordingly, the increasing penetration of WPG in recent years, a significant amount of wind power spillage (WPS) exists in practice. On the other hand, significant uncertainty and variability of high penetration of WPGs over shorter time scales can be problematic in power system operation.

One of the serious issues is how to keep increasing wind power penetration without endangering network reliability and security. Power system conditions will be more in danger when the uncertainty of high penetration of WPGs and equipment failures occurs simultaneously. In order to integrate the large penetrations of WPG without compromising the system security, more flexibility services are required to cope with the forecasted and expected changes in generation and system equipment failures.

Hence, the flexibility services provided by:

- ***Supply side* (*SS*):** Flexibility from the SS can be provided by up/down ramping capability or up/down-spinning reserve provided by this side (SSR).
- ***Storage Availability* (*SA*):** Storage units allow shifting the demand in time by storing electrical energy at the off-peak with low prices and high WPG periods and injecting it during peak hours with high prices and low WPG periods.
- ***Demand side* (*DS*):** The hourly DR can contribute to system flexibility through a number of actions, by lowering/increasing the peak/valley demand periods and shifting energy from high demand and low WPG to low demand and high WPG periods. In addition, the

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Nomenclature

A. Indices and Sets

$(\cdot)^s$ related to scenario s
g,w,e index for units, wind units and storage, respectively
$g(n)/w(n)$ set of units/winds connected to the bus n
$e(n)$ set of storages connected to the bus n
i,j energy blocks offered by (unit)/(load)
n bus index
k,b transmission line index
t time periods indices
$k(n,.)/k(.,n)$ set of line with n as the "to"/"from" bus
$\wedge$ Given variables/parameters

B. Constants

P_g^{max}/P_g^{min} max/min capacity of unit g
$X_{(\cdot),t-1}^{on}/X_{(\cdot),t-1}^{off}$ ON/OFF time of a demand at time t-1
$DT_{(\cdot)}/UT_{(\cdot)}$ minimum ON/OFF time of a demand
$UL_k^{(\cdot)}/UG_g^{(\cdot)}$ simulated (line k)/(unit g) outage status
P_k^{max} maximum power flow of line k
$P_{w,(\cdot)}^{(\cdot)}$ forecasted wind power output of unit w
π_s probability of scenario s
M separative factor; a large positive number
B_k admittance of line k
$\lambda_{i,g,(.)}^G$ marginal cost of the ith block of energy offer by unit g
$\lambda_{j,n,(.)}^D$ marginal benefit of the jth block of energy bid by demand n
C_n^{up}/C_n^{dn} cost of up/down spinning reserve of load n
C_g^{up}/C_g^{dn} cost of up/down spinning reserve of unit g
$DR_{(\cdot)}^{max}/DR_{(\cdot)}^{min}$ max/min curtailed demand
$DE_{(\cdot)}$ fixed hourly demand
ΔD_n pick-up or drop-off rate of demand n
$E_{(\cdot)}^{max}$ maximum energy change of a demand in the scheduling horizon
$D_{(\cdot),t}^{max}$ maximum hourly load
MSR_g^{up}/MSR_g^{dn} maximum up/down SR limits of unit g
$SR_n^{up,max}/SR_n^{dn,max}$ maximum up/down SR limits of demand n
$\overline{E}_e/\underline{E}_e$ Max/Min state of storage e
ρ_n/ρ_w VAlue of (lost load)/(wind power spillage)
$\overline{P}_e^c/\underline{P}_e^c$ max/min charge of storage e
$\overline{P}_e^d/\underline{P}_e^d$ max/min discharge of storage e
$\alpha_e^{c/d}$ charge/discharge efficiency of ES unit

C. Variables

$P_{g,(\cdot)}^{(\cdot)}/P_{e,(\cdot)}^{(\cdot)}$ power generation of (unit g)/(energy storage e)
$SR_{n,(\cdot)}^{up}/SR_{n,(\cdot)}^{dn}$ up/down spinning reserve of demand n
$SR_{g,(\cdot)}^{up}/SR_{g,(\cdot)}^{dn}$ up/down spinning reserve of unit g
$SU_{(\cdot)}/SD_{(\cdot)}$ startup/shutdown cost of a unit
$MP_{1,(\cdot)}^{(\cdot)}/MP_{2,(\cdot)}^{(\cdot)}$ slack variables
$WS_{(\cdot)}^{(\cdot)}/LS_{(\cdot)}^{(\cdot)}$ (Wind power spillage)/(load shedding)
$\Delta P_{i,(\cdot)}^{(\cdot)}/\Delta d_{j,(\cdot)}^{(\cdot)}$ corrective dispatch capability of a unit/demand at segment (ith)/(jth)
$\Delta R_{g,(\cdot)}^{(\cdot)}$ reserve deployed by unit g
$\Delta D_{n,(\cdot)}^{(\cdot)}$ reserve deployed by load n
$DR_{(\cdot)}/D_{(\cdot)}^{(\cdot)}$ (Demand Response)/(hourly demand)
$W_{(\cdot)}^{(\cdot)}$ objective function amount of the sub-problem
$p_{i,(\cdot)}/d_{j,(\cdot)}$ a (unit output)/(demand bid) at segment i/j. limited to $p_{i,g}^{max}/d_{j,n}^{max}$
$\Delta r_{i,(\cdot)}^{(\cdot)}/\Delta d_{j,(\cdot)}^{(\cdot)}$ corrective dispatch capability of a unit/demand at segment (ith)/(jth)
$P_{k,(\cdot)}^{(\cdot)}$ power flow of line k
$\theta_{k,(\cdot)}^{(\cdot)}$ phase angle of line k
$z_{(\cdot)}/u_{(\cdot)}$ binary variable for state of (line k)/(unit g)
$u_{n,(\cdot)}$ binary variable for demand n
$C_{e,(\cdot)}^{(\cdot)}$ state of charge of storage e, in %
$\lambda_{(\cdot)}^{(\cdot)},\mu_{(\cdot)}^{(\cdot)},\eta_{(\cdot)}^{(\cdot)},\vartheta_{(\cdot)}^{(\cdot)}$ $\psi_{(\cdot)}^{(\cdot)},\xi_{(\cdot)}^{(\cdot)},\gamma_{(\cdot)}^{(\cdot)},\zeta_{(\cdot)}^{(\cdot)}$ dual variables

D. Abbreviations

BD bender's decomposition
DR demand response
DS demand side
DSR demand side reserve
ES energy storage
MIP mixed-integer linear programming
NS network side
PSS proposed solution strategy
RER renewable energy resource
RMSE root mean square error
SA storage Availability
SS supply side
SSCUC stochastic security constrained unit commitment
SSR supply side reserve
TS transmission switching
WFE wind forecast error
WPG wind power generation
WPS wind power spillage
WSFE wind speed forecast error

DS flexibility can be fully utilized by up/down spinning reserve (DSR). Indeed, it contributes to lower the stress on highly inflexible base-loaded units (e.g., nuclear power plants) to reduce their generation levels.

– ***Network side* (*NS*):** The most common reasons for curtailment are insufficient transmission capacity local congestion, and excessive supply during off-peak periods. Network reconfiguration, using TS action, is the capability of the network to mitigate the congestion and distribute energy and reserve throughout the network in real-time and increase the utilization of wind power under uncertainty.

The term *flexibility* describes the ability of a power system to cope with variability and uncertainty while maintaining a satisfactory level of reliability at a reasonable cost, over different time horizons. This definition interprets flexibility from both technical and economic points of view. Technically, flexibility is required to cope with uncertainties and fluctuations in both generation and grid side. Economically, providing flexibility results in additional cost and this cost should be constrained within a reasonable range.

This paper proposes a stochastic SCUC model (SSCUC) which considers *cooperation of simultaneous flexibility resource options* including the hourly economic and emergency DR program, network reconfiguration by the TS action, ES system, up/down- spinning reserve provided by dispatchable units for minimizing the daily expected operation cost (EOC) under uncertainty condition. The day-ahead forecast errors of hourly WPG and random outages of generators and transmission lines are treated as uncertainties in this study. The solution to the original stochastic SCUC problem with the DR program in each load bus, the TS action, for all transmission lines, the ES system, and thermal generation flexibility, *simultaneously*, in such cases would be an intractable task