Two-stage stochastic scheduling model of wind-photovoltaic-storage providing flexible ramp capacity

Ruanming Huang1, Xinqin He1,2, Jingjing Zhao2, Fei Fei1 and Mingxing Guo1
1 State Grid Shanghai Economic Research Institute, Shanghai;
2 Electric Power Engineering, Shanghai University of Electric Power, Shanghai

Abstract. The increasing penetration of renewable energy resources in power system has contributed to the increasing demand for operation flexibility. To address the deficiency of flexibility in wind-photovoltaic-storage hybrid system with deepening penetration of intermittent and uncertain renewable energy resources, this paper proposes emerging flexible resources including wind, photovoltaic and energy storage providing flexible ramp capacity to improve flexibility. Considering the uncertainty of load and intermittent generation, the wind-photovoltaic-storage providing flexible ramp capacity are integrated into a two-stage stochastic dispatch model including 1h day-ahead unit commitment and 15min real-time economic dispatch. To test the efficiency of the proposed model, simulation are carried out on a modified IEEE 118-bus with 54 thermal units, the results indicate that wind-photovoltaic-storage providing flexible ramp capacity can effectively alleviate the deficiency of operation flexibility, and improve the overall economic benefit.

1. Introduction
Maintaining balance in power system dispatch requires flexible resources to match the time-vary net load. The net load, which equals to the actual load power minus the renewable generation. The increasing penetration of renewable energy resources in power system has contributed to the increasing need for flexibility. Flexibility are attracting increased interest from researchers and power engineers in operation and dispatch[1-2]. It is difficult to quantify flexibility, so both the North American Electric Reliability Commission (NERC) and the International Energy Agency (IEA) qualitatively define flexibility. To address the ability of maintaining power balance, this paper use Flexible Ramp Capacity (FRC) to quantify flexibility. Currently, FRCs are mainly provided by conventional units[3]. However, due to the increasing share of renewable energy, conventional units always fail to deal with the uncertainty of renewable energy[4]. Hence, researchers and power engineers begin studying the potential FRC providers[5-6].

In [7], renewable energy sources are considered to be the main cause of increasing flexibility requirements, while we should not deny the idea of renewable energy sources as FRC providers. [8] analyzed the reliability of wind provide FRC, and proposed a two-stage RT market operation framework for integrating the wind power into the FRC markets. [9] coordinated gas turbine with demand response as FRC providers, which alleviated the burden of gas turbine in providing FRC and improved the economy and flexibility in power system. Considering the respective characteristics and mutual influence of emerging flexible resources such as energy storage and electric vehicles. [10] proposed a flexible ramp market model with emerging flexible resources participating in flexible
scheduling on the basis of traditional energy and reserve markets.[11] proposed A new rolling optimization algorithm to solve the power imbalance caused by the large fluctuation of photovoltaic.

This paper considers a set of FRC providers, including wind, photovoltaic, and energy storage, participate in providing FRC to improve the flexibility in power system. Then, integrates wind-photovoltaic-storage providing FRC into a two-stage stochastic dispatching model, including day-ahead dispatch and real-time dispatch. The day-ahead dispatch takes an hour as interval to determine the status of conventional units and the approximate power output and FRC distribution of various sources. Then, correct the power output and FRC distribution of various energy sources based on latest 15min forecast data.

2. Wind/photovoltaic providing FRC
The wind/photovoltaic’s capacity to provide FRC is illustrated in Figure 1. \( A_0 \) is the actual output of wind/photovoltaic (W/PV) at time \( t \), \( B_0 \) is the expected output at time \( t+1 \), and \( B^* \) is the actual power output at time \( t+1 \), which is a random point of the uncertainty interval \([B_d, B_u]\).

![Figure 1. Wind/photovoltaic providing FRC.](image)

2.1. Upward FRC
Wind/photovoltaic must deload to provide more schedulable capacity for subsequent time. For example, we conduct deloading from \( A_0 \) to \( A_1 \), which will leave more controllable capacity for the subsequent periods, quantified as \((A_0-A_1)\)[8]. Considering the uncertainty of W/PV, the upward FRC is limited by the point \( B_\alpha \), which is the lower \( \alpha \) quantile of predicted W/PV power distribution. Therefore, the W/PV’s capability to provide upward FRC can be expressed by

\[
\begin{align*}
\hat{r}_{t,s}^{w/p,u} &\leq \hat{P}_{t+1,s}^{w/p,\alpha} - p_{t,s}^{w/p} \\
\hat{r}_{t,s}^{w/p,u} &\leq R_{w/PV}^{\alpha} \cdot 15 \text{ min}
\end{align*}
\]  

(1a, 1b)

Where, \( \hat{r}_{t,s}^{w/p,u} \) represents the upward FRC provided by W/PV at time \( t \), \( \hat{P}_{t+1,s}^{w/p,\alpha} \) represents the \( \alpha \) quantile of the predicted W/PV, \( p_{t,s}^{w/p} \) represents the actual output of W/PV at time \( t \), and \( R_{w/PV}^{\alpha} \) indicates the maximum ramp rate of W/PV.

2.2. Downward FRC
W/PV provides downward FRC directly by conducting curtailment, and the downward FRC at time \( t \) is limited by the predicted power output at time \( t+1 \). Considering the uncertainty, the lower \( \alpha \) quantile of predicted W/PV power probability distribution at time \( t+1 \) is used to limit the W/PV’s capacity to provide downward FRC. Therefore, the W/PV’s capability of providing downward FRC can be expressed by
3. Two-stage stochastic scheduling model

To study the influence of emerging sources providing FRC on dispatch, we integrate wind-photovoltaic-storage providing FRC into a two-stage stochastic dispatch model. The model is divided into the upper day-ahead unit commitment and the lower real-time economic dispatch.

3.1. The objective function

The objective function given in (3) minimizes the total operation cost of system, which is consisted of the operation cost of conventional units, the operation cost of wind power, the operation cost of photovoltaic, the operation cost of energy storage, and the corrective cost of the real-time economic dispatch, as expressed by

$$
\min F = F_g + F_w + F_{pv} + F_{es} + F_{\text{re-dispatch}}
$$

(3)

Where, $F_g$, $F_w$, $F_{pv}$ and $F_{es}$ respectively represents the day-ahead operation cost of conventional units, wind power, photovoltaic and energy storage. $F_{\text{re-dispatch}}$ is related to the expected cost changes due to corrective actions of conventional units, wind power, photovoltaic and energy storage in the real-time economic dispatch.

3.2. Constraints

3.2.1. Constraints of conventional units.

Day-ahead unit commitment decides the commitment of conventional units, which remains unchanged in real-time economic dispatch. Thus, the complexity of the real-time economic dispatch is much lower than the day-ahead unit commitment. We consider generation capacity constraint and ramp rate constraint of conventional units during day-ahead unit commitment and economic dispatch process. Meanwhile, we must also consider start-up/shutdown status constraint and minimum startup/shutdown constraint of conventional units during day-ahead unit commitment.

3.2.2. Constraints of W/PV.

The day-ahead constrains of W/PV is similar to the real-time process constraints, so we only model the real-time constraints of W/PV.

a) Up/down FRC constraints

$$
\begin{align}
\Delta p_{w,pv,t} &\leq \Delta p_{w,pv,t+1} \\
\Delta p_{w,pv,t} &\geq 0
\end{align}
$$

(4a)

Where, $\Delta p_{w,pv,t}$, $\Delta r_{w,pv,u,t}$ and $\Delta r_{w,pv,d,t}$ respectively represents the output power, upward FRC, and downward FRC of W/PV, $\hat{p}_{w,pv,t}$ represents the predicted output of W/PV at time $t$.

b) Wind/photovoltaic ramp constraints

$$
\begin{align}
\Delta p_{w,pv,t} &\leq R_{w,pv} \cdot 15 \text{ min} \\
\Delta p_{w,pv,t} &\leq 0
\end{align}
$$

(5a)

3.2.3. Energy storage constraints.

Energy storage provides upward FRC by discharging, and the energy storage’s state of charge should not be less than the minimum state of charge. Similarly, energy storage provides downward FRC by charging, and the energy storage’s state of charge should not more than the maximum state of charge.

a) Maximum charge/discharge power constraints
\[ \bar{p}_{t,s}^{ch} + \Delta p_{t,s}^{ch} + \bar{p}_{t,s}^{d} + \Delta p_{t,s}^{d} \leq P_{max}^{ch} I_{t,s}^{ch} \]  \hspace{1cm} (6a) \\
\[ \bar{p}_{t,s}^{dc} + \Delta p_{t,s}^{dc} + \bar{p}_{t,s}^{u} + \Delta p_{t,s}^{u} \leq P_{max}^{dc} I_{t,s}^{dc} \]  \hspace{1cm} (6b)

Where, \( \bar{p}_{t,s}^{ch/dc} \) and \( \bar{p}_{t,s}^{u/d} \) are the charging/discharging power and up/down FRC of the energy storage in the day-ahead process; \( \Delta p_{t,s}^{ch/dc} \) and \( \Delta p_{t,s}^{u/d} \) respectively represents the adjustment of corresponding real-time process; \( P_{max}^{ch/dc} \) is the maximum charging/discharging power of energy storage; \( I_{t,s}^{ch/dc} \) represents charging and discharging binary status variable of energy storage.

b) Charging and discharging status constraints

\[ I_{t,s}^{ch} + I_{t,s}^{dc} \leq 1 \]  \hspace{1cm} (7)

c) Upward/downward FRC constraints of energy storage

\[ S_{t,s} = S_{t-1,s} + \eta_d \left( \bar{p}_{t,s}^{ch} + \Delta p_{t,s}^{ch} + \bar{p}_{t,s}^{d} + \Delta p_{t,s}^{d} \right) 15\text{ min}/ E \]

\[ -\left( \bar{p}_{t,s}^{dc} + \Delta p_{t,s}^{dc} + \bar{p}_{t,s}^{u} + \Delta p_{t,s}^{u} \right) 15\text{ min}/ \left( \eta_d E \right) \]  \hspace{1cm} (8)

\[ 0 \leq \bar{p}_{t,s}^{u} + \Delta p_{t,s}^{u} \leq \left( S_{t,s} - S_{t,min} \right) E \eta_{dc} \left( \frac{15\text{ min}}{E} \right) \]  \hspace{1cm} (9a)

\[ 0 \leq \bar{p}_{t,s}^{d} + \Delta p_{t,s}^{d} \leq \left( S_{t,max} - S_{t,s} \right) E \eta_{dc} \left( \frac{15\text{ min}}{E} \right) \]  \hspace{1cm} (9b)

The state of charge of energy storage in time \( t \) is shown in (8). (9a) and (9b) respectively represents the upward and downward FRC constraints of energy storage.

4. Simulation of the example

4.1. Model parameters

Numerical case studies are conducted on a modified IEEE 118-bus test system with 54 thermal units and it’s data is extracted from reference [12]. The model is consisted of 91 load notes, five 400MW wind power plants, nine 300MW photovoltaic power plants, and five 120MW-h bulk energy storage power stations. The maximum ramp rate of each wind plants is 20MW/min, and the photovoltaic plants is 12MW/min. The compensation factor of wind power in providing FRC is based on the standards of reference[10], which is 20% of the Offered cost of energy. The Offered cost of energy of wind power and photovoltaic is 75$/\text{MW}$.[13]. Assuming that the initial state of charge of energy storage is 0.5, and other relevant parameters of the energy storage are shown in Table 1.

| \( E \) (\text{MW}hr) | \( S_{min} \) | \( S_{max} \) | \( P_{max} \) (MW) | \( \eta_{ch}/\eta_{dc} \) | \( Ces \) (\$/\text{MW}hr) | \( \pi u/\pi d \) (\$/\text{MW}hr) |
|------------------|-----|-----|--------|-----------------|-----------------|-----------------|
| 120              | 0.1 | 0.9 | 120    | 0.85           | 195             | 39              |

This paper uses the scenario method to describe the uncertainty of load, wind power and photovoltaic. Load, wind power and photovoltaic respectively generate 500 scenarios through Latin oversampling in day-ahead dispatch and real-time dispatch, then reduce 500 scenarios to 5 scenarios using scenario reduction technology. Hence, the total number of scenarios is equal to 125 scenarios. We call the Gurobi optimizer in the matlab platform to solve the optimization problem.
4.2. Simulation result of a typical day

Figure 2. Expected load, wind and photovoltaic power curves.

Figure 2 shows the expected day-ahead and real-time power for the wind, PV, and load, which are used to respectively generate 125 day-ahead and real-time scenarios.

4.2.1. Analysis of FRC distribution results. In order to obtain the FRC distribution of all "flexible sources" in a day. We calculate the FRC results in day-ahead process, then calculate the corrective FRC in each 15min interval, finally obtain the FRC results in real-time process. To figure out the advantage of coordinating wind, photovoltaic and energy storage into providing FRC, we compare FRC results of conventional units solely providing FRC (C1) with wind, photovoltaic and energy storage providing FRC (C2).

Figure 3 shows the FRC results in real-time process. The analysis of the FRC results of the above 2 strategies are as follows:

- From the C1 that the conventional units can meet the FRC requirements in most of intervals, but there are still FRC deficiency in some intervals with high FRC requirements.
- Conventional units, wind power, photovoltaic coordinate with energy storage providing FRC (C2) can meet the FRC requirements in all intervals. From the perspective of FRC results, C2 is the optimal strategy.
4.2.2. Economic analysis of different FRC dispatch strategies. Since load shedding does not occur in the dispatch process, there is no penalty cost for load shedding. As shown in Table 2, the other operation cost are divided into four categories, namely conventional units’ operation cost, operation cost of wind power, FRC cost provided by wind power and the penalty cost of FRC deficiency.

Table 2. The 24h operation cost of C1 and C2.

| strategy | Cost (unit: $) | total cost | Conventional units | wind power energy | FRC provided by wind power | Penalty cost of FRC deficiency |
|----------|----------------|------------|--------------------|-------------------|--------------------------|-------------------------------|
| C1       | 10498050       | 6016051    | 1113389            | 0                 | 3368610                  |
| C2       | 7102753        | 5790579    | 1147587            | 164856            | 0                        |

Wind-photovoltaic-storage does not participate in providing FRC (C1) can not meet the system's FRC requirements, there is a large penalty cost of FRC deficiency, reaching 32.1% of the total cost. Comparing C1 with C2, we can find that adding other sources providing FRC can reduces the penalty cost of FRC deficiency and the cost of conventional units. From the perspective of the FRC results and economy, C2 is a better strategy to C1.

4.3. Flexibility assessment of different FRC requirements
Fluctuations in load, wind power, and PV power directly lead to system’s FRC demand. Table 3 shows the flexibility assessment comparison of C1 and C2 under different FRC requirements. In this paper, we consider economic flexibility and technical flexibility. We use the total operation cost of the system to assess economic flexibility and the capacity of FRC deficiency to assess technical flexibility.

Table 3. Flexible evaluations in different FRC requirements.

| FRC requirements (MW) | Strategy | Total operation cost ($) | FRC Provided by wind-photovoltaic-storage (MW) | FRC deficiency (MW) |
|-----------------------|----------|--------------------------|-----------------------------------------------|---------------------|
| 9437                  | C1       | 6975515                  | —                                             | 0                   |
|                       | C2       | 6975515                  | 0                                             | 0                   |
| 11796                 | C1       | 8419473                  | —                                             | 141                 |
|                       | C2       | 6993116                  | 787                                           | 0                   |
| 14156                 | C1       | 9591681                  | —                                             | 319                 |
|                       | C2       | 7016365                  | 1549                                          | 0                   |

The results show that: When the FRC requirements is small, the system will not choose the wind-photovoltaic-storage to provide FRC, and the additional FRC provision of wind-photovoltaic-storage does not show it’s economic and technical advantage. As the FRC requirement increases, C2 begins to show economic and technical advantages, and the advantage is becoming more and more obvious. This trend indicates that when the penetration of wind power and PV in power system increases to a certain extent, the additional FRC provision of wind-photovoltaic-storage has more economical and technically flexibility than conventional units solely participate in providing FRC.

5. Conclusions
To address the deficiency of operation flexibility with high renewable energy penetration, this paper proposes that emerging “flexible sources” such as wind power, photovoltaic, and energy storage
participate in providing FRC. Then integrates the wind-photovoltaic-storage providing FRC into a two-stage stochastic dispatch model including 1h day-ahead unit commitment and 15min real-time economic dispatch. The validity of the model is verified by a modified IEEE 118-bus with 54 thermal units. The results are as follows:

1) The conventional units can meet the FRC requirements in most of intervals, but there are still FRC deficiency for some intervals with high FRC requirements. The additional FRC provision of wind-photovoltaic-storage provides a significant improvement in the FRC deficiency of the system and increases the economic efficiency of the system.

2) For systems with high wind power and PV penetration, the participation of wind-photovoltaic-storage in providing FRC shows improved economic and technical flexibility.

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