Grid dispatching domain division related to large-scale renewable energy grid-connecting

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Abstract. As the proportion of renewable energy access to the grid increases, regional phenomenon of wind power and photovoltaic curtailment highlights. In order to improve the capacity of new energy consumption and alleviate the complexity of power grid scheduling, a regional power grid scheduling domain partitioning method for high proportion of renewable energy access is proposed. The renewable energy regional grid operation domain is divided into normal domain, abnormal domain and emergency domain, and combined with the regulation capability of conventional thermal power units and the power fluctuation ability of energy storage, the divide indicators of each operation domain is defined. Finally, an example analysis of the Dalian regional power grid in Liaoning is carried out to verify the validity and correctness of the grid multi-domain division method.

1. Introduction
With the development of new energy technologies, the proportion of renewable energy power generation in the power grid is increasing [1]. On the one hand, the ability of Chinese power grid to accept wind power has not kept up with the development of wind power installed capacity, and the wind abandonment phenomenon is serious. On the other hand, renewable energy power generation is affected by short-term fluctuations in weather and cyclical changes in climate. Its output power is characterized by intermittent, random, unstable and uneven distribution, which makes regional power grid scheduling more complicated [2]. Therefore, the division of grid operation domain for large-scale renewable energy access has become one of the hot issues of concern to experts and scholars.

Experts and scholars have done a lot of research on the integration of new energy sources. The power optimization calculation model for smooth power output is established by analyzing wind power fluctuations in [3]. In [4], the maximum entropy value is used as an index to measure the uncertainty of wind power, and the variation law of wind power uncertainty in each time period is analyzed to study the influence of wind power access on system peak shaving. In addition, conditional risk value is used to measure the risks that renewable energy output and load uncertainty pose to power generation scheduling in [5].

In summary, considering the operational risk to some extent eases the uncertainty in the power generation scheduling process, but lacks specific scheduling domain partitioning to simplify grid scheduling. Aiming at the above problem, this paper proposes a regional power grid scheduling
domain division method based on the thermal power regulation ability and the energy storage, and defines the division index of each operation domain.

2. Renewable energy model construction

a. Wind power generation model

The random variation of wind speed can usually be described by Weibull distribution [6], and its probability density function can be expressed as

\[ f_w(v) = \frac{K}{C} \left( \frac{v}{C} \right)^{K-1} \exp\left(-\left(\frac{v}{C}\right)^K\right) \]  

(1)

where:

- \( v \) - the wind speed;
- \( C, K \) - the scale parameter and the shape parameter.

According to the relationship between wind speed and output and formula (1), the power output of the wind plant is

\[
P_w = \begin{cases} 
0, & 0 \leq v_i < v_{cin} \\
\sum_{i=1}^{N} \frac{(v_i - v_{cin}) P_{rew}}{v_i - v_{cin}}, & v_{cin} \leq v_i < v_i \\
\sum_{i=1}^{N} P_{rew}, & v_i \leq v_i < v_{cost} \\
0, & v_i \geq v_{cost}
\end{cases} \quad (i = 1, 2, \ldots, N) 
\]  

(2)

where:

- \( P_w \) - the power output of the wind plant;
- \( v_{cin}, v_{cost} \) - the cut-in and cut-out wind speed;
- \( v_i \) - the wind speed of the unit reaching the rated power \( P_{rew} \).

b. Photovoltaic power generation model

Solar radiation is highly uncertain. Photovoltaic cell output power is related to time factor, environmental conditions, illumination incident angle, etc., showing significant intermittency. In general, the probability density function of solar radiation can be represented by a beta distribution function [7]:

\[ f(R) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha) \Gamma(\beta)} R^{\alpha-1}(1-R)^{\beta-1} \]  

(3)

where:

- \( R \) - the solar radiation value (unit: W/m\(^2\));
- \( \alpha, \beta \) - the shape parameter (\( \alpha > 0, \beta > 0 \)).

According to the solar radiation value obtained by formula (5), the output power \( P_R \) of the photovoltaic station can be calculated by the radiation power curve.

\[
P_R = \begin{cases} 
\sum_{i=1}^{N} \frac{P_{rew}}{R_i R_i}, & 0 \leq R < R_c \\
\sum_{i=1}^{N} \frac{P_{rew}}{R_i R_i}, & R_c \leq R < R_k \quad (i = 1, 2, \ldots, N) \\
\sum_{i=1}^{N} P_{rew}, & R_k \leq R
\end{cases} \]  

(4)

where:

- \( P_R \) - the output power of the photovoltaic station;
- \( P_{rew} \) - the rated power of the \( i \) photovoltaic array;
- \( R_c, R_k \) - the standard solar radiation value (usually 1000 W/m\(^2\)) and the reference radiation point (usually 150 W/m\(^2\)).
c. Battery energy storage model

The energy storage system can dynamically absorb energy and release it at the right time to make up for the intermittent and volatility of wind power generation and improve controllability, which not only ensures the reasonable consumption of wind power, but also ensures the safe operation of the system [8].

Zinc-bromine liquid battery stores energy in solution, which has the advantages of flexible design and deep discharge [9]. During the operation of the liquid battery, the electrolyte needs to be pumped from the liquid storage tank to the reactor through the pump. Therefore, the charging and discharging power of the system is directly related to the electrolyte flow rate of the pump into the stack, that is, the charging and discharging power is related to the state of charge of the battery:

$$\text{SOC}^t - \text{SOC}^{t-1} = \frac{P_{\text{cd}} \cdot T_{\text{cd}}}{E}$$  (5)

where:
- $P_{\text{cd}}$ - the average charge and discharge power of the liquid battery at time $t$;
- $E$ - the equilibrium voltage;
- $\text{SOC}^t$ - the state of charge of the battery at time $t$;
- $T_{\text{cd}}$ - the time interval.

Lead-acid battery energy storage is an early and mature electrochemical energy storage method, which is widely used in wind plants. Lead-acid batteries are characterized by low cost and high reliability, and their discharge degree and service life are greatly affected by temperature [10]. Taking a common valve-regulated lead-acid battery as an example, when the temperature is above 0 °C, the discharge amount of the lead-acid battery is approximately linear with the temperature; when the temperature is lower than 0 °C, the charge and discharge capacity decreases due to the decrease in the viscosity of the electrolyte. [11]. The relationship between the charge and discharge capacity $S_{\text{ch}}$ of a lead-acid battery as a function of temperature $T$ can be approximated by

$$S_{\text{ch}} = \begin{cases} S_0 e^{k_1 T} & -20^\circ C < T \leq 0 \\ S_0 + k_2 T & 0 < T \leq 50^\circ C \end{cases}$$  (6)

where:
- $S_0$ - the charge and discharge capacity of the lead-acid battery at 0 °C;
- $k_1, k_2$ - the temperature compensation coefficients when the temperature is below zero or above zero.

Since the zinc-bromine liquid battery has deep dischargeability, and the cost of the lead-acid battery is low, when a small-scale discharge of the energy storage system is required, the lead-acid battery should be continuously and smoothly discharged, and when the required amount of electricity is large, the liquid battery should be used for high current deep discharge.

3. Multi-domain partitioning indicator definition

When the power grid is in normal operation, it is called the normal operation domain. At this time, the system does not exceed the regulation capability of the conventional thermal power unit. When the power grid lacks the adjustment capability, it is called the abnormal operation domain. At this time, the energy storage battery is charged and discharged to the system to stabilize the wind power fluctuations; when the power grid loses its control capability, it is called the emergency operation domain, and the safe and stable operation of the power grid is ensured by reasonable abandonment of wind/light.

The division of the operation domain is related to the power imbalance $\Delta P'$ in the system during the period.

$$\Delta P' = \sum_{j=1}^{N} P_{t Lj} + P_{\text{kab}}^{t-1} - \left( P_{r W} + P_{r r}^{t} + \sum_{i=1}^{N} P_{r G}^{t-1} \right)$$  (7)

where:
- $P_{t Lj}$ - the real power load connected to bus $j$ at time $t$, 

• \( N_l \) - the number of buses;
• \( P_{t-1} \) loss - the power losses at time t-1;
• \( P_{tW}, P_{tR} \) - the wind and the PV power output at time t;
• \( P_{t-1} Gi \) - the real power output of the i conventional unit at time t-1.

The calculation of the operation domain partitioning index \( K_{con} \) is calculated by the calculated power imbalance and the adjusted output force of the conventional thermal power unit:

\[
K_{con} = \frac{\sum_{i} \Delta P_{t Gi}}{\Delta P} \tag{8}
\]

where:
• \( \Delta P_{t Gi} \) - the adjustable power output of the i conventional unit at time t, which is up-regulated to a positive value and down-regulated to a negative value, which is affected by the upper and lower limits of the unit output and the power climbing slope constraints.

When the imbalance of the system exceeds the adjustment range of the conventional unit, it is necessary to access the energy storage output to ensure the balance of the system. When the energy storage battery is working, the charge and discharge factor of the energy storage battery is defined as

\[
f_{ch.con} = \frac{\Delta P_{t ch}}{\Delta P} \tag{9}
\]

where:
• \( \Delta P_{t ch} \) - the maximum chargeable and dischargeable power at time t considering the real-time state of the energy storage SOC.

Since the power output of the unit is equal to the positive and negative of the imbalance, the value of \( K_{con} \) is positive. The operation domain division is defined by (9) as shown in Table 1 and in Fig. 1.

**TABLE 1 OPERATOR DOMAINS DIVISION**

| Indicator quantity | Operation domain | Energy storage state |
|--------------------|------------------|----------------------|
| \( K_{con} > 1 \)  | Normal domain    |                     |
| \( 1-f_{ch.con} < K_{con} < 1 \) | Abnormal domain | \( \Delta P > 0 \)  Discharge |
|                    |                  | \( \Delta P' < 0 \) Charging |
| \( K_{con} < 1 \)  | Emergency domain | \( \Delta P > 0 \) Reach the discharge limit |
|                    |                  | \( \Delta P < 0 \) Reach the charging limit |

Figure 1. Operation domain division diagram. The value of the indicator quantity \( K_{con} \) determines which operation domain the current system is in:

• \( K_{con} > 1 \) - the system runs in the normal domain, and the power balance is satisfied by adjusting the output of the conventional unit;
• \( 1-f_{ch.con} < K_{con} < 1 \) - the system runs in the abnormal domain, it exceeds the adjustment range of the conventional unit;
• \( K_{con} < 1 \) - the system runs in the emergency domain, it reaches the discharge limit.
conventional unit, and accesses the energy storage output to ensure the balance of the system. The direction of charge and discharge of the energy storage depends on the positive and negative of $\Delta P_t$:

- $K_{con} < 1 - f_{ch,con}$ - the system runs in the emergency domain, and there are too many deviations from the normal domain. Long-term operation will have an adverse impact on the system. The wind power/photovoltaic should be discarded in time to restore the operating state.

### 4. Case analysis

$U_B=220kV$, $S_B=100MW$, with a time period of every 30 minutes, total time $T=24h$. Take the wind speed model Weibull distribution scale parameter $C=7.45$, shape parameter $K=2.5$, rated power $48MW$, cut-in wind speed $V_{cin}=3m/s$, rated wind speed $V_r=11m/s$, cut-out wind speed $V_{cout}=20m/s$. The photovoltaic model beta distribution parameters are $\alpha = 0.151$, $\beta = 0.963$, and the rated power is $40MW$.

![Figure 2. The diagram of actual system. This example uses the actual regional power grid of Dalian to analyze. By calculating the power imbalance amount $\Delta P_t$ and the value of the operation domain division index $K_{con}$, a operation domain division diagram as shown in Fig. 3 is obtained.](image1)

![Figure 3. Actual grid operation domain division diagram. As can be seen from the figure, $K_{con}$ has fewer fluctuations and fewer divisions in the operation domain. The values of the indicator amounts for each time are shown in Table 2.](image2)

| Time/h | $K_{con}$ | Indicator quantity | Operation domain |
|--------|-----------|-------------------|------------------|
| 8      | 0.183     | $-0.384 < K_{con} < 1$ | Abnormal domain |
| 8.5    | 0.247     | $0.103 < K_{con} < 1$ | Abnormal domain |
| 10     | 0.471     | $0.239 < K_{con} < 1$ | Abnormal domain |
It can be seen from Fig. 3 and Table 2 that the system is in the positive abnormal domain ($\Delta P_t > 0$) in the time of 8~8.5, 10~11, and is charged by the energy storage battery to the system. The system is in the negative abnormal domain of 16~18.5 and the system delivers excess power to the energy. In the emergency domain range from 9 to 9.5, the system loses its ability to adjust, and wind power/photovoltaic should be discarded in time to ensure stable operation of the system.

5. Conclusion
Based on the characteristics of the multi-source model, this paper proposes three operation domain theories and specific judgment indicators, and the conclusions are as follows:

- The method proposed in this paper provides a theoretical basis for the division of regional grid operation domain.
- By defining the operation domain partitioning indicator ($K_{con}$), the current operation domain of the system can be quantitatively determined.
- Under the intervention of high proportion of renewable energy, quantitatively dividing the operating state of the grid provides important auxiliary decision-making significance for grid dispatching.

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