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A coordinated dispatching strategy for wind power rapid ramp events in power systems with high wind power penetration

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A B S T R A C T

High wind power penetration poses a challenge for the dispatch of the power system when rapid ramp events occur. This paper proposes an optimal dispatching strategy against wind power rapid ramp events during peak load periods by coordinating generation units with different time intervals. Special attention is given to the definition of the wind power rapid ramp events considering operation conditions of the system. Then, the online prediction of wind power rapid ramp events and its influence on the spinning reserve procurement of the system is analyzed. Based on the principle of coordination among generation units with different time intervals, the optimal dispatch during peak load periods when wind power rapid ramp events occur is formulated as an optimization problem considering thermal generation units, the energy storage system, interruptible load and load shedding. To improve computational efficiency, the power output calculation of the generation units with different time intervals is decomposed. The results show that the proposed dispatching strategy is feasible for accommodating wind power rapid ramp events during peak load periods.

Introduction

High wind power penetration poses a great challenge to power systems [1–3]. During peak load periods, when wind power continues to decrease, the net load (load minus wind power) might be greater than predicted. If wind power decreases severely and a WRRE occurs, the net load may increase abruptly [4,5]. As the wind power penetration level keeps increasing [6,7], WRRE becomes a major threat to the power dispatch during peak load periods. WRRE increases the complexity of daily generation power scheduling. To make matters worse, the considerable prediction error of WRRE usually needs a power system to store high spinning reserves, thus increases the difficulty of peak load dispatching. If the power system is short of spinning reserve, or is unable to provide appropriate regulation strategy, WRRE periods cannot be ridden through successfully.

The issues regarding the WRRE definition, prediction, and dispatch strategy can be found in many existing research papers. Kamath [8] defined WRRE and investigated statistic characteristics of WRREs in different time intervals. In [9], the author also proposed a data mining algorithm based on the concept of WRRE. Zareipour et al. [10] classified several WRREs and applied the support-vector-machine method to predict them. Ortega Vazquez and Kirschen [11] proposed an offline method for the spinning reserve setting based on the provision cost and the availability benefit. Han and Gooi [12] investigated the impact of the decoupled conditions on the optimality of economic dispatch solutions.

Much of the existing research has focused on dispatch when the load and wind power fluctuated smoothly [13,14]. However, these conventional dispatching strategies cannot be adopted when WRRE occurs. For example, in [15–17], the spinning reserve demand of wind power is simplified to a constant in the dispatch model. However, a problem of such simplification that cannot be neglected is that when WRRE occurs during peak load period, the spinning reserve demand differs at different time levels. Thus, the spinning reserve procurement should be analyzed more precisely. In [18], wind power curtailment is used as extra spinning reserve. However, this technique cannot be used either when WRRE occurs during peak load periods because the wind power curtailment might further increase both the magnitude of WRRE and the steepness of the net load, intensifying the danger of the system operation.

With the technique development of power dispatch, multiple time interval dispatch has been put into practice under the coordination of the generation units with different time intervals.

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Nomenclature

Abbreviation

WRRE	wind power rapid ramp event
AGC	automatic generation control
BLO	base load off regulated
BLR	base load regulated
PDI	pre dispatch interval
ODI	online dispatch interval
TME	total magnitude error

Parameters

$P_{BLR,k}^{\max}$	maximum power output of BLR-AGC unit k
$P_{BLR,k}^{\min}$	minimum power output of BLR-AGC unit k
f_{BLO}^{m}	operation cost of BLO-AGC units at mth ODI
f_{IL}^{m}	operation cost of the interruptible load at mth ODI
f_{eps}^{m}	operation cost of the energy storage system at mth ODI
f_{lack}^{m}	power shortage cost at mth ODI
f_{LS}^{m}	load shedding cost at mth ODI
f_{Non}^{n}	the day-ahead schedule modification cost of non-AGC units at nth PDI
$P_{BLO,j}^{\max}$	maximum power output of BLO-AGC unit j
$P_{BLO,j}^{\min}$	minimum power output of BLO-AGC unit j
$P_{eps}^{\max}$	maximum discharging power of the energy storage system
$P_{eps}^{\min}$	minimum discharging power of the energy storage system
E_{eps}	the stored energy in the energy storage system before WRRE occurs
$P_{IL}^{\max}$	maximum of the available interruptible load
$k_{BLO,j}$	unit generation cost of BLO-AGC unit j
$u_{BLO,j}$	unit spinning reserve cost of BLO-AGC unit j
k_{IL}	unit cost of the interruptible load
k_{eps}	unit generation cost of the energy storage system
u_{eps}	unit reserve cost of the energy storage system
k_{lack}	unit cost of the power shortage
k_{LS}	unit cost of the load shedding
k_{Non}	unit cost of the total power adjustment of non-AGC units
$k_{Non,i}$	unit cost of the power adjustment of non-AGC unit i
r_j	the regulation rate of BLO-AGC unit j

Variables

$P_{BLO,j}^{m}$	power output of BLO-AGC unit j at mth ODI
$R_{BLO,j}^{m}$	upward reserve of BLO-AGC unit j at mth ODI
P_{IL}^{m}	the interruptible load value at mth ODI
P_{eps}^{m}	power output of the energy storage system at mth ODI
R_{eps}^{m}	upward reserve of the energy storage system at mth ODI
P_{lack}^{m}	power shortage of the system at mth ODI
ΔL_{shed}^{m}	the load shedding at mth ODI
$\Delta P_{Non,i}^{n}$	power adjustment of non-AGC unit i at nth PDI

Sets

G_{Non}	set of non-AGC units
G_{BLO}	set of BLO-AGC units
G_{BLR}	set of BLR-AGC units

According to regulation intervals and regulation response characteristics, generation units in the power system are usually divided into three types, i.e., non-AGC units, BLO-AGC units and BLR-AGC units. Non-AGC units usually consist of thermal generators with large capacities. The regulation rate of the non-AGC units is low, and the power output at each PDI (usually 30 min) follows the day-ahead schedules, which are economically optimal. The power output of the non-AGC units changes at the beginning of each PDI. BLR-AGC units mainly consist of hydro generators. BLR-AGC units have very fast regulation rates and they are capable of area control error regulation. The response time of the BLR-AGC units can be within 1 min. BLO-AGC units consist of special thermal generators which regulate faster than non-AGC units, but slower than BLR-AGC units. BLO-AGC units can adjust their power output at each ODI (usually 10 min). In a real power system, most of the generators are non-AGC units, some are BLO-AGC units, and only a very small portion are BLR-AGC units. In any case, only non-AGC units and BLO-AGC units can be dispatched. BLR-AGC units cannot be dispatched, and they are always auto-regulated according to the controllers. The optimal coordination of these generation units can improve the adjusting capability of the power system. However, currently very little research has discussed using the optimal coordinated dispatching strategy with different types of generators when WRRE occurs.

This paper proposes a dispatching strategy against WRREs during peak load periods by coordinating the non-AGC units, BLO-AGC units, BLR-AGC units and other dispatch sources with multiple time intervals. Under the condition that the regulation intervals of these generation units are quite different, a unified dispatch model with multi-time intervals is proposed in this paper. The model considers the coordination among BLR-AGC units, BLO-AGC units and non-AGC units. Based on the coordination of these generators, special resources that can be dispatched (such as interruptible load and the bulk energy storage system that is capable of fast regulation) are also included in the model. In order to procure enough spinning reserve against WRREs and to ensure the power balance of the power system, certain strategies such as margin utilization of BLR-AGC units and load shedding are also considered in the model.

Influence of WRRE on the peak load dispatch

Relationship between sequence number of PDI and ODI

In this paper, the time interval for PDI Δt is set to 30 min, and the time interval for ODI $\Delta\tau$ is set to 10 min. It means that one PDI corresponds to three ODIs. PDI and ODI are directly related to the dispatch interval of the non-AGC units and BLO-AGC units, respectively.

The number of segments for the online wind power prediction time length in the online dispatch interval and pre-dispatch interval are denoted as N_{on} and N_{pre}, respectively (e.g., if the time length of the online wind power prediction is 60 min, then N_{pre} is 2 and N_{on} is 6). N_{on} and N_{pre} satisfies:

$$\frac{N_{on}}{N_{pre}} = \frac{\Delta t}{\Delta\tau} \tag{1}$$

If the mth ODI is within the nth PDI in a day, then m and n satisfies:

$$n = \left(m\frac{\Delta\tau}{\Delta t}\right) m = 1, \ldots, \frac{T_{\text{day}}}{\Delta\tau} \tag{2}$$