Design and implementation of active frequency control algorithm for virtual power plant based on flexible resource rapid response

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Abstract: At present, the power generation resources in the power system show a clean and decentralized development trend. These distributed generation resources are small in scale and lack of special regulation system. Aiming at the uncertain and intermittent output characteristics of photovoltaic distributed generation virtual power plant (VPP), this paper puts forward the scheme of active frequency response intelligent control, completes the hardware and communication design, algorithm design and software implementation. Finally, the actual engineering practice is carried out in three photovoltaic VPP in Zhongshan City, Guangdong Province, which verifies the feasibility of relevant schemes and algorithms, and provides a certain basis for the next research.

1. Introduction

Under the current situation, the power generation resources in the power system show a clean and decentralized development trend. These distributed generation resources are small in scale and scattered in layout. At present, there is no special regulation system, which can not fully meet the requirements of the rapid promotion of power marketization.

Virtual power plant (VPP), as an independent controllable system containing flexible loads and a variety of distributed generators, organically integrates distributed generators, loads, energy storage devices, converters and monitoring and protection devices, which can flexibly switch between grid connected operation and isolated island operation modes, so as to greatly improve the reliability of power supply security and main network friendliness. [1] There are a lot of flexible resources existed in the VPP, such as various energy storage equipment, new energy power generation equipment, etc. This kind of equipment responds quickly. By adjusting its power output, the active power of the VPP can quickly respond to the frequency fluctuation of the external network, so that the VPP can provide active frequency support to the outside world. [2]

In the photovoltaic distributed generation VPP, its power output is random and intermittent, which is not conducive to maintaining the active power balance of the photovoltaic distributed generation VPP, and even serious frequency oscillation.[3] In this case, how to adjust effectively and control the frequency of photovoltaic distributed generation VPP intelligently needs further exploration. The purpose is to quickly and effectively realize the frequency adjustment to ensure the stable and reliable operation of the system. [4]
2. Design of active frequency control algorithm for photovoltaic distributed generation VPP

The project adopts the cluster primary frequency regulation control algorithm in the VPP based on feedback optimization. The structure of feedback optimization is shown in Figure 1.

![Feedback optimization control structure](image1)

Specifically, after the VPP collects the frequency deviation of the parallel node, the active power gap in the current state is calculated according to the deviation and the reported regulation characteristics of the VPP, and the optimal power flow solution algorithm based on second-order cone relaxation is used to dynamically solve the active power allocation problem. After the active power is distributed, each controlled equipment is controlled in place. At this time, the power gap is calculated again according to the measurement information, the above optimization problem is corrected, and the iteration converges to the optimal solution.

### 2.1. Active frequency response control process of VPP

When the power grid frequency changes beyond the manually defined active frequency response dead zone, the fast control device of the VPP forms the control target command according to the active frequency response active frequency droop characteristics (realized by setting the frequency and active power broken line function), and can distribute the control command of each unit according to the control constraint conditions and the operating conditions of the unit. It shall be forwarded to the monitoring system and the unit for execution through fast Ethernet.[5]

The schematic diagram of active frequency response control process (Fig. 2) is as follows:

![Schematic diagram of active frequency response control flow of VPP](image2)
1) Algorithm 1 - Initial value of FM target command: when the power grid frequency changes beyond the manually defined dead zone of active frequency response, the system forms the initial value of control target command according to the active frequency droop characteristics of active frequency response (realized by setting the broken line function of frequency and active power).

2) Algorithm 2 - FM target command execution value: coordinate control logic judgment according to control constraints and AGC control target value to form control target command execution value.

3) Algorithm 3 - Active control allocation command for each unit: combined with the operation information of the unit, the active control command of each unit is formed through the definition of control command allocation strategy, and transmitted to the monitoring system through fast Ethernet or directly distributed to each unit for execution.

4) Performance index algorithm: It mainly includes theoretical contribution power, actual contribution power, primary frequency modulation contribution rate, correct frequency modulation action rate, and real-time frequency modulation response.

2.2. Active frequency control algorithm of photovoltaic distributed generation VPP

2.2.1. Initial value algorithm for FM target command

The active power variation is realized by the given active power frequency droop characteristic curve function (Fig. 3):

\[
\Delta P = P_{0} - P_{n} \left( \frac{f - f_{d}}{f_{n}} \right) \frac{1}{8%}
\]

Parameter definition:
- \( f_{N} \), system rated frequency: 50Hz
- \( f_{d} \), Action threshold for active frequency response (for Photovoltaic power station): dead band is set to ± 0.06Hz; At \( f > 50.06 \text{Hz} \), \( f_{d} = 50.06 \text{Hz} \); At \( f < 49.94 \text{Hz} \), \( f_{d} = 49.94 \text{Hz} \)
- \( P_{n} \), rated power: installed capacity, unit MW or kW, pay attention to unit consistency
- \( \delta \% \), Adjustment rate: 3% for photovoltaic power station

Input:
- \( f \), Real time frequency value of parallel node
- \( P_{0} \), Initial value of parallel power

Output:
- \( P_{\text{target}} \), FM control target initial value

Constraints:
When $|\Delta P| > P_{N*}^\delta$, then $\Delta P = P_{N*}^\delta$

- When high frequency disturbance ($f > 50.06$Hz for Photovoltaic power station), $P_0 < 10\% P_N$, It can no longer be adjusted downward, as $P_{\text{target}} = P_0$
- When low frequency disturbance ($f < 49.94$Hz for Photovoltaic power station), $P_0$ is Maximum generating capacity (There is no up regulation space, and there is no need to reserve spare FM capacity.) , then $P_{\text{target}} = P_0$

2.2.2. *Coordinated control algorithm with AGC*

The FM target command execution value is algebraic sum of AGC command value ($P_{\text{AGC}}$) and active frequency response adjustment $\Delta P$.

Among $\Delta P = P_{\text{target}} - P_0$

That is, the execution value of FM target command:

$$P = P_{\text{AGC}} + \Delta P = P_{\text{AGC}} + P_{\text{target}} - P_0 \quad (3)$$

Constraints:

- When grid frequency $f > 50.1$Hz, and AGC Instruction value ($P_{\text{AGC}}$) $> P_0$, then $P = P_{\text{target}}$
- When grid frequency $f < 50.1$Hz, and AGC Instruction value ($P_{\text{AGC}}$) $< P_0$, then $P = P_{\text{target}}$

2.2.3. *Instruction allocation algorithm for target value unit*

The optimal control algorithm for the characteristics of VPP, on the premise of meeting the control target value of active frequency response coordinated with AGC and various safety constraints of power grid and equipment, and combined with the operation status of the unit, allocates the overall control target command, which can provide the following distribution strategies (consistent adjustment direction, smooth adjustment and optimization strategy):

Proportional distribution method:

$$P_1 = P_2 = \ldots = P_n = P/n$$  (4)

Constraints: single unit control difference $\Delta P_n$ meets the climbing rate requirements.

Similarity margin distribution method:

$$P_1 = P_0 + \left(\frac{P - P_0}{n}\right)$$  \ldots

$$P_n = P_n0 + \left(\frac{P - P_0}{n}\right)$$  (6)

Constraints: single unit control difference $\Delta P_n$ meets the climbing rate requirements.

2.2.4. *Real time index algorithm of active frequency response*

The adjustment of active frequency response frequency step disturbance process of photovoltaic power station is shown in the following figure (Figure 4).
1) Load response lag time of active frequency response
The load response lag time of active frequency response refers to the time required for the VPP from the grid frequency crossing the dead zone of active frequency response to the load change of the VPP.

2) Adjustment and stabilization time of active frequency response
   - $t_{0.9}$: When the power grid frequency changes beyond the dead zone of the active frequency response of the VPP, the load adjustment amplitude of the active frequency response of the VPP shall reach 90% of the maximum load adjustment amplitude of the theoretical calculated active frequency response within the required time;
   - $t_s$: When the power grid frequency change exceeds the active frequency response dead band of the VPP, within the required time, the average deviation between the actual output of the VPP and the response target of the VPP shall be within ± 1% of the rated active output of the VPP.

3) Active frequency response performance index of photovoltaic power station

   - Load response lag time of active frequency response: $t_{thx} \leq 2s$
   - Adjustment and stabilization time of active frequency response: $t_{0.9} \leq 5s, t_s \leq 15s$

### 3. Engineering implementation of algorithm
At present, photovoltaic power generation accounts for the largest proportion of distributed power generation in Zhongshan, Guangdong. The real-time monitoring networking schemes adopted by photovoltaic power stations are different according to the type of grid connected inverter and the power response time of inverter.

The intelligent control sub station of the VPP is deployed in Changhong Photovoltaic Station, Galanz Photovoltaic Station and Midea Photovoltaic Station to complete self-discipline control.

According to the actual situation of field equipment of Changhong Photovoltaic Station, Galanz Photovoltaic Station and Midea Photovoltaic Station, two equipment transformation schemes in Photovoltaic Station are designed as follows:

1) After fast control communication transformation, the inverter is directly connected to the intelligent control substation of the VPP to realize the fast power control of the photovoltaic inverter. Support steady-state AGC / AVC control of photovoltaic power station and primary frequency regulation of photovoltaic power station.

2) The inverter is connected to the intelligent control substation of the VPP through the existing station monitoring system to realize the conventional power control of the photovoltaic inverter. Support steady-state AGC / AVC control of photovoltaic power station.
The layout transformation scheme of demonstration application in Changhong Photovoltaic Station, Galanz Photovoltaic Station and Midea Photovoltaic Station is as follows (Table 1):

| Tab. 1 Demonstration application scheme of photovoltaic power plant |
|---|
| **number** | **Point distribution equipment** | **Total capacity (MW)** | **inverter** | **Single capacity (kW)** | **Total number** | **Transformation scheme** |
| 1 | Changhong Photovoltaic Station | 13.16 | | 500 | 18 |
|  | | | | 630 | 2 |
|  | | | | 30 | 44 |
|  | | | | 20 | 52 |
| 2 | Galanz Photovoltaic | 52.38 | | 40 | 859 |
|  | | | | 28 | 560 |
| 3 | Midea Photovoltaic Station | 23.87 | | | | Option 2 |
| **Summary statistics** | **Total controllable capacity (MW)** | 89.41 | **Fast controllable total capacity (MW)** | 10.26 |

After the transformation of demonstration application, all demonstration application photovoltaic power stations have the function of coordinating and controlling with the intelligent control master station of VPP. The total capacity of controllable photovoltaic power stations is 89.41MW, of which the power generation output capacity of photovoltaic power stations supporting rapid power control is 10.26MW.

The active frequency step test is conducted at the substation of Changhong VPP. The disturbance test parameters are shown in the following table (Table 2):

| Tab. 2 Table of test parameters |
|---|
| **number** | **Parameter name** | **Parameter value** |
| 1 | Adjustment coefficient (%) | 2 |
| 2 | Installed capacity (MW) | 10.26 |
| 3 | Sampling period (MS) | 100 |
| 4 | Step upper limit frequency (Hz) | 50.1 |
| 5 | Step lower limit frequency (Hz) | 49.9 |

The test results of active frequency step disturbance are shown in the following table (Table 3):

| Tab. 3 Table of test results |
|---|
| **number** | **Frequency disturbance type** | **Step experiment disturbance value (Hz)** | **Response time (s)** | **Adjustment time (s)** | **Target adjustment** | **Active power before step (MW)** | **Active power after step (MW)** | **Control deviation (N)** |
| 1 | Step up disturbance | 50.15 | 0.281 | 0.280 | -0.013 | 3.00456 | 2.41456 | 2.09 |
| 2 | Step down disturbance | 49.8 | 0.199 | 0.195 | 1.026 | 1.09745 | 2.1135 | 1.00 |

According to the statistical analysis in the above table, the average active power regulation time of the active frequency step test of the substation of Changhong VPP (that is, when the power grid frequency change exceeds the active frequency response dead band of the VPP, the average deviation between the actual output of the VPP and the response target of the VPP shall be within ± 1% of the rated active output of the VPP within the required time) is about 200ms, It shows good fast response performance.

4. Conclusion

By effectively adjusting and intelligently controlling the frequency of the photovoltaic distributed
power VPP, maintaining its active power balance and eliminating serious frequency oscillation, the frequency adjustment can be realized quickly and effectively to ensure the stable and reliable operation of the system.

The active frequency control algorithm design of VPP based on flexible resource and rapid response is based on the active frequency intelligent control project of photovoltaic distributed generation VPP in Zhongshan City, Guangdong Province. The results of this practice meet the predetermined verification objectives, and reflect the good fast response performance of the algorithm under certain constraints. This engineering practice, aiming at the intermittent characteristics of new energy after grid connection, provides a certain research method and engineering demonstration for its intelligent frequency control.

However, for the frequency control of photovoltaic VPP and other flexible resources, there are still many aspects that need to be further studied, such as the participation of more constraints in model optimization, the improvement of algorithm convergence performance and computational efficiency, etc. These are the topics to be studied in the next step.

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