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Data-driven real-time power dispatch for maximizing variable renewable generation

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HIGHLIGHTS

- A novel real-time power dispatch framework for variable renewable generation (VRG) is developed.
- A data-driven approximation model is formulated to determine the do-not-exceed limits of VRG without parameter preselection.
- A data selection strategy is proposed to obtain the most relevant samples for DNE limit calculation.
- The proposed method has greater potential for improving VRG integration than the original do-not-exceed limit method.

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ABSTRACT

Traditional power dispatch methods have difficulties in accommodating large-scale variable renewable generation (VRG) and have resulted in unnecessary VRG spillage in the practical industry. The recent dispatchable-interval-based methods have the potential to reduce VRG curtailment, but the dispatchable intervals are not allocated effectively due to the lack of exploiting historical dispatch records of VRG units. To bridge this gap, this paper proposes a novel data-driven real-time dispatch approach to maximize VRG utilization by using do-not-exceed (DNE) limits. This approach defines the maximum generation output ranges that the system can accommodate without compromising reliability. The DNE limits of VRG units and operating base points of conventional units are co-optimized by hybrid stochastic and robust optimization, and the decision models are formulated as mixed-integer linear programs by the sample average approximation technique exploiting historical VRG data. A strategy for selecting historical data samples is also proposed to capture the VRG uncertainty more accurately under variant prediction output levels. Computational experiments show the effectiveness of the proposed methods.

1. Introduction

Large-scale variable renewable generation (VRG) is being integrated into the power grids for its economical and environmental benefits. In China, more than 90 GW of wind farms have been built and the wind power penetration rate is expected to reach 11% by 2020 [1]. In the United States, wind energy is expected to supply 20% of the electricity generation by 2030 [2]. Meanwhile, VRG brings significant challenges to power system operations owing to its inherent uncertainty and variability. Since it is difficult to forecast the availability of VRG accurately in advance, the traditional dispatch paradigm for conventional power sources would incur excessive VRG curtailment because it ignores potential transmission congestion and insufficient regulation capability of conventional units caused by VRG volatility. The curtailment levels in major U.S. regions have been up to 4% in the past years [2].

Recently, the power industry has launched initiatives to reduce wind curtailments by improving wind dispatchability. For example, the Electric Reliability Council of Texas (ERCOT) has redesigned market pricing and used faster generation schedules [3]. The Midcontinent Independent System Operator (MISO) implemented the Dispatchable Intermittent Resource protocol to perform an automatic process for wind curtailment [4].

Methodologies to promote VRG in power dispatch have also drawn much attention in the recent literature. To explore the impact of wind power uncertainty on power system scheduling, wind power uncertainty is described using scenario-based stochastic approach for unit commitment (UC) and economic dispatch (ED) in [5]. The multiple scenario approximation method is also employed to hedge the sub-hourly variability of renewable energy

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Nomenclature

Sets

$\mathcal{D}^{\text{hist}}$	index set of historical data of forecast errors of variable renewable generation (VRG)
$\mathcal{G}^{\text{CC}}$	index set of corrective control units
$\mathcal{G}^{\text{NCC}}$	index set of non-corrective control units
$\mathcal{G}^{\text{VRG}}$	index set of renewable energy generation (VRG) units
$\mathcal{G}_n^{(\cdot)}$	index set of $(\cdot)$-type units connected to bus n
$\mathcal{I}^{\text{bus}}$	index set of buses
$\mathcal{I}^{\text{line}}$	index set of transmission lines
$\mathcal{S}^{\text{DNE}}$	index set of data samples for the do-not-exceed (DNE) limit determination problem
$\mathcal{S}^{\text{OBP}}$	index set of data samples for the operating base point (OBP) optimization problem

Parameters and functions

$C_i(\cdot)$	generation cost of generation unit i
D_n	load demand at bus n
$e_j^{(k)}$	k-th sample of forecast error of VRG unit j
$F_l^{\max}$	transmission capacity of line l
LMP_j	locational marginal price at the bus connected to VRG unit j
N^{s}	number of selected samples
$P_i^{\min}$	minimum output of generation unit i
$P_i^{\max}$	maximum output of generation unit i
p_i^0	generation output of unit i in the current period
p_i^*	base point of generation unit i
$SF_{l,n}$	generation shift factor of line l to bus n
W_j^{f}	forecast available output of VRG unit j
$W_j^{\max}$	generation capacity of VRG unit j
ε	convergence tolerance
Δ_i	maximum corrective output adjustment of unit i

Decision variables

l_j	lower DNE limit of VRG unit j
p_i^{B}	OBP of generation output of conventional unit i
p_i^{C}	corrective dispatch output of conventional unit i
$\boldsymbol{s}$	slack variable
u_j	upper DNE limit of VRG unit j
w_j	generation output of VRG unit j
$z^{(k)}$	binary indicator variable that is equal to 0 if the k-th forecast error sample lies within the DNE limits and equal to 1 otherwise
$\alpha_j^{(m)}$	auxiliary binary indicator variable
$\beta_j^{(m)}$	auxiliary binary indicator variable

Random variables

$\tilde{v}_j$	coefficient that denotes the actual generation output of VRG unit j as a convex combination of the DNE limits
$\tilde{w}_j$	actual available output of VRG unit j

Acronyms

CCU	corrective control unit
DNE	do-not-exceed
ED	economic dispatch
ERCOT	electricity reliability council of texas
IO	interval optimization
LMP	locational marginal price
MILP	mixed-integer linear program
MISO	Midcontinent Independent System Operator
NCCU	non-corrective control unit
OBP	operating base point
RO	robust optimization
SAA	sample average approximation
UC	unit commitment
VRG	variable renewable generation

for stochastic UC problem in [6]. The accuracy of scenario-based stochastic optimization relies on the presumption of probabilistic distribution of random variables, which is difficult to describe accurately in practice. Alternatively, interval optimization (IO) method is used in [7] for operating strategy decision with wind power uncertainty, where interval numbers are employed to represent the variability of wind power. The IO method uses upper and lower bounds to describe the uncertain parameters, and derives optimistic and pessimistic solutions for satisfying the constraints under uncertainties. Wind power correlation is not effectively captured using such technique. Robust optimization (RO) is another option to formulate decision-making problems considering parameter uncertainty. In contrast to IO, the RO approach seeks the optimal solution that ensures the satisfaction of all constraints under any realization of uncertain parameters within the uncertainty sets. Given the possible realizations of uncertain parameters, the RO method yields an optimal solution that is robust to randomness, rather than ranges of solutions. In [8], two-stage RO is employed to model building energy scheduling considering chillers and ice thermal energy storage, and this method is shown to outperform the deterministic method. Ref. [9] proposes an RO-based wind power dispatch framework for look-ahead dispatch. In this framework, wind farms are scheduled by using allowable power generation intervals, within which the system security can be guaranteed, as their dispatch guidance. In [10], this framework is extended to real-time power dispatch while the affine control rules of automatic generation control units are addressed. Similar to the allowable power generation intervals in [9,10], the do-not-exceed (DNE) limit is introduced in [11] to describe the maximum ranges of VRG that can be accommodated by the system without causing reliability issues, and a two-step dispatch framework using the DNE limits is also proposed. At the first stage of this dispatch framework, a conventional ED problem is solved to procure the operating base points (OBPs) as dispatch targets for conventional units at the next period. At the second stage, DNE limits of VRG units are calculated based on fixed OBPs and are used as dispatch signals for VRG units at the next period.

Power dispatch frameworks based on dispatchable intervals for VRG in [9–11] have been reported to outperform the conventional ED approach in terms of wind integration improvement with reliability guarantee, but several issues prevent these approaches from being further improved. First, the range allocation among different VRG units relies on the choice of weights, which might be misleading due the following reason. The weight factors can be predefined according to the operators' preference [9,10] or based on the locational marginal prices (LMPs) [11]. However, these strategies may not yield weight coefficients that reflect the actual demand of VRG units for flexibility. For example, in the LMP-weighted range calculation, a high LMP at a bus could possibly indicate congestion at that bus; thus, allocating a wider DNE range for VRG units at that bus would not be very helpful. The DNE limits are likely to be misled by the inappropriate choice of weights, and the VRG output could consequently be curtailed unnecessarily. Second, in [11], the DNE limits are calculated with fixed OBPs of conventional units. Since the regulation capability of conventional units is affected by the OBPs, fixing the OBPs might unnecessarily restrict