Wind Power Ramping Product for Increasing Power System Flexibility

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***Abstract*—With increasing penetrations of wind power, system operators are concerned about a potential lack of system flexibility and ramping capacity in real-time dispatch stages. In this paper, a modified dispatch formulation is proposed considering the wind power ramping product (WPRP). A swinging door algorithm (SDA) and dynamic programming are combined and used to detect WPRPs in the next scheduling periods. The detected WPRPs are included in the unit commitment (UC) formulation considering ramping capacity limits, active power limits, and flexible ramping requirements. The modified formulation is solved by mixed integer linear programming. Numerical simulations on a modified PJM 5-bus System show the effectiveness of the model considering WPRP, which not only reduces the production cost but also does not affect the generation schedules of thermal units.**

***Index Terms*—Dynamic programming, spinning reserve, swinging door algorithm, unit commitment, wind power, wind power ramping products**

NOMENCLATURE

Parameters:

NI	Number of thermal units.
NW	Number of wind turbine generators.
NT	Number of time periods.
NB	Number of buses.
NL	Number of transmission lines.
t	Index for time periods, t=1, 2, …, NT.
i	Index for thermal units, i=1, 2, …, NI.
b	Index for buses, b=1, 2, …, NB.
w	Index for wind turbine generators, w=1, 2, …, NW.
$R_i^{\mathrm{up}},\ R_i^{\mathrm{dn}}$	Maximum ramp up/down capability of thermal unit i, in MW/min.
$WRU_{w,t},\ WRD_{w,t}$	Upward/downward wind power ramping product of wind turbine w during period t, in MW.
$\gamma_{i,t}^{\mathrm{sp}},\ \gamma_{i,t}^{\mathrm{ns}},\ \gamma_{i,t}^{\mathrm{reg}},\ \gamma_{i,t}^{\mathrm{rep}}$	Bidding price of spinning, non-spinning, regulation, and replacement reserve of thermal unit i during period t, in \$/MWh.
$\gamma_{i,t}^{\mathrm{up}},\ \gamma_{i,t}^{\mathrm{dn}}$	Bidding price of flexible up/down-ramping products of thermal unit i during period t, in \$/MWh.
$P_i^{\max},\ P_i^{\min}$	Max/min generation capacity of unit i, in MW.
$FRUR_t,\ FRDR_t$	Total flexible up/down ramping product requirement of thermal units during period t, in MW.

Variables:

$FRU_{i,t},\ FRD_{i,t}$	Scheduled flexible up/down ramping products of thermal unit i during period t, in MW.
$SP_{i,t},\ NS_{i,t},\ REG_{i,t},\ REP_{i,t}$	Spinning, non-spinning, regulation, and replacement reserve of thermal unit i during period t, in MW.
$p_{i,t}$	Dispatch of thermal unit i at the end of period t, in MW.
$u_{i,t}$	1 if unit i is scheduled on during period t and 0 otherwise.
ρ	Percentage of up/down-ramping product requirement accounting for spinning reserve requirement.

I. INTRODUCTION

The flexible ramping products have become a new area of interest for independent system operators (ISO) experiencing high renewable penetrations. For example, the California Independent System Operator (CAISO) proposes to design a market for the upward and downward flexible ramping products of thermal generators [1]. The purpose of flexible ramping products is to improve the market dispatch flexibility and address the operational challenges of maintaining power balance, as the variable outputs of renewable resources increase.

Xu and Tretheway [1] have designed up and down flexible ramping products to address operational challenges of maintaining power balance in the real-time dispatch. Wu *et al.* [2] modeled flexible up/down ramping capability of thermal units to respond to hourly load, and found that flexible ramping would reduce renewable energy curtailments. Navid *et al.* [3] suggested that existing generators of all types maximized the availability of their operational load-following ramp flexibility, and also suggested introducing new flexible ramp suppliers such as demand response. Wang *et al.* [4] assumed that the purpose of a flexible ramping product market was to manage the increasing load ramp events resulting from the growth in renewable energy, and illustrated that flexible ramping product could enhance market efficiency. Ela *et al.* [5] showed that an up ramp and down ramp product market could be estab-

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lished with renewable energy to cope with load ramps.

In this paper, we propose a wind power flexible ramping product (WPRP) to respond to the need for new ramping products that are being implemented by ISOs to ensure that sufficient ramping is available during real-time operations. The purpose of developing wind friendly flexible ramping products is to take advantage of the wind power ramps typically known for their negative characteristics: large fluctuations (significant increases or decreases) of wind power in a short time period. Key points in developing WPRP include: (i) how WPRP quantitatively impacts the up- and down-ramping product schedules and the production costs, and (ii) how WPRP behaves under different ramping product requirements. To address these challenges, we proposed a detection method to identify WPRP and present a modified Unit Commitment and Economic Dispatch (UCED) formulation considering WPRP on a simplified power system.

The organization of this paper is as follows. In Section II, a wind power ramping product detection method is briefly introduced. In Section III, the modified formulation including wind ramping products is presented. The experimental results are described in Section IV. Section V concludes the paper.

II. WIND POWER RAMPING PRODUCT DETECTION

The swinging door algorithm (SDA) is a data compression algorithm that was originally proposed by Bristol [6], and has been widely used in many areas. Figure 1 illustrates the SDA method for identifying ramping products in the power signal. A power value is compressed if a straight line drawn between the last stored power value and the next power value does not cause any intermediate point to fall outside the area partitioned by the up and down segment bounds; otherwise, a power value is kept and the last power value is set as the start of the next coming compression interval.

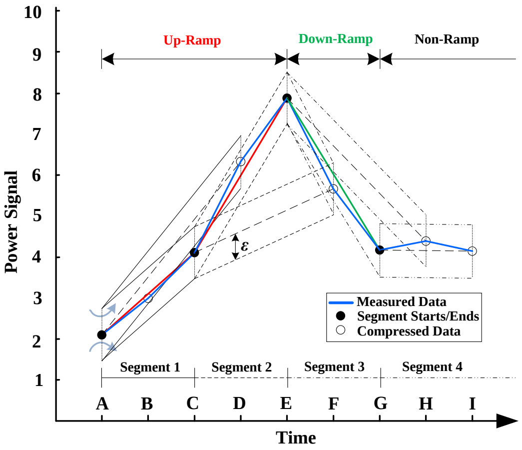


Fig. 1. The SDA for detecting wind power ramping product.

As shown in Fig. 1, Point B falls within the area ABC (Segment 1) and therefore is compressed; whereas, Point C falls outside the area ABCD and makes the compression process of the area ABC (Segment 1) terminate at Point C. Then the next segment (Segment 2) is started at Point C. Likewise, the other segments (Segment 2, 3, and 4) are generated. After compression, Points B, D, F, H, and I are all compressed. The only tunable parameter for SDA is the compression deviation, which is defined as the ‘swinging door width’, $\pm\varepsilon$.

When SDA is used to detect ramping products, some modification and improvements should be applied to this method. For example, there should only be one up-ramp in the area ABCDE in Fig. 1 through visual examination. This indicates that after the SDA segregation, adjacent segments could be combined or merged to optimize the SDA detection results. We use a dynamic programming algorithm to optimize the segments generated by SDA. Detailed descriptions of the optimized SDA can be seen from the References [7-9].

III. MODIFIED FORMULATION

Day-ahead scheduling, which considers the aforementioned ramping products of thermal units and wind power ramping product, is formulated as a mixed-integer linear programming (MILP) problem in this section.

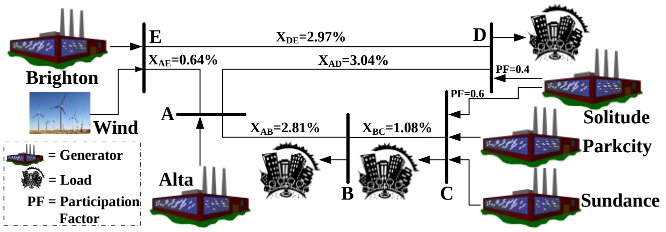


Fig. 2. PJM 5-bus system with variable wind added to bus E.

A. Objective Function

The objective function of traditional UC considers only the operation and start-up cost of generators over all periods of the scheduling horizon (usually 24 hours of the next day). In this section, we utilize the formulation proposed by CAISO to add the bid costs from the flexible ramping products [1] in thermal generators. The objective function consists of the operation cost, start-up cost, conventional reserve cost, and flexible ramping product cost. The piece-wise linear approximation of the cost curves of generators is utilized to retain an MILP formulation. The objective function is stated as:

$$\begin{aligned}\min \sum_{t=1}^{NT} \Bigg\{ \sum_{i=1}^{NI} & [C_{i,t}(p_{i,t}, u_{i,t}) + S_{i,t}(u_{i,t}, u_{i,t-1}) \\ & + \gamma_{i,t}^{\mathrm{sp}} SP_{i,t} + \gamma_{i,t}^{\mathrm{ns}} NS_{i,t} + \gamma_{i,t}^{\mathrm{reg}} REG_{i,t} + \gamma_{i,t}^{\mathrm{rep}} REP_{i,t} \\ & + \gamma_{i,t}^{\mathrm{up}} \cdot FRU_{i,t} + \gamma_{i,t}^{\mathrm{dn}} FRD_{i,t}] \Bigg\} \end{aligned} \tag{1}$$

B. Constraints

The objective function must be subject to a number of constraints, which are modified based on the constraints of CAISO. The regulation reserve is supplied in both the up and down operating directions with the same attributes whereas the spinning, non-spinning, and replacement reserves are supplied only in the up operating direction. The main modification includes ramping capacity limits, active power limits, and flexible ramping requirements, which are stated as:

Up-ramping capacity limit:

$$FRU_{i,t}+SP_{i,t}+NS_{i,t}+REG_{i,t}+REP_{i,t} \le$$

$$R_i^{\mathrm{up}}\times 60+M\times(2\text{-}u_{i,t-1}\text{-}u_{i,t})\quad \forall i,\ \forall t \qquad (2)$$

Down-ramping capacity limit:

$$FRD_{i,t}+REG_{i,t}\ \le\ R_i^{\mathrm{dn}}\times 60+M\times(2\text{-}u_{i,t-1}\text{-}u_{i,t})\quad \forall i,\ \forall t \qquad (3)$$

Active power maximum limit:

$$p_{i,t}+FRU_{i,t}+SP_{i,t}+NS_{i,t}+REG_{i,t}+REP_{i,t}\ \le\ P_i^{\max}\times u_{i,t} \quad \forall i,\ \forall t \qquad (4)$$

Active power minimum limit:

$$p_{i,t}\text{-}FRD_{i,t}\text{-}REG_{i,t}\ \ge\ P_i^{\min}\times u_{i,t}\quad \forall i,\ \forall t \qquad (5)$$

Upward flexible ramping requirement:

$$\sum_{i=1}^{NI} FRU_{i,t}+\sum_{w=1}^{NW} WRU_{w,t}\ \ge\ FRUR_t\quad \forall i,\ \forall t \qquad (6)$$

Downward flexible ramping requirement:

$$\sum_{i=1}^{NI} FRD_{i,t}+\sum_{w=1}^{NW} WRD_{w,t}\ \ge FRDR_t\quad \forall i,\ \forall t \qquad (7)$$

Additionally, each unit is subject to its own operating constraints, including minimum up and down time constraints and initial condition constraints [1]. The main contribution of this work is made in formulating and examining constraints (6) and (7), where wind power up- and down-ramping products are involved.

IV. EXPERIMENTAL RESULTS

In this section, we perform numerical simulations using the Flexible Energy Scheduling Tool for Integration of Variable Generation (FESTIV) [10] on a modified PJM 5-bus system. FESTIV is a multi-timescale steady-state power system operations simulation tool and uses five scheduling sub-models: the day-ahead security-constrained unit commitment (DASCUC), the real-time security-constrained unit commitment (RTSCUC), real-time security-constrained economic dispatch (RTSCED), automatic generation control (AGC), and security-constrained reserve pickup (SCRPU). The proposed MILP formulation is solved using MATLAB and the General Algebraic Modeling System (GAMS). The modified PJM 5-bus system, shown in Fig. 2, has five transmission lines, one wind plant, five thermal units, and three load clusters. Generators' detailed data for the PJM 5-bus system are shown in Table I. The participation factor of Solitude on Bus C is 60% and 40% on Bus D. The capacity of the wind plant is 125 MW. Hourly reserve and ramping product requirements are shown in Table II, where the percentage of up- and down-ramping product requirements accounting for spinning reserve requirements is ρ=0.6. For the sake of simplicity, there are no regulation, replacement, and non-spinning reserve schedules in this study. In Table III, the total daily load is 19,250 MWh.

The following three cases are studied to illustrate the impact of the increased wind penetration level, impact of increased up- and down-ramping product requirements with and without WPRP, and the impact of increased wind penetration level on up- and down-ramping product schedules.

Case 1: Impact of the increased wind penetration level on thermal unit operations.

Fig. 3 illustrates how the increased wind penetration levels impact the operations of thermal units with ρ=0.6. It is seen that the outputs of generators Solitude and Sundance are very similar even though the wind penetration increases. However, the outputs of generators Alta, Parkcity, and Brighton are significantly decreased. For the generator Brighton, the decrease is 103 MWh (i.e., 1216 MWh–1113 MWh). For the generator Parkcity, the decrease is 129 MWh (i.e., 1149 MWh–1020 MWh). For the generator Alta, the decrease is 604 MWh (i.e., 1696 MWh–1092 MWh), which indicates that the output of the generator Alta is the most significantly impacted by the increasing wind penetration.

TABLE I

GENERATIONS' DATA FOR PJM 6-BUS SYSTEM

Unit	Pmax (MW)	Pmin (MW)	Min Run (h)	Min Down (h)	Ramp (MW /min)	Initial run time (h)	Initial output (MW)
AL	110	40	4	6	4	3	110
PA	100	40	4	8	4	5	100
SO	520	100	8	6	8	4	190
SU	200	50	1	1	8	2	0
BR	600	200	8	8	3.5	24	400

Note: AL - Alta, PA - Parkcity, SO - Solitude, SU - Sundance, BR – Brighton.

TABLE II

HOURLY RESERVE AND RAMPING PRODUCT REQUIREMENTS WITH ρ=0.6

Hour	SPR	URP	DRP	Hour	SPR	URP	DRP
1	26.52	15.91	15.91	13	37.46	23.05	23.05
2	24.32	14.59	14.59	14	36.54	22.48	22.48
3	22.74	13.65	13.65	15	35.94	21.92	21.92
4	21.79	13.07	13.07	16	35.79	21.56	21.56
5	21.63	12.98	12.98	17	36.99	21.48	21.48
6	22.24	13.34	13.34	18	39.72	22.20	22.20
7	24.90	14.94	14.94	19	39.42	23.83	23.83
8	29.59	17.76	17.76	20	36.83	23.65	23.65
9	34.39	20.63	20.63	21	34.08	22.10	22.10
10	36.43	21.86	21.86	22	31.00	20.45	20.45
11	37.37	22.42	22.42	23	28.46	18.60	18.60
12	37.93	22.76	22.76	24	37.46	17.08	17.08

Note: SPR - Spinning Reserve, URP - Up-Ramping Product, DRP - Down-Ramping Product.

TABLE III

HOURLY LOAD FOR PJM 5-BUS SYSTEM

Hour	Load (MWh)	Hour	Load (MWh)	Hour	Load (MWh)	Hour	Load (MWh)
1	673	7	582	13	954	19	957
2	635	8	676	14	955	20	1005
3	586	9	807	15	922	21	954
4	555	10	889	16	906	22	888
5	540	11	924	17	894	23	813
6	546	12	943	18	904	24	742

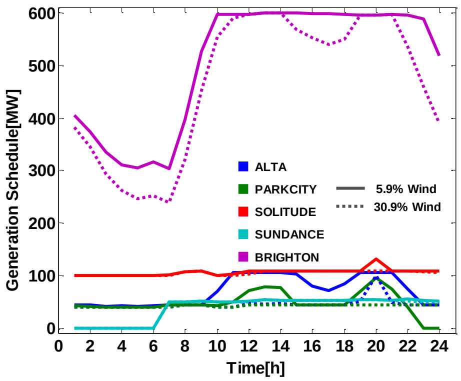


Fig. 3. Thermal unit operations with increasing wind penetrations.

Case 2: Comparison of increasing ramping product requirements and with and without WPRP.

Fig. 4 compares three types of costs, i.e., the operation cost, reserve cost, and production cost, when ramping product requirements increase. In this case, the ramping reserve requirement is calculated as a percentage, ρ, of the spinning reserve requirement for contingency reserves. This parameter is varied over a range of values in the case studies to examine its impact. This is done as a proxy for the required ramping reserve since there is no definitive approach which has been adopted for specifying these reserve levels. However, in theory the ramping reserve requirement should increase with increasing wind penetration levels.

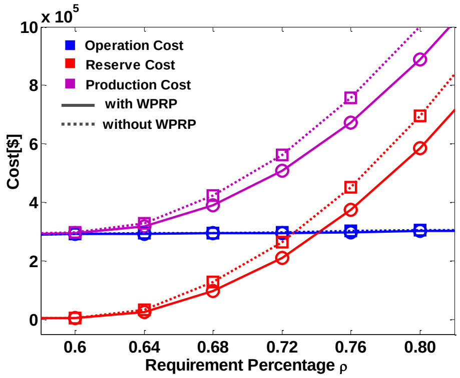


Fig. 4. Cost comparisons of increasing ramping product requirements.

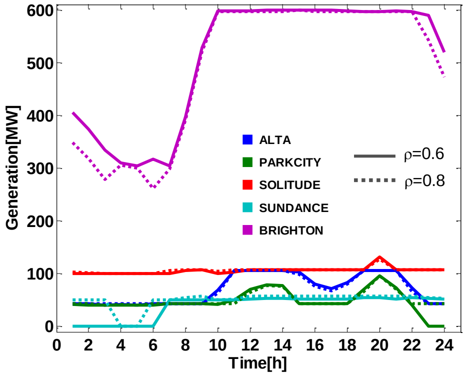
In Fig. 4, it is seen that the operation cost remains consistent with the increasing ramping product requirement. However, the reserve cost curve shows an exponential growth along with the increasing ramping product requirement; likewise for the production cost, which is the sum of the operation cost and reserve cost.

Another interesting finding is that both the reserve cost and the production cost are reduced when considering WPRP and the percentage of the ramping product requirement accounting for spinning reserve is greater than 0.6. Moreover, the cost reductions increase when the ramping product requirement increases. This means that WPRP plays an important role in decreasing the reserve cost, especially when more ramping product is required for power system operations.

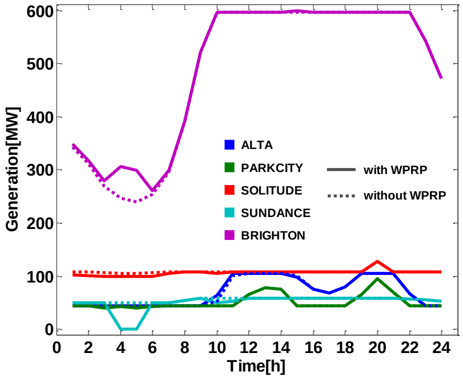
Fig. 5 compares generation schedules of five generators in two cases: Fig. 5(a) increasing ramping product requirements and Fig. 5(b) considering WPRP or not. Even though there are slight differences after increasing ramping product requirements and considering WPRP or not, the total generation is quite consistent. For Fig. 5(a), the total generation changes from 1.8491×10^4 MWh to 1.8484×10^4 MWh when the requirement percentage ρ increases from 0.6 to 0.8. For Fig. 5(b), the total generation changes from 1.8484×10^4 MWh (with WPRP) to 1.8481×10^4 MWh (without WPRP) when the requirement percentage ρ equals 0.8. However, more operation and production costs are saved after considering WPRP (ρ=0.8) in Fig. 4. Overall, it indicates that WPRP will not significantly affect the total generation schedules but save reserve costs.

Case 3: Impact of increased wind penetration level on up- and down-ramping product schedules.

Fig. 6 presents the impact of increased wind penetration on up-ramping product schedules for five generators. Even though generator Brighton schedules more up-ramping product after wind penetrations increase from 5.9% to 30.9%, other four generators schedule much less up-ramping products.



(a) Increasing ramping product requirements



(b) With/without WPRP

Fig. 5. Generation comparisons for PJM 5-bus system.

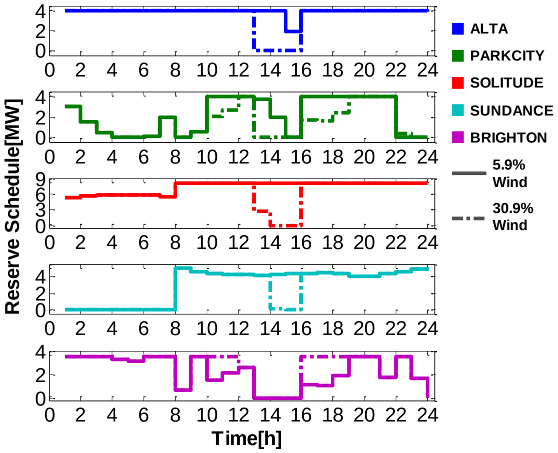


Fig. 6. Up-ramping product schedule with two wind penetrations.

Table IV enumerates the saved up-ramping product with the increasing wind penetration from 5.9% to 30.9%. Taking 5.9% wind penetration without WPRP as the benchmark, the most up-ramping product from thermal units saved is 60.08MW and the largest saved percentage is 13.02% when the wind penetration is 30.9%. If not using WPRP in 5.9% wind penetration, there are 15.03MW of up-ramping products that are supposed to be supplied by the five conventional generators.

TABLE IV
SCHEDULED UP-RAMPING PRODUCT WITH INCREASING WIND

Wind Penetration Level	Total Up-Ramping Product [MW]	Saved Up-Ramping Product [MW]	Saved Percentage [%]
5.9% (non-WPRP)	461.54	0	0
5.9% (WPRP)	446.51	15.03	3.26
10.9%	434.21	27.33	5.92
15.9%	421.55	39.99	8.66
20.9%	413.91	47.63	10.32
25.9%	407.68	53.86	11.67
30.9%	401.46	60.08	13.02

Note: Total Up-Ramping Product is provided by all the thermal units.

Fig. 7 presents the impact of increased wind penetration on down-ramping product schedules for the five generators. Even though the generator Parkcity in the hours 21-24 schedules more down-ramping product after the wind penetration increases, the other four generators schedule much less down-ramping products.

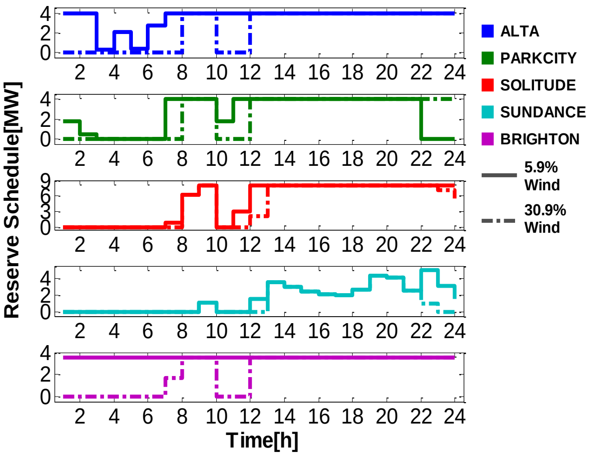


Fig. 7. Down-ramping product schedule with two wind penetrations.

Table V enumerates the saved down-ramping product with the increasing wind penetration from 5.9% to 30.9%. More down-ramping products are saved than up-ramping products using WPRP within different wind penetrations.

TABLE V
SCHEDULED DOWN-RAMPING PRODUCT WITH INCREASING WIND

Wind Penetration Level	Total Down-Ramping Product [MW]	Saved Down-Ramping Product [MW]	Saved Percentage [%]
5.9% (non-WPRP)	462.30	0	0
5.9% (WPRP)	390.84	71.46	15.46
10.9%	340.82	121.48	26.28
15.9%	324.31	137.99	29.85
20.9%	319.29	143.01	30.93
25.9%	315.67	146.63	31.72
30.9%	312.04	150.26	32.51

Note: Total Down-Ramping Product is provided by all the thermal units.

Taking 5.9% wind penetration without WPRP as the benchmark, the most down-ramping product from thermal units saved is 150.26MW and the largest saved percentage is 32.51% when the wind penetration is 30.9%. If not using WPRP in 5.9% wind penetration, there are 71.46MW of down-ramping products that are supposed to be supplied by the five conventional generators.

V. CONCLUSION

A modified dispatch formulation considering wind power ramping products was proposed in this paper. First, an optimized swinging door algorithm was developed to detect the WPRP in the coming period by combining the SDA and dynamic programming. Then, ramping capacity limits, active power limits, and flexible ramping requirements are all modified based on the detected WPRP. Numerical results showed that (i) WPRP could decrease the reserve cost and the total production cost, especially if more ramping product was required for power system operations, and (ii) both up- and down-ramping product schedules of thermal units were reduced after using WPRP.

In future work, a larger case study, such as the IEEE 118-bus system, or an actual power system will be tested considering WPRP based on the modified dispatch formulation. Furthermore, the non-spinning, regulation, and replacement reserve schedules will also be investigated.

ACKNOWLEDGEMENTS

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