Adaptive droop control of DC distribution network considering photovoltaic output power margin

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Abstract. When multiple photovoltaic power sources are connected in parallel in the DC distribution network, photovoltaic with different output have differences in the regulation capacity of unbalanced power of the system. In order to make full use of the power margin of photovoltaic to adjust the DC bus voltage, this paper proposes an adaptive droop control of DC distribution network considering the photovoltaic output power margin. The voltage signals of the input and output terminals of the PV side converter are used to judge the system load change and the output of the photovoltaic power supply. On the basis of traditional droop control, the droop coefficient is modified based on the input voltage deviation of PV side converter to realize the reasonable distribution of the unbalanced power between photovoltaic power sources with different power margin. The output impedance characteristic model of PV side converter is established, and the adaptive droop control proposed in this paper can effectively improve the stability of multi PV parallel connected DC distribution system. Finally, the effectiveness of the proposed control method is verified by MATLAB/simulink platform simulation.

1. Introduction
With the wide application of distributed generation and the increase of DC load, multiple photovoltaic power sources are connected in parallel to DC distribution network structure through converter, which can not only meet the demand of local DC load, but also be a beneficial supplement to external transmission and distribution network, and has been widely concerned [1-2].

Droop control is widely used in DC distribution network because of its high reliability, communication independence and good redundancy [3]. The droop coefficient of traditional droop control is set in proportion to the capacity of distributed generation. When the total unbalanced power of the system is fixed, the unbalanced power borne by each converter is inversely proportional to its droop coefficient [4]. However, the inherent randomness and volatility of photovoltaic power supply bring new challenges to the reliable operation of droop control in parallel system.

In [5], a droop control strategy based on voltage tracking at the head-end of feeder is proposed, which can reduce line loss on the basis of ensuring good bus voltage control characteristics. In [6], [7] the coordinated control of energy storage device and photovoltaic power supply is used to maintain the power balance of DC distribution network. In [8], the virtual capacitance of DC side is much larger than the actual capacitance, which improves the transient regulation capability of DC microgrid. In [9], [10] the output voltage deviation information of converter is used to adjust the operation point and droop coefficient of droop control in real time to reduce the DC voltage deviation. However, the virtual inertia control method can only regulate the output voltage of the converter when it changes,
and the droop coefficient will return to the original value after the system is re-stabilized, so it can not maintain its regulating effect all the time. In the existing literature, the change of droop coefficient is still based on the change of grid voltage, and the uncertainty of new energy output is not considered. For the parallel system of multiple photovoltaic power sources, the voltage difference between the grid connected terminals of each converter is small, and the voltage variation characteristics of the grid connected terminals can not fully reflect the output variation characteristics of PV.

Based on the analysis of the influence of photovoltaic output on the input voltage of photovoltaic side converter, this paper uses the voltage variation of input and output sides of converter to judge the load and photovoltaic output, and introduces the correction based on the input voltage deviation of photovoltaic side converter to the droop coefficient, so that the photovoltaic power supply with large output can generate more power when the system load increases, and the photovoltaic power supply with small output can generate less power when the system load is reduced. The output impedance model of the PV side converter is established, and the influence of the proposed optimization method on the system stability is analyzed theoretically. Finally, based on MATLAB/Simulink, a simulation model of multi photovoltaic power parallel connected to DC distribution network is built to verify the feasibility of the proposed control strategy.

2. Topology of multi PV converters connected in parallel to DC distribution network

The topological structure of multi photovoltaic parallel access DC distribution network system is shown in Figure 1, which mainly includes photovoltaic power supply, DC load and AC power grid. In order to study the influence of photovoltaic output on the voltage of photovoltaic side, three photovoltaic power sources with equal rated capacity are used in this paper. $U_{\text{pv}}$, $I_{\text{pv}}$ and $P_{\text{pv}}$ are the output voltage, current and power of PV, respectively. $U_{\text{o}}$, $I_{\text{o}}$ and $P_{\text{o}}$ are the output voltage, current and power of PV side DC/DC, respectively; $I_{\text{d}}$ and $P_{\text{d}}$ are the input DC bus current and power of PV side DC/DC, respectively; $C_{\text{pv}}$ is the input capacitance of PV side DC/DC; $C_{\text{o}}$ is the output capacitance of PV side DC/DC; $R_{\text{d}}$ is the equivalent impedance of load; the local DC rated load is $P_{\text{dc}}$.

The DC distribution network exchanges energy with the AC network through the grid side G-VSC converter.

![Figure 1. Topology of multi photovoltaic parallel connected DC distribution network system.](image)

Under normal circumstances, the grid-side converter assumes the role of stabilizing the DC bus voltage, and the photovoltaic side DC/DC converter operates in MPPT mode. When the AC grid voltage sag and other faults need certain active power and reactive power support, the grid side converter switches from constant voltage control to active and reactive power (PQ) control, and the
grid side G-VSC converter does not undertake the bus voltage regulation task of DC distribution network; The photovoltaic side converter switches from MPPT control to droop control, which assumes the role of stabilizing the bus voltage of the DC distribution network and output constant power to the AC power network and DC load.

3. Adaptive droop control of DC distribution network considering photovoltaic output power margin

3.1. Relationship between input voltage of PV side converter and power margin of PV

The maximum output power of PV is the power margin of PV. The droop control depends on the output power margin of PV. When the PV has enough power margin, according to the output power characteristics of PV [11], the photovoltaic output current is equal to the short-circuit current in the charging stage of the capacitor on the photovoltaic side. When the maximum output power point is reached, the output power will decrease with the increase of voltage, and finally achieve the balance of input and output power of photovoltaic side converter.

The output characteristic equation of PV is [12]:

\[
P_{pv} = [I_{sc}(R_s + R_p)U_{pv} - U_{pv}^2 - P_{pv}R_s]/R_p + U_{oc} - I_{sc}(R_s + R_p)U_{pv}/R_p e^{q(U_{oc} - R_s U_{pv})/kT}
\]

Where: \(A\) is the ideal constant of photovoltaic power diode; \(R_s\) is the series resistance, \(\Omega\); \(R_p\) is the parallel resistance, \(\Omega\); \(q\) is the amount of charge; \(I_{ph}\) is the photogenerated current, \(A\); \(I_{sc}\) is the short circuit current, \(A\); \(K\) is the Boltzmann constant; \(T\) is the ambient temperature, \(^\circ C\); \(U_{oc}\) is the open circuit voltage, \(V\).

As shown in Figure 2, \(P_{mppt}^*\) is the maximum output power of PV under the rated condition of 25\(^\circ\)C and 1000W/m\(^2\). When the output of photovoltaic power decreases due to the decrease of irradiance, the increase of temperature, the increase of shadow coverage area and other factors, the power margin of PV becomes \(P_{mppt}^-\); when the output of photovoltaic power increases due to the increase of irradiance, the increase of temperature and other factors, the power margin of PV becomes \(P_{mppt}^+\).

When the rated load of PV is \(P_{in}\), the rated voltage of photovoltaic side \(U_{pv}^*\) can be calculated according to formula (1). When the load increases, the maximum output power is \(\Delta P_{zf}\). When the PV output decreases, the PV side voltage will decrease from \(U_{pv}^*\) to \(U_{pv}^+\) and the PV available power will
be \( \Delta P_{st} \); when the PV output increases, the PV side voltage will increase from \( U'_{pv} \) to \( U''_{pv} \) and the PV available power will be \( \Delta P'_{st} \).

Therefore, when \( U'_{pv} > U''_{pv} \), the output power margin of PV is proportional to \( (U'_{pv} - U''_{pv}) \). When \( U'_{pv} < U''_{pv} \), the output power margin of PV is inversely proportional to \( (U''_{pv} - U'_{pv}) \).

### 3.2. Adaptive droop control of DC distribution network considering photovoltaic output power margin

**P-U** traditional expressions for droop control are:

\[
U_{oi} = U^*_{oi} + k_{\text{droop}}(P^*_{oi} - P_{oi})
\]

\[
k_{\text{droop}} = \frac{U^*_{oi} - U_{oi\text{min}}}{P^*_{\text{mppt}} - P^*_{oi}}
\]

Where: \( U^*_{oi} \) is the rated output voltage; \( P^*_{oi} \) is the output power command value; \( P^*_{\text{mppt}} \) is the maximum output power under the rated condition of PV; \( U_{oi\text{min}} \) is the minimum allowable voltage when the distributed generation outputs the maximum power. The droop coefficient of adaptive droop control for DC distribution network considering photovoltaic output power margin is as follows:

\[
\Delta k_{\text{droop}} = k_{\text{droop}} + \Delta k_{\text{droop}} + \Delta k_{\text{droopb}}
\]

\( \Delta k_{\text{droop}} \) is the correction of droop coefficient when the system load decreases; \( \Delta k_{\text{droopb}} \) is the correction of droop coefficient when the system load increases. When judged as load increases, \( \Delta k_{\text{droopb}} = 0 \), in order to make the rated output PV also participate in the power regulation, take \( \mu(U^*_{m} - \Delta U_{m} - U_{pv}) \) as a step to reduce the droop coefficient increment \( \Delta k_{\text{droopb}} \) of the converter whose PV side the voltage is higher than \( (U^*_{m} - \Delta U_{m}) \). Before the load cut-off voltage is restored to the rated voltage, the values of \( \Delta k_{\text{droop}} \) and \( \Delta k_{\text{droopb}} \) are kept, so that the PV with large power margin can output more power, and the photovoltaic droop coefficient with small power margin remains unchanged; when the load is judged to be reduced, \( \Delta k_{\text{droopb}} = 0 \), in order to make the photovoltaic power supply with rated output also participate in power regulation, take \( -\mu(U^*_{m} + \Delta U_{m} - U_{pv}) \) as a step to reduce the droop coefficient increment \( \Delta k_{\text{droopb}} \) of the converter whose PV side voltage is lower than \( (U^*_{m} + \Delta U_{m}) \), and the values of \( \Delta k_{\text{droop}} \) and \( \Delta k_{\text{droopb}} \) are maintained until the load is put back into operation and the rated voltage is restored.

If the droop coefficient is too small, it will lead to large circulation loss, so it is necessary to limit the minimum value of the droop coefficient. The setting method of the minimum droop coefficient is [13]:

\[
k_{\text{droopmin}} = \alpha k_{\text{droop}} \quad \alpha \in [1, 5]
\]

The reasonable sampling time is set to discretize the voltage signals on both sides. \( \varepsilon \) is the judgment threshold of the output voltage of the converter. Draw the calculation flow chart of sag coefficient correction \( \Delta k_{\text{droop}} \) and \( \Delta k_{\text{droopb}} \), as shown in the figure 3.
Figure 3. Calculation flow chart of $\Delta k_{\text{droop_a}}$ and $\Delta k_{\text{droop_b}}$.

When the system load increases, the droop coefficient changes as shown in Figure 4(a). The dotted line is the extension line of the original droop coefficient $k_{\text{droop}},$ and the PV with large output will generate more power. When the system load decreases, the droop coefficient changes as shown in Figure 4(b). The dotted line is the extension line of the original droop coefficient $k_{\text{droop}},$ and the PV with small output will generate less power.

Figure 4. Changes of droop coefficient.
4. Design of adaptive droop control system for DC distribution network considering photovoltaic output power margin and modeling of output impedance characteristics

4.1. Design of voltage and current double loop control system based on P-U droop control

The control block diagram of voltage and current double loop control of adaptive P-U droop control for PV side DC/DC converter is shown in Figure 5.

![Control block diagram](image)

Figure 5. Control block diagram of voltage and current double loop control of P-U droop control.

The main function of the voltage outer loop is to determine the reference value of the output current of the DC/DC converter \( I_d^* \) to stabilize the output voltage. The function of the current inner loop is to realize the current tracking control according to the \( I_d^* \). The droop coefficient correction is adjusted by inputting \( U_{pv} \) and \( U_o \) signals. \( G_{DC/DC-I} \) is the transfer function between the output current \( I_d \) and the duty cycle \( D \) of the PV side DC/DC converter.

4.2. Equivalent impedance model of parallel PV side converter

In this paper, the state equation of photovoltaic side DC/DC converter [14-16] is listed, and on this basis, \( G_{DC/DC-I} \) is derived. The state variables of photovoltaic side DC/DC converter are selected as output current \( I_d \) and output voltage \( U_o \). Under the condition of transformer T turns ratio of 1:1 and no loss, the state space equation is listed:

\[
\begin{bmatrix}
\frac{dl_d(t)}{dt} \\
\frac{dU_o(t)}{dt}
\end{bmatrix} = \begin{bmatrix}
0 & \frac{1}{L_s} \\
-\frac{1}{C_o} & -\frac{1}{C_oR_o} - \frac{2D-1}{2fC_oL_s} \\
\end{bmatrix} \begin{bmatrix}
l_d(t) \\
U_o(t)
\end{bmatrix} + \begin{bmatrix}
\frac{2D-1}{L_s} \\
\frac{D(1-D)}{2fC_oL_s}
\end{bmatrix} U_m
\]

(6)

\( Y = [1 \quad 0] \begin{bmatrix}
l_d(t) \\
U_o(t)
\end{bmatrix} \)  

(7)

The state space equations are transformed into complex frequency domain by Laplace transform, and the state variable \( I_d(s) \) is obtained by solving the algebraic equations:

\[
I_d(s) = \frac{(2D-1)(s + \frac{1}{C_oR_o})}{s^2 + \frac{1}{C_oR_o}s + \frac{1}{C_oL_s}} + \frac{D(1-D)}{2fC_oL_s}
\]

(8)

The expression of \( G_{DC/DC-I} \) is:

\[
G_{DC/DC-I} = \frac{\partial I_d(s)}{\partial D}
\]

(9)
According to figure 6, the system transfer function related to the droop coefficient is obtained:

\[ U_o = \frac{G_{p1} G_b}{C_s + G_{p1} G_b} \left( U_o^r + k_{\text{droop}} \Delta P_o \right) - \frac{1}{C_s + G_{p1} G_b} I_o \]  \hspace{1cm} (10)

Small signal processing is carried out for \( \Delta P_o \) of formula (10):

\[ U_o = \frac{G_{p1} G_b}{C_s + G_{p1} G_b} \left( U_o^r + k_{\text{droop}} \Delta I_o \right) - \frac{1}{C_s + G_{p1} G_b} I_o \]  \hspace{1cm} (11)

The expression of output impedance when droop control is equivalent to voltage source is obtained:

\[ Z_{c1} = \frac{1 - G_{p1} G_b k_{\text{droop}} \Delta U_o}{C_s + G_{p1} G_b} \]  \hspace{1cm} (12)

The equivalent output impedance \( Z_{bl} \) of parallel system is expressed as follows:

\[ \frac{1}{Z_{c1}} + \frac{1}{Z_{c2}} + \frac{1}{Z_{c3}} = \frac{1}{Z_{bl}} \]  \hspace{1cm} (13)

In the topology shown in Figure 1, the PV side converter and the grid side converter are interactive subsystems. The PV side converter is equivalent to a voltage source in droop control mode, and the grid side converter is equivalent to a current source in PQ control mode. In the two interactive subsystems, the smaller the impedance of the subsystem equivalent to voltage source is, the larger the impedance of the subsystem equivalent to current source is, and the more stable the system is. It can be seen from formula (13) that the reduction of equivalent output impedance of any photovoltaic converter will reduce equivalent output impedance \( Z_{bl} \) of parallel system and improve system stability.

4.3. Example analysis

The main parameters of the system are shown in Table 1.

| Parameter                                    | Value          |
|----------------------------------------------|----------------|
| Rated DC voltage/V                          | 800            |
| Rated capacity of PV1~PV3/kW                | 25.02          |
| Local rated DC load \( P_{dc}^r \)/kW       | 32             |
| DC distribution network outward transmission | 20             |
| Allowable fluctuation range of DC voltage/V | \( \pm 10\% U_o^r \) (720~880) |
| Filter inductor/H                           | 0.00015        |
| Filter capacitor/F                          | 0.002          |
| Switching frequency/Hz                      | 500            |
| Sampling frequency of voltage at both ends  | 500            |
| Coefficient \( \mu \)                       | 0.00002        |

Suppose that the temperature of the PV1~PV3 is 25℃, of which the irradiance of PV1 is 1300 W/m², the irradiance of PV2 is 1000W/m², and the irradiance of PV3 is 800W/m². Under rated load condition, according to formula (1), the output voltage of PV1~PV3 is about 178V, 173.5V and 167V when the output power is equally divided. Assuming that the total output power of the DC distribution network changes from the rated power of 52kW to 60kW at a certain time, and the simultaneous drop time of output voltage is 0.1s. Then the droop coefficients of PV1~PV3 are changed from 0.0104 to 0.0054, 0.0075 and 0.0104 respectively. According to formula (12), the output impedance bode diagrams of
the three PV converters before and after the droop coefficient optimization are drawn, as shown in Figure 6. The dotted line in the Bode diagram represents the traditional droop control, and the solid line represents the adaptive droop control proposed in this paper. Figure 7 (a), (b) and (c) are the equivalent output impedance bode diagrams of DC/DC$_1$, DC/DC$_2$ and DC/DC$_3$ respectively.

It can be seen from Figure 6 that the adaptive droop control of DC distribution network considering photovoltaic output power margin reduces the output impedance amplitude of all photovoltaic converters in the system. According to formula (13), the equivalent output impedance $Z_{bl}$ of parallel system will also decrease. The adaptive droop control proposed in this paper will improve the stability of the system when the load changes.

5. Simulation model verification and comparative analysis of adaptive droop control for DC distribution network considering photovoltaic output power margin

Based on MATLAB/Simulink, the parallel connection of PV converter to DC distribution network as shown in Figure 1 is built, and the simulation is carried out to verify the feasibility of adaptive droop control of DC distribution network considering PV output power margin proposed in this paper. The main simulation parameters of the system are shown in Table 1, the temperature of the PV$_1$–PV$_3$ is 25°C, the irradiance of PV$_1$ is 1300W/m$^2$, the irradiance of PV$_2$ is 1000W/m$^2$, and the irradiance of PV$_3$ is 800W/m$^2$. 

![Figure 6. Equivalent output impedance bode diagram of photovoltaic side converter.](image-url)
5.1. Simulation and comparative analysis of adaptive droop control and traditional droop control for DC distribution network considering photovoltaic output power margin when load increases

The adaptive droop control proposed in this paper is compared with the traditional droop control method shown in formula (2-3) when the system load increases. The output power of DC distribution network keeps the rated value unchanged. The value of local DC load is 32kW in 1 ~ 2 seconds, 37kW in 2 ~ 4 seconds, 43kW in 4 ~ 6 seconds, and 32kW in 6 ~ 8 seconds. The comparison diagram of DC bus voltage obtained by simulation is shown in Figure 7.

![Figure 7. Voltage comparison in case of load increase.](image)

It can be seen from figure 7 that both control methods can maintain the stability of DC bus voltage under the condition of 1 ~ 2 second rated power operation. When the system load increases in 2 ~ 4 seconds, both control methods can maintain voltage stability, and the adaptive droop control considering photovoltaic output power margin proposed in this paper can reduce DC bus voltage deviation. When the system load continues to increase 6kW in 4 ~ 6 seconds, only the adaptive droop control considering the photovoltaic output power margin proposed in this paper can maintain the DC bus voltage stability. The traditional droop control method can not restore the system voltage when the system load is restored to rated value in 6 ~ 8 seconds.

The output power comparison diagram obtained by simulation is shown in Figure 8. Figure 8(a) shows the output power of each converter in the adaptive droop control of DC distribution network considering the photovoltaic output power margin proposed in this paper, and Figure 8(b) shows the output power of each converter in the traditional droop control.

![Figure 8. Comparison of output power under load increase.](image)

It can be seen from Figure 8 that the adaptive droop control proposed in this paper can meet the requirement that the photovoltaic power supply with large output can generate more power and the photovoltaic power supply with small output can generate less power when the load increases. However, the traditional droop control method requires that all photovoltaic power supply can generate the same power for the unbalanced power of the system.
5.2. Simulation and comparative analysis of adaptive droop control and traditional droop control for DC distribution network considering photovoltaic output power margin when load is reduced

The adaptive droop control proposed in this paper is compared with the traditional droop control method shown in formula (2-3) when the system load decreases. The output power of DC distribution network keeps the rated value unchanged. The value of local DC load is 32kW in 1~2 seconds, 22kW in 2~4 seconds, 17kW in 4~6 seconds, and 32kW in 6~8 seconds. The comparison diagram of DC bus voltage obtained by simulation is shown in Figure 9.

![Figure 9. Voltage comparison under load reduction.](image)

As can be seen from Figure 9, when the system power is sufficient, the two control methods can maintain the stability of DC bus voltage. The adaptive droop control proposed in this paper can further reduce the DC bus voltage deviation.

The output power comparison diagram obtained by simulation is shown in Figure 10. Figure 10(a) shows the output power of each converter in the adaptive droop control of DC distribution network considering the photovoltaic output power margin proposed in this paper, and Figure 10(b) shows the output power of each converter in the traditional droop control.

![Figure 10. Comparison of output power in case of load reduction.](image)

It can be seen from Figure 10 that the adaptive droop control of DC distribution network considering photovoltaic output power margin proposed in this paper can meet the requirement that the photovoltaic power supply with small output can generate less power when the load is reduced, while the traditional droop control method requires all photovoltaic power supply to generate the same power.

6. Summary

In the system of multi PV parallel connected to DC distribution network, the power margin of each PV power source is different. Based on the analysis of the influence of load variation and photovoltaic output variation on the voltage at both ends of the converter, an adaptive droop control for DC distribution network considering photovoltaic output power margin is proposed. The output impedance of PV side converter is modeled and analysed:
1) The adaptive droop control proposed in this paper can control the PV with large output to generate more power when the system load increases, and the PV with small output to generate less power when the system load decreases.

2) The adaptive droop control proposed in this paper can improve the stability of multi PV parallel connected DC distribution system and reduce the DC bus voltage deviation when the load changes.

Acknowledgments
This work is supported by the National Key Research and Development Program of China (No.2018YFB0904104).

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