Research on voltage coordinated control strategy of large-scale renewable energy access to grid optimization

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Abstract. With the increasing consumption of traditional energy sources and the destruction of the environment, traditional energy generation cannot meet the development of today's society. Replaced by renewable clean energy, a large number of new energy access to the power grid, but large numbers of unconstrained access to the grid will seriously cause problems with unqualified voltage quality. In this paper, the reactive power demand Q of the grid is determined based on the difference between the measured voltage value and the voltage target value collected at the grid point exceeds the allowable range. And by calculating the SVG reactive power adjustment margin of each new energy power plant. For the adjustment margins of reactive power compensation equipment in each new energy power plant, reactive power distribution is implemented using strategies such as equal ratio or equal margin or priority allocation.

1. Introduction

With the continuous destruction of traditional energy sources and the increasingly destructive environment, in the report of the 19th National Congress of the Communist Party of China, President Xi Jinping clearly pointed out that it is necessary to promote the energy production and consumption revolution and build a clean, low-carbon, safe and efficient energy system. In this era of rapid development, environmental issues have also become a concern of the entire society. Replacing non-renewable resources with renewable resources, realizing clean energy such as renewable resources, and occupying a large proportion of primary energy production and consumption, realizing energy transformation and building a clean, low-carbon, safe, and efficient modern energy system has become a new energy revolution in China. In recent years, the continuous access of new energy to the power grid has brought new challenges to the development of the power grid. While the entire social environment has been continuously improved, unconstrained new energy will also have a corresponding impact on the power grid in [1-3].

At present, there is a large amount of literature on the voltage control of new energy access to the power grid. The mainly to use different algorithms and the characteristics of distributed photovoltaic grid to develop the corresponding voltage control strategy to deal with the voltage quality problems of large photovoltaic power plants after accessing the grid in [4-9]. These control strategies effectively control the voltage pass rate to a certain extent. It mainly gives the corresponding voltage control strategy by studying the characteristics of wind power connected to the grid and combining the characteristics of doubly-fed wind power generation in [10-12]. A multi-objective hybrid automatic
voltage control method is proposed for power systems with renewable energy, which has been used to deal with the problems faced by power hybrid control systems in [13-14].

At present, although many experts and scholars have done a lot of research on new energy access to the power grid, the research process does not specifically study the situation of large-scale new energy centralized access to the power grid, which makes a large number of special substations centralized. The voltage problem in the case of new energy sources cannot be solved. This article focuses on the integration of large-scale hybrid new energy sources into a single substation, and provides an optimized coordination and control strategy under the condition of satisfying the voltage quality qualification, and provides relevant recommendations for large-scale new energy access to the power grid.

2. Model establishment
At present, some Substations under the State Grid or China Southern Power Grid have become more and more concentrated in large-scale hybrid renewable energy due to the superiority of the local natural environment. As such large-scale new energy sources are collected at the same time, because of the special nature of its access to new energy sources and the instability of its output, a site will inevitably cause a certain impact on the power grid, and some Substations will have a greater impact on the corresponding traction. Through the analysis of the Substation system diagram, no matter what the voltage level of the Substation can be similar to the renewable energy (wind, photovoltaic) hybrid centralized access to the power grid schematic topology, as shown in figure 1.

![Diagram of wind power and photovoltaic hybrid access network](image)

**Figure 1.** Diagram of wind power and photovoltaic hybrid access network.

Equivalence, \( q \) is the current reactive power value, \( \Delta q \) is the reactive power regulation value, \( q + \Delta q \) is the reactive power target value, \( q_1 \) is the sum of actual reactive power generated by equivalent photovoltaic power plants, \( q_2 \) is the sum of real reactive power generated by equivalent wind farms, \( up \) represents the sum of upgradable reactive power of new energy power plants, and \( down \) represents the sum of downgradable power of new energy power plants. \( q_c \) represents the rated capacity of a single Capacitor, \( c \) represents the number of adjustable Capacitors, \( m \) represents the number of Capacitors thrown back.

3. Theoretical analysis
   Through the analysis, it can be concluded that the system's demand for reactive power is divided into the following situations as a whole, and a corresponding control strategy is derived through specific analysis of the following situations.

3.1. Reactive power is positive
   - The current reactive power generation value is less than 0, and the target reactive power value is greater than 0, according to formula (1).
Calculate the number of Capacitors to be put in, and the remaining reactive power adjustments are allocated to each new energy plant using a strategy such as equal-proportion or equal margin allocation.

- The current reactive power generation value is less than 0, and the target reactive power value is still less than 0. In this case, the reactive power adjustment quantity $|\Delta q| - m q_c$ is selected to be allocated to each new energy power plants using a strategy such as equal-proportion or equal margin allocation.

- The current reactive power is greater than 0, and the target reactive power is still greater than 0, according to formula (2).

$$m = \frac{|\Delta q| - |q_1| - |q_2|}{q_c}, \text{if} (m > c, m = c)$$

(1)

Calculate the number of Capacitors to be invested. If the remaining reactive power adjustment is smaller than the new energy plant's up liftable line, use equal-proportion/equal margin allocation strategies to allocate to each new energy power plant, if the remaining reactive power adjustment is greater than the new energy power plants. The ability to increase the amount of credit, then calculate more investment in a Capacitor is closer to the target value.

3.2. Reactive power is negative

- The current reactive power generation value is greater than 0, the target reactive power value is still greater than 0, and the number of Capacitors to be removed is calculated according to formula (2), if the remaining reactive power regulation quantity is less than the new energy power plant's reactive power generation. The value is then allocated to each new energy power plant using a strategy such as equal-proportion or equal margin allocation. If the remaining reactive power adjustment is greater than the new energy power plant's reactive power generation value, then it is calculated whether the removal of a Capacitor is closer to the target value.

- The current reactive power generation value is greater than 0, and the target reactive power value is less than 0. In this case, all running Capacitors are first removed, and the remaining reactive power adjustment amount is allocated to each new energy power plant using a strategy such as equal ratio or equal margin allocation.

- The current reactive power generation value is less than 0, and the target reactive power value is still less than 0. In this case, the remaining reactive power regulation amount is allocated to each new energy power plant using a strategy such as equal-proportion or equal margin allocation.

When it is necessary to increase the reactive power demand is greater than the entire system can increase the reactive power quota, all Capacitors are put into use. Each new energy power plant allocates reactive power according to the upper limit, calculates the remaining required voltage difference, and increases the main variable tap. When it is necessary to lower the reactive power demand more than the entire system can lower the reactive power quota, remove all the Capacitors, each new energy power plant below the allocation of reactive power, calculate the remaining need to adjust the voltage difference, down the main Transformer tap.

4. Key algorithm for optimizing voltage coordination

4.1. Voltage regulation algorithm
Through equivalent analysis, it can be known that can be adjusted in the system include Capacitors,
Reactors, new energy power plants, and Transformer. According to different priorities and adjustment parameters, the system will select different adjustment strategies, mainly including the following:

- According to the above analysis, it can be concluded that the current reactive power generation value is less than 0, the reactive power needs to be adjusted, and the target reactive power value is greater than 0. In this case, the number of input Capacitors is calculated according to formula (1). The remaining reactive power adjustments are allocated to each new energy power plant, the design flow chart is shown in figure 2.

\[
m = \frac{|\Delta q| - |q_1|}{q_2}, \text{ if } (m > c, m = c)
\]

\[
m = |\Delta q| + 1, \text{ if } (m > c, m = c)
\]

**Figure 2.** Scenario 1 design flow chart.

- The current reactive power generation value is less than 0, the reactive power needs to be adjusted upward, and the target reactive power value is still less than 0. In this case, the reactive power adjustment amount \(\Delta q\) is selected and assigned to each new energy power plant by a strategy such as equal-proportion or equal margin allocation, the design flow chart is shown in figure 3.
Fig. 3. Scenario 2 design flow chart.

**Comments 1:**

- **Exit m+1:**
  \[ \Delta q' = (m + 1)q_c - \Delta q \]
  
  *if* \((\Delta q' < \text{down})\)

- **Exit m+1 Reactors, new energy plants adjust down \(\Delta q\)**
  
  else
  
  \[ q' = q + (m + 1)q_c - \text{down} \]
  \[ q'' = mq_c + q + |q_1| + |q_2| \]

- **Compare** \(q'\) and \(q''\) *which is closer to the target value.*

**Comments 2:**

- **Exit m Reactors, new energy station adjust down \(\Delta q_c - \Delta q\)**
  
  else
  
  \[ q' = q + mq_c - \text{down} \]
  \[ q'' = (m - 1)q_c + q + |q_1| + |q_2| \]

- **Compare** \(q'\) and \(q''\)*which is closer to the target value.*
  
  - The current reactive power is greater than 0, the reactive power needs to be adjusted upward,
and the target reactive power is still greater than 0. In this case, the number of Capacitors to be added is calculated according to formula (2). If the remaining reactive power adjustment is smaller than new energy, the capacity of the power plant can be allocated to each new energy power plant using a strategy such as equal-proportion or equal-margin allocation. If the remaining reactive power adjustment amount is greater than the new energy power plant's up-raising quota, it is calculated whether more inputs of a Capacitor are closer to the target value, the design flow chart is shown in figure 4.

**Figure 4.** Scenario 3 design flow chart.

**Comments 1:**

\[
\text{if } (m = c) \\
\text{Input m Capacitors, new energy power plant is full} \\
\text{else} \\
\Delta q' = (m + 1)q_c - \Delta q
\]

\[
\text{if } (\Delta q' < q_1 + q_2) \\
\text{Input m+1 Capacitors, new energy power plants adjust down } \Delta q' \\
\text{else} \\
q' = q + mq_c + up \\
q'' = (m + 1)q_c + q - |q_1| + |q_2|
\]

Compare \( q' \) and \( q'' \) which is closer to the target value.

**Comments 2:**

\[
\text{if } (mq_c - \Delta q) < q_1 + q_2 \\
\text{Input m Capacitors, new energy power plants adjust down } mq_c - \Delta q \\
\text{else} \\
\]
\[ q' = mq_e + q - |q_1| - |q_2| \]
\[ q'' = (m-1)q_e + q + up \]

Compare \( q' \) and \( q'' \) which is closer to the target value.

- The current reactive power generation value is greater than 0, and the reactive power needs to be adjusted downwards. The target reactive power value is still greater than 0. In this case, the number of Capacitors to be removed is calculated according to formula (2), if the remaining reactive power adjustment quantity less than the new energy power plant's unrealized value, it is allocated to each new energy power plant using equal-proportion or equal margin allocation strategy. If the remaining reactive power adjustment is greater than the new energy power plant's unrealized value, then calculate the multiple removal. Whether a capacitor is closer to the target value, the design flow chart is shown in figure 5.

**Start**

Whether or not Capacitors

**NO**

Capacitors or Reactors

**YES**

New Energy Power Plant adjustment(Δq)

\[ m = \frac{|Δq|}{q_q} \quad \text{if} \quad (m > c, m = c) \]

**NO**

Calculate the number of capacitors that exit (m)

\[ |Δq| - mq_c > q_1 + q_2 \]

**YES**

New Energy Power Plant adjust down|Δq|

Calculate the exit (m+1) capacitors and capacitors which is closer to the target

\[ |Δq| - mq_c > q_1 - q_2 \]

Comments 1:

\[ Δq' = (m+1)q_e - |Δq| \]
\[ if \quad (Δq' < up) \]

Exit m+1 Capacitors, new energy power plants adjust up Δq'

else

\[ q' = q - (m+1)q_e + up \]
\[ q'' = q - mq_e - q_1 - q_2 \]

Compare \( q' \) and \( q'' \) which is closer to the target value.

**Figure 5.** Scenario 4 design flow chart.
Comments 2:

\[ (mq_c - |\Delta q| < up) \]

Exit m Capacitors, new energy power plants adjust up \( mq_c - \Delta q \)

else

\[ q' = q - mq_c + up \]

\[ q'' = q - (m - 1)q_c - q_1 - q_2 \]

Compare \( q' \) and \( q'' \) which is closer to the target value.

- The current reactive power generation value is greater than 0, and the reactive power needs to be adjusted downwards. The target reactive power value is less than 0. In this case, all operating Capacitors are first removed, and the remaining reactive power adjustment is equal-proportion or equal margin allocation. Other strategies are allocated to various new energy power plants, the design flow chart is shown in figure 6.

**Figure 6.** Scenario 5 design flow chart.

- The current reactive power generation value is less than 0, and the reactive power needs to be adjusted downward. The target reactive power value is still less than 0. In this case, the reactive power remaining regulation is allocated to various new energy sources using a strategy such as equal-proportion or equal margin allocation, the design flow chart is shown in figure 7.
Figure 7. Scenario 6 design flow chart.

**Comments 1:**

\[
\text{if } ((m + 1)q_e - |\Delta q| < |q_1| + |q_2|) \\
\text{Input } m+1 \text{ Reactors, new energy plants adjust up } (m + 1)q_e - |\Delta q| \\
\text{else} \\
q' = q - mq_e - \text{down} \\
q'' = q - (m + 1)q_e + |q_1| + |q_2|
\]

**Comments 2:**

\[
\Delta q' = (m + 1)q_e - |\Delta q| \\
\text{if } (\Delta q' < |q_1| + |q_2|) \\
\text{Input } m+1 \text{ Reactors, new energy plants adjust up } \Delta q' \\
\text{else} \\
q' = q - (m + 1)q_e + |q_1| + |q_2| \\
q'' = q - mq_e - \text{down} \\
\text{Compare } q' \text{ and } q'' \text{which is closer to the target value.}
\]

4.2. Reactive power distribution algorithm for similar devices

- The same power factor

This distribution method makes each Generator have the same power factor. After eliminating non-adjustable Generator, the target total reactive power is calculated according to the target instruction.
According to the total active power of the adjustable Generator, the total reactive power is used to calculate the adjustable Generator target. The power factor is as in formula (3).

\[
\cos \phi = \frac{\sum P_{\text{Adjustable Generator}}}{\sqrt{\sum Q_{\text{Target}}^2 + \sum P_{\text{Adjustable Generator}}^2}}
\]  

(3)

Then according to the active power of each adjustable Generator, calculate the target reactive power of each adjustable Generator as shown in equation (4).

\[
Q_{\text{Target Generator}} = P_{\text{Generator}} \times \frac{\sqrt{1 - \cos^2 \phi}}{\cos \phi}
\]  

(4)

- **Equal-proportion (such as reactive reserve)**

This method allows all Generators to have the same percentage of reactive power as their upper and lower reactive power. According to the P-Q diagram of each Generator, the reactive power upper limit \(Q_{\text{max}}\) and the lower reactive power lower limit \(Q_{\text{min}}\) of each adjustable Generator's current operating point are obtained, and the deviations of the target reactive power and the ideal reactive power operating point are calculated as in formula (5).

\[
\frac{Q_1 - Q_{\text{min}}}{Q_{\text{max}} - Q_{\text{min}}} = \frac{Q_2 - Q_{\text{min}}}{Q_{\text{max}} - Q_{\text{min}}} = \ldots = \frac{Q_i - Q_{\text{min}}}{Q_{\text{max}} - Q_{\text{min}}} = \frac{(Q_{\text{Target}} - \sum Q_{\text{min}})}{\sum (Q_{\text{max}} - Q_{\text{min}})}
\]  

(5)

The reactive power allocated by the m-th Generator is shown in equation (6).

\[
Q_m = Q_{\text{min}} + (Q_{\text{max}} - Q_{\text{min}}) \times \frac{(Q_{\text{Target}} - \sum Q_{\text{max}})}{\sum (Q_{\text{max}} - Q_{\text{min}})}
\]  

(6)

Check whether the target reactive power exceeds the limit. If it exceeds the limit, use the limit-limited Generator as the non-adjustable Generator. The target reactive power is subtracted from the reactive power of the limit-limited Generator. Repeat the determination until there is no adjustable Generator.

- **Equal margin allocation**

This method has the goal of controlling the back-end generating Generators to have equal reactive up or down reserves. When the voltage needs to increase, there are more Generators with more reactive power and more backups and more reactive power, and when there is a need to reduce, more Generators with more reactive power are used. Reducing reactive power, this strategy ensures that the power plant has the maximum reactive power reserve.

The voltage of the high-voltage bus is lower than the target value given by the system, that is, each control generator is required to increase the reactive power. The size of the reactive power to be adjusted is allocated according to the magnitude of the margin of the reactive power of each Generator. The increment of reactive power distribution of each Generator participating in the control is formula (7).

\[
\Delta Q_m = \frac{Q_{\text{max}} - Q_{\text{min}}}{\sum_j (Q_{j,\text{max}} - Q_j)} \times (Q_{\text{Target}} - Q_{\text{Generator Actual}})
\]  

(7)

If the voltage of the high voltage bus is higher than the target value given by the system, that is, each control Generator is required to reduce the reactive power, the reduction value should also be allocated according to the magnitude of the reactive power reduction margin of each Generator. The allocated increment of reactive power is formula (8).
\[ \Delta Q_m = \sum_j (Q_j - Q_{\text{min}}) \times (Q_{\text{Target}} - Q_{\text{Generator Actual}}) \] (8)

**Comments:**
- \( Q_{\text{Target}} \): Total plant target of reactive power,
- \( Q_{\text{Generator Actual}} \): Total reactive power,
- \( Q_{\text{max}} \): The upper limit of reactive power of the \( j \)-th unit,
- \( Q_{\text{min}} \): The lower limit of reactive power of the \( j \)-th unit,
- \( Q_j \): The actual reactive power of the \( j \)-th unit,
- \( P_{\text{Adjustable Generator}} \): Adjustable Generator active power.

### 5. Instance applications

Taking a 220 kV terminal Substation as an example, the 220 kV Substation is connected with a 500 kV Substation and the two main Transformers of the 220 kV Substation are all 180 MVA. The Substation has a large-scale hybrid renewable new energy source, including 2 wind farms and 3 photovoltaic power plants with a total installed capacity of 678.5 MW (ZGS Wind Farm (247.5 MW), MT Wind Farm (141 MW), BDC Photovoltaic Power Plant (130 MW), SMH Photovoltaic Power Plant (60 MW), XJK Photovoltaic Power Plant (100 MW)), as shown in figure 8. At present, the main equivalent load of the 220 kV Substation is 20 MW (with two 110 kV electric traction Substations and one 110 kV step-down Substation). On the basis of this voltage coordinated control strategy, the Substation operation data is dynamically calculated in real time, and the adjustment strategy is given in a visual way to ensure the voltage stability of the grid point, voltage control system deployment diagram is shown in figure 9. The main working interface of the system is shown in figure 10. The system mainly includes online monitoring, alarm window, historical event query, database configuration tool, parameter configuration tool, active and reactive configuration tool, optimization strategy calculation, communication, system dual-machine redundancy switching and other functions. Through this voltage control strategy, the Substation is operating for nine months. When the voltage is abnormal, the system promptly gives advice on adjustments in a visual manner and guides the operation personnel to operate. Reduce the workload of operation and maintenance personnel and improve operational reliability. The 220 kV terminal variable resistance 110 kV busbar parallel operation, terminal change, photovoltaic and wind power normal operation, bus voltage normal condition table, as shown in table 1. The 220 kV terminal is changed to the 110 kV busbar in parallel operation, the terminal changes, the photovoltaic and wind power operate normally, and the upper limit of the bus voltage is exceeded, as shown in table 2.

![Figure 8. Schematic diagram of wind and photovoltaic hybrid access network.](image-url)
Table 1. Bus voltage normal condition table.

| 220 kV Terminal Substation | BDC Photovoltaic Power Plant | SMH Photovoltaic Power Plant | XJK Photovoltaic Power Plant | MT Wind Farm |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|---------------|
| 110 kV bus voltage (kV)     | 112 kV                      |_features                    | Input                       | features      | Input                       | features |
| Ua (kV)                     | 64.5                        | Communication status        | Normal                      | Communication status | Normal                  | Normal |
| Ub (kV)                     | 65.7                        | Operating status            | Normal                      | Operating status | Normal                  | Normal |
| Uc (kV)                     | 64.7                        | Blocking signal             | No                          | Blocking signal | No                      | No      |
| 35kV#1 Capacitor            | Input                       | Remote or local             | Local                       | Remote or local | Local                   | Local   |
| 35kV#2 Capacitor            | Input                       | Reactive lock               | No                          | Reactive lock  | No                      | No      |
| 35kV#3 Capacitor            | Quit                        | Actual reactive             | 0.00                        | Actual reactive | 0.1                     | 1.0     |
| 35kV#4 Capacitor            | Quit                        | Reactive power can be increased | 12.6                       | Reactive power can be increased | 12.5               | 8 10                     |
| Transformer active power (MW) | -96.9                      | Reactive power can be reduced | 12.6                       | Reactive power can be reduced | 12.7               | 10 33.5                 |
| Transformer power factor    | -0.97                       | Reactive power distribution target value | | Reactive power distribution target value | | 33.5 |

Table 2. The upper limit of the bus voltage.

| 220 kV Terminal Substation | BDC Photovoltaic Power Plant | SMH Photovoltaic Power Plant | XJK Photovoltaic Power Plant | MT Wind Farm |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|---------------|
| 110 kV bus voltage (kV)     | 118.5                       | features                    | Input                       | features      | Input                       | Input |
| Ua                          | 68.4                        | Communication status        | Normal                      | Communication status | Normal                  | Normal |
| Ub                          | 68.3                        | Operating status            | Normal                      | Operating status | Normal                  | Normal |
| Uc                          | 68.3                        | Blocking signal             | No                          | Blocking signal | NO                      | NO     |

Control Strategy
The 110 kV bus voltage is -3%~+7% (107~118), which is set within the range of (109-116). According to the regulations, there is no need to adjust normally.
Comprehensively, and a voltage optimization coordinated control strategy is proposed. The voltage control strategy can form a set of voltage optimization coordinated control strategies to adapt to different hybrid new energy access conditions. Reliable demand Q is reliably judged when large-scale hybrid new energy sources cause grid voltage quality problems. When carrying out reactive power distribution, there is an optimal reactive power distribution and adjustment sequence to avoid causing large voltage changes.

The voltage control strategy can adapt to the situation where different types of renewable energy of different voltage levels are centralized and connected to the Substation. By implementing this control strategy, the voltage quality requirements can be met, which has a certain degree of promotion.

6. Conclusions

- Substations connected with large-scale hybrid new energy sources are considered as research objects, and integrated Transformers, Transformer taps, and new energy power plants AVC are considered comprehensively, and a voltage optimization coordinated control strategy is proposed.
- The voltage control strategy can form a set of voltage optimization coordinated control strategies to adapt to different hybrid new energy access conditions.
- Reliable demand Q is reliably judged when large-scale hybrid new energy sources cause grid voltage quality problems. When carrying out reactive power distribution, there is an optimal reactive power distribution and adjustment sequence to avoid causing large voltage changes.

The voltage control strategy can adapt to the situation where different types of renewable energy of different voltage levels are centralized and connected to the Substation. By implementing this control strategy, the voltage quality requirements can be met, which has a certain degree of promotion.

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