A Coordination Strategy between PV Generators and Storages based on Droop Control in AC Microgrids

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Abstract. In an islanded AC microgrid, the coordination strategy between generations and storages is often designed to ensure the stability and economy of the system. In this article, for an AC microgrid dominated by photovoltaic (PV) generators, a strategy based on droop control is proposed to realize the generation-storage coordination. PV generators change their active and reactive power output by catching the changes in bus frequency and voltage, which can prevent storages from over-charged and make the bus voltage more stable. Storages are controlled by a droop algorithm based on state-of-charges (SOCs) to achieve SOCs balance among multiple storages. When the SOCs are too low, secondary loads (SLs) will be removed through a loads management, and the rest primary loads (PLs) will be powered entirely by PVs, which can prevent storages from over-discharged. Simulation based on Matlab successfully verifies the proposed coordination strategy.

1. Introduction

With the rapid development of the society, the traditional power grids have more and more disadvantages. In recent years, the construction of AC microgrids with renewable energy sources (RESs) has become an important strategy in various countries. AC microgrids are the main form of microgrids, they can effectively integrate distributed generations, energy storages and loads in the distribution network.

Figure 1 shows a typical AC microgrid structure. When connected to utility, AC bus is supported by the utility, the PV generators, wind turbines (WTs) and fuel cells all output maximum power. In island mode, the AC bus is supported by storages, RESs will be controlled as a power source. Considering the intermittence and volatility of RESs\textsuperscript{[1]}, unbalanced power flow may lead to overcharge or over discharge of the storages. And with the diversification of the loads, when the reactive power demand between storages and loads cannot be met, the AC bus voltage (ACBV) will exceed the limit, at that time, generations are required to provide reactive power to protect microgrids. In addition, the SOCs between storages are often unbalanced, which resulting in low efficiency. According to these conditions, a coordinated control strategy between storages and generations is necessary. Considering there are lots of PVs access in the distribution network, the islanded AC microgrids dominated by high-density PVs will be the main research object of this paper.

The rest of this paper is organized as follows. In section 2, some related research works will be introduced. In section 3, the coordinated control strategy will be described in detail. In section 4, simulation results based on Matlab are presented. In section 5, the conclusion of this article will be obtained.
2. Related research works

Some researchers have proposed their own control methods. Lu et. al. proposed a modified droop control based on SOCs for the storages, SOCs were added into the $P-f$ droop coefficients as their denominators, so the storages with higher SOCs would have higher power output, the storages with lower SOCs would have lower power output, finally they achieved SOCs balancing[2]. But this study only focuses on the cooperative control among multiple storages, the control of generations is not discussed. Park et. al. took the RESs generations into consideration, they proposed a strategy of using multiple storages and multiple generations to improve the reliability of microgrids with all generations operated at maximum power point tracking (MPPT) mode[3]. However, the cooperative control method between storages and generations is not designed in this strategy. Urtasun et. al. put forward a distributed generation-storage cooperative control strategy, pointing out that if a storage was over-charged, its output voltage or input current would exceed the limit, therefore, using the voltage and current as the main basis of inverter frequency, when the storage was over-charged, the AC bus frequency (ACBF) would rise, PVs could decrease their output power by capturing this signal to prevent storage from over-charged, to prevent storage from over-discharged, when the SOCs of the storage were too low, diesel engine would be started[4]. This strategy can effectively prevent storage from overused, but it only considers a single storage, without considering the SOCs balancing in the case of multiple storages. Sorouri et. al. proposed a microgrid frequency control (MFC) method based on multiple storages, for the multiple parallel storages, using $SOC-f$ droop control to generate the inverter reference frequency, when the SOCs increased, the ACBF raised, when the SOCs decreased, the ACBF dropped, then a PV power control (PVPC) method was used to capture this signal, which let PVs output power was adjustable to prevent the storages from over-charged or over-discharged[5]. However, this method only focuses on the SOCs, the maximum and minimum output power of the storages are not considered, so there is a possibility of unbalance in power output, at the same time, PVPC ignores the problems of reactive power support. Further more, L.Diaz et. al. proposed a PVs reactive power support method under voltage control mode (VCM)[6], but it is no useful in current control mode (CCM), it means PVs unable to support reactive power when they operate in MPPT. After that, Moondee et. al. proposed a modified $V-Q$ droop control for PVs in the case of grid connection[7], which provided ideas for solving this problem. In order to understand the research works intuitively, these related methods are summarized in table 1.

In order to solve these problems, this paper proposes a generation-storage coordination strategy based on droop control. In islanded mode, multiple storages support AC bus through $P-f$ and $Q-V$ droop control, they can realize the reasonable distribution of output power by designing different droop coefficients. Since the SOCs of different storages may be different, a reference frequency offset algorithm based on SOCs is introduced to the $P-f$ droop control, the higher SOCs will lead to the larger offset, therefore the storages with higher SOCs are slower to charge or faster to discharge than the storages with lower SOCs, finally they achieve a SOCs balance. If SOCs are too high, PVs will enter the power limit mode instead of MPPT mode to prevent storages from over-charged. When the
SOCs are low, the PVs will be in the MPPT mode. However, if SOCs continue to decrease beyond a threshold, loads management will automatically cut off the SLs, leaving only PLs to prevent storages from over-discharged. Considering the reactive power flow, a reactive power support algorithm based on $dq$ transform is designed on PVs to realize the reactive power support to AC bus. In these ways, the coordination between PV generators and storages can be realized, the following goals will be achieved:

First, storages can reasonably distribute the power output, no overuse, and their SOCs are balanced.

Second, PVs can automatically adjust the output power according to the bus signals, they will provide active power support and reactive power support for the bus.

Third, the loads in the AC microgrids will be designed and managed reasonably to ensure the stable operation of the system.

### Table 1. Summary of research methods.

| Existing Methods | Multiple Storages | Multiple Generators | Generation-storage Coordination | SOCs Balancing | PVs Reactive Power Support in CCM | Loads Management |
|------------------|-------------------|---------------------|---------------------------------|----------------|-----------------------------------|-----------------|
| Ref. [2]         | √                 | ×                   | ×                               | √              | ×                                 | ×               |
| Ref. [3]         | √                 | √                   | ×                               | ×              | ×                                 | ×               |
| Ref. [4]         | ×                 | √                   | √                               | ×              | ×                                 | ×               |
| Ref. [5, 6]      | √                 | √                   | ×                               | ×              | ×                                 | ×               |
| Ref. [7]         | ×                 | √                   | ×                               | √              | ×                                 | ×               |
| This paper       | √                 | √                   | √                               | √              | √                                 | √               |

3. **Generation-storage coordination strategy**

The coordination strategy will be divided into two parts for storages and PV generators respectively. The storages through a SOCs based droop control will be controlled as voltage sources to maintain the ACBV, and the PV generators through an adjustable power control will be controlled as power sources to provide active and reactive power support. ACBF can be divided into two regions according to its height, named high frequency region (HFR) and low frequency region (LFR), PV generators operate in power limit mode and MPPT mode at HFR and LFR respectively, as shown in figure 2.

![Figure 2. AC bus frequency regions.](image)

3.1. **SOCs based droop control for storages**

There are multiple storages connected on the AC bus. The control block diagram for any $i$-th storage is shown in figure 3. Considering the limitations of $P$-$f$ and $Q$-$U$ droop control[8], this article assumes the line is inductive.

As shown in figure 3, the strategy is divided into outer loop and inner loop. Outer loop is based on traditional $P$-$f$ and $Q$-$V$ droop control. Active power $P$ and reactive power $Q$ can be calculated by sampling the three-phase voltage $v_{a}$ and the three-phase current $i_{a}$, three-phase voltage reference amplitude $V_{ref}$ can be obtained by using $Q$-$V$ droop method. Due to the difference of SOCs of different storages, the reference frequency rise $\Delta f$ based on SOCs is introduced, which can get the final reference frequency $f^{ref}$ with the $P$-$f$ droop method together. $V_{ref}$ and $f^{ref}$ will provide the three-phase voltage reference for the inner loop after passing a three-phase voltage generator.
Figure 3. SOCs based droop control for i-th storage.

Inner loop is based on three-phase dq transformation, a proportional-integral (PI) controller is designed to be a voltage controller to make the output voltage $v_{od}$ and $v_{oq}$ track their reference value $v_{od}^{ref}$ and $v_{oq}^{ref}$ accurately. A proportional controller is designed to be a current controller to increase the damping of the system. Inner loop finally generates three-phase inverter pulse width modulation (PWM) waves to the converter.

According to this strategy, the inverter reference frequency of i-th storage can be expressed as:

$$f_{i}^{ref} = f + \Delta f = (f^* - r_{p,i} \times P_i) + r_{\Delta,i} \times SOC_i$$  \hspace{1cm} (1)$$

Where $i$ is any i-th storage, $f_{i}^{ref}$ is the reference value of ACBF, which is limited between the bus maximum frequency $f_{max}$ and minimum frequency $f_{min}$, $f$ is the output of P-f droop control, $\Delta f$ is the reference frequency rising, $f^*$ is the rated frequency of AC bus, $r_{p,i}$ is a droop coefficient, $r_{\Delta,i}$ is a rising coefficient, $P_i$ is the active power output, $SOC_i$ is the SOCs of the battery.

The design of the droop coefficient $r_{p,i}$ is related to the capacities of the storage, it can be set as:

$$r_{p,i} = \frac{f_{max} - f_{min}}{P_{max,i} - P_{min,i}}$$  \hspace{1cm} (2)$$

Where $P_{max,i}$ and $P_{min,i}$ are the maximum active power output and maximum active power input of the storage respectively.

The detailed expression of $r_{\Delta,i}$ is:

$$r_{\Delta,i} = \frac{f_{max} - f^*}{100 \%}$$  \hspace{1cm} (3)$$

It can be seen from equation (3) all the rise coefficients should be consistent in an AC microgrid.

For any one storage, its SOCs can be calculated as:

$$SOC_i = SOC_{i,t=0} - \frac{1}{C_i} \int i_t dt$$  \hspace{1cm} (4)$$

Where $SOC_{i,t=0}$ is the initial SOCs of the storage, $C_i$ is its capacity, and $i_t$ is its output current.

According equation (1) to equation (4), for active power, its output value with lower SOCs is smaller or its input value is larger, and its output value with higher SOCs is larger or its input value is smaller, finally SOCs balancing between storages will be realized. After that, the size of power output or input will only depend on storages own capabilities.
The reference amplitude of inverter voltage can be expressed as:

\[ V_{i}^{ref} = v^* - r_{q,i} \times Q_i \]  

(5)

Where \( V_{i}^{ref} \) is limited between the highest peak-to-peak value \( v_{\text{max}} \) of the phase voltage and the lowest peak-to-peak value \( v_{\text{min}} \) of the phase voltage, \( v^* \) is the rated peak-to-peak voltage of the bus, \( r_{q,i} \) is the droop coefficient, \( Q_i \) is the reactive power exchanged by the converter.

The design of the droop coefficient \( r_{q,i} \) is related to the reactive power exchange capability of the converter, it can be set as:

\[ r_{q,i} = \frac{v_{\text{max}} - v_{\text{min}}}{Q_{\text{max},i} - Q_{\text{min},i}} \]  

(6)

Where \( Q_{\text{max},i} \) and \( Q_{\text{min},i} \) are the maximum positive reactive power and the maximum negative reactive power of the converter respectively.

Considering the relationship between active power and reactive power exchange of the converter, they should always meet:

\[ P_i^2 + Q_i^2 \leq S_i^2 \]  

(7)

Where \( S_i \) is the apparent power of the converter.

According equation (5) to equation (7), when the converter can provide enough reactive power, ACBV will not exceed the limit, but in fact, due to the limited apparent power of the converter, the supply of reactive power will be restricted after thinking to meet the active power output first. To solve this problem, the converters connected to the PVs can provide reactive power support. It will be described in detail in next section.

### 3.2. Adjustable power control for PV generators

According to figure 3, when SOCs are too high, ACBF will enter the HFR. When the reactive power supply by storages is insufficient, ACBV will exceed the limit. PV generators can adjust their active and reactive power output by catching these two signals to ensure the system stability. For any \( m \)-th PV, the control block diagram is shown in figure 4.

![Figure 4. Adjustable power control for m-th PV generator.](image)

According to figure 4, PV control strategy is also divided into outer loop and inner loop. The outer loop will generate active power reference \( P^{ref} \) and reactive power reference \( Q^{ref} \), the former can be expressed as:

\[
P_m^{ref} = \begin{cases} 
P_{\text{mppt},m} & f_{\text{bus}} < f_H \\ r_{pv,m}(f_{\text{max}} - f_{\text{bus}}) & f_H \leq f_{\text{bus}} < f_{\text{max}} \\ 0 & f_{\text{bus}} \geq f_{\text{max}} \end{cases}
\]  

(8)
Where \( m \) is any \( m-th \) PV, \( f_{bus} \) is the ACBF, \( f_H \) is the threshold to enter HFR, \( P_{mppt,m} \) is the output power when PV operates in MPPT mode, \( r_{pv,m} \) is regulation coefficient, it can be set as:

\[
 r_{pv,m} = \frac{P_{mppt,m}}{f_{max} - f_H}
\]  
(9)

Combining figure 2 and equation (8), when ACBF is located in LFR, PV operates in MPPT mode which can ensure economy. When ACBF is located in HFR, PV will operate in power limit mode, and its active power output is negative correlation of the frequency, the higher the frequency is, the lower the output power is. When the frequency is higher than \( f_{max} \), the reference output power will be zero.

Since the reactive power exchange needs to be considered, two thresholds of the ACBV are set to \( v_L \) and \( v_H \). When the bus voltage is lower than \( v_L \) or higher than \( v_H \), it means the system has a high demand for reactive power. In this case, PV converter will be asked to support reactive power.

According to figure 4, the reference value of converter reactive power is expressed as:

\[
 Q_m^{ref} = \begin{cases} 
 Q_{max,m} & v_{pd,m} < v_{min} \\
 r_{L,m} (v_L - v_{pd,m}) & v_{min} \leq v_{pd,m} < v_L \\
 0 & v_L \leq v_{pd,m} \leq v_H \\
 r_{H,m} (v_{pd,m} - v_H) & v_H < v_{pd,m} \leq v_{max} \\
 Q_{min,m} & v_{max} < v_{pd,m}
\end{cases}
\]  
(10)

Where \( v_{pd,m} \) is the component of the inverter voltage on \( d \)-axis in \( dq \) transformation, \( Q_{max} \) and \( Q_{min} \) are the maximum positive reactive power and the maximum negative reactive power of the converter respectively. Their relationship with the active power should also meet equation (7). \( r_{L,m} \) and \( r_{H,m} \) are control coefficients, they can be set as:

\[
 r_{L,m} = \frac{Q_{max,m}}{v_L - v_{min}}, r_{H,m} = \frac{Q_{min,m}}{v_{max} - v_H}
\]  
(11)

From equation (8) to equation (11), we can know the outer loop can make PV generator automatically adjust the active power output and reactive power output according to ACBF and ACBV, PV can provide reactive power support for AC bus while preventing the storages from over-charged.

The inner loop control of PV is mainly to achieve accurate tracking of active power and reactive power. The active power output of the PV depends on the \( P-V \) characteristic curve. By using the perturbation and observation (P&O) method to control the output voltage of PV, the output power can be controlled to achieve active power tracking.

Based on instantaneous reactive power theory of three-phase circuits, we can get:

\[
 \begin{align*}
 P_m &= \frac{2}{3} (v_{pd}i_{pd} + v_{pq}i_{pq}) \\
 Q_m &= \frac{2}{3} (v_{pq}i_{pd} - v_{pd}i_{pq})
\end{align*}
\]  
(12)

Where \( P_m \) and \( Q_m \) are the instantaneous active output and instantaneous reactive output respectively, \( v_{pd} \) and \( v_{pq} \) are the \( d \)-axis component and \( q \)-axis component in three-phase voltage \( dq \) transformation respectively, \( i_{pd} \) and \( i_{pq} \) are the \( d \)-axis component and \( q \)-axis component in three-phase current \( dq \) transformation respectively.

Because this coordination strategy is a master-slave mode, for PV generators, the values of \( v_{pd} \) and \( v_{pq} \) are little changed. At this time, for any given \( P_m \) and \( Q_m \), the unique \( i_{pd} \) and \( i_{pq} \) can be get according to equation (12). The decoupling algorithm designed with this characteristic can realize the decoupling from \( Q_m^{ref} \) to \( i_{pq}^{ref} \), and the reactive power tracking can be realized by controlling \( i_{pq} \).

3.3. Characteristics of the coordination strategy

First of all, the analysis starts from active power characteristics. When all PV generators are running in MPPT, the total active power output is set as \( P_{mppt,all} \), which satisfies:

\[
 P_{mppt,all} = \sum_{i=1}^{n} P_{mppt,i}
\]  
(13)

Set the total active power consumption of PLs and SLs are \( P_{PL} \) and \( P_{SL} \) respectively, when they meet:

\[
 P_{PL} + P_{SL} < P_{mppt,all}
\]  
(14)
In this situation, it is considered that the system is initially located in LFR. PV will operate in MPPT mode, storages will be continuously charged, SOCs will continue to rise, and ACBF will continue to rise and finally enter HFR. Then, PVs will operate in power limit mode, their active power output will continue to decrease, the charging power of the storages will continue to decrease until it is zero. Finally all the active powers of the loads will only be provided by PVs, SOCs of all the storages are equal and there is no power exchange. At this time, the loads should meet:

\[
P_{PL} + P_{SL} = \sum_{i=1}^{n} P_{mppt,i} (f_{max} - f^* - r_{q,i} \times SOC_i)
\]

(15)

Where \(SOC_1 = SOC_2 = \cdots = SOC_n\).

Combined equation (1), equation (8) and equation (15), under the same initial conditions, in the steady state, it can be concluded that the smaller the total active power consumption of the loads, will have the lower PVs active power output, the higher bus frequency and the higher SOCs balancing state, vice versa.

When the total loads meet:

\[
P_{PL} + P_{SL} > P_{mppt,alt}
\]

(16)

In this case, considering the system is initially located in LFR, the PVs will always run in the MPPT mode, the storages will continue to discharge, and SOCs will continue to decrease. To prevent storages from over-discharged, a loads management mechanism is introduced to set a minimum threshold value for SOCs. When any SOC falls to the threshold value, SLS will be cut off, and the total active power consumption of the rest PLs should be less than \(P_{mppt,alt}\), then, the system can be analyzed as before.

Next, considering the reactive power characteristics, ACBV can be expressed as \(v_{bus}\), and according to equation (5), reactive power exchange for any \(i\)-th storage can be expressed as:

\[
Q_i = \frac{v_{i} - v_{bus}}{r_{q,i}}
\]

(17)

Let the total reactive power consumption of loads be \(Q_{load}\), when it meets:

\[
\sum_{i} \frac{v_{i} - v_{bus}}{r_{q,i}} \leq Q_{load} \leq \sum_{i} \frac{v_{bus} - v_{i}}{r_{q,i}}
\]

(18)

At this time, the reactive power of the loads will be supported by storages, and the reactive power flow at PVs is zero. When \(Q_{load}\) does not meet equation (18), the reactive power of loads will be shared by storages and PVs together. In order to protect the system, \(Q_{load}\) should meet:

\[
\sum_{i} Q_{pvmi,n,i} + \sum_{i} Q_{batmi,n,i} \leq Q_{load} \leq \sum_{i} Q_{pmx,i} + \sum_{i} Q_{batmx,i}
\]

(19)

Where \(Q_{pvmi,n,i}\) and \(Q_{batmi,n,i}\) are the maximum negative reactive power of PVs and storages respectively, and \(Q_{pmx,i}\) and \(Q_{batmx,i}\) are the maximum positive reactive power of PVs and storages respectively.

4. Simulation based on Matlab

In this section, a four nodes AC microgrid coordination simulation is carried out based on Matlab, two storages and two PV generators are connected. The parameters are designed as follows: rated ACBF \(f^*\) is 50Hz, while \(f_{min}\) is 49.7Hz, \(f_{H}\) is 50.3Hz and \(f_{max}\) is 50.5Hz, rated ACBV \(v^*\) is 311V, while \(v_{min}\) is 300V, \(v_{L}\) is 305V, \(v_{H}\) is 315V and \(v_{max}\) is 320V. The PLs are 4kW, -1.2kVar, SLS are 6kW, -4.1kVA. The MPPT power of first PV (PV_1) is 2.5kW, and the MPPT power of second PV (PV_2) is 3.5kW, the maximum positive and negative reactive power provided by the two PV generators are the same, which are 7kVar and -7kVar respectively. The maximum active output power of first storage (Storage_1) is 5.6kW, its maximum active input power is 1.4kW, and the maximum active output power of second storage (Storage_2) is 7kW, its maximum active input power is 2.1kW, their maximum positive and negative reactive output power are the same, which are 6kVar and -6kVar respectively. The initial SOCs of two storages are 80% and 65% respectively. The related coefficients can be calculated through these parameters.

Simulation steps are as follow: first, two storages are used DC/AC conversion to support AC bus, then two PVs are input. After the bus voltage is stable, PVs begin decoupling algorithm to provide...
reactive support for the bus, at the same time, they will capture the ACBF to determine their own operation mode. When any SOC is detected to be too low, the system will cut off SLs to prevent the storages from over-discharged. The total simulation time is 80 seconds, the results are shown in figure 5.

From figure 5 (a) to figure 5 (d), it can be seen that when the simulation starts, VCBF is in LFR, both PV generators operate in MPPT mode. Since the total loads meet equation (14), two storages will continue to discharge, the SOCs will continue to decline, and the VCBF will continue to decrease. When it is detected that the SOCs of Storage_2 reach the minimum threshold (20%), the SLs are cut off, and the total power consumed by the PLs less than $P_{\text{mppt,all}}$. Because the VCBF is still in LFR, the PVs still operate in MPPT mode, and the extra power will be used to charge the storages, their
SOCs will rise, and the VCBF will continue to rise. After a period of time, when the VCBF is in HFR, the PVs will operate in the power limit mode, their active output power decreases with the rising of VCBF, and the charging power of these two storages will decrease. In the steady state, the two storages have no power exchange with microgrids, their SOCs are balanced, and the total power of the PLs will be only supported by PVs.

From figure 5 (e) to figure 5 (g), it can be seen that there is a large reactive power exchange in the system at the beginning of simulation. When the bus is stable, if the PVs do not provide reactive power support, ACBV exceeds $v_H$, after adding the reactive power support algorithm in 6s, the PVs continue to provide reactive power according to the ACBV, the value of $v_{bus}$ will decrease. After SLs are removed, the demand of reactive power decreases, ACBV is between $v_L$ and $v_H$, and PVs no longer provide reactive power. Since the reactive power control coefficients of PVs are the same, the reactive power provided by two PV generators is the same, so are the storages.

5. Conclusion
In this paper, a control strategy is proposed to realize the generation-storage coordination based on droop control. Through the SOCs-based storages droop control, the SOCs between the storages can be balanced. With the adjustable power control for PV generators, PVs can automatically adjust the active power output according to ACBF to prevent the storages from over-charged, and they also can automatically adjust the reactive power output according to ACBV to provide reactive power support for the bus to keep the bus voltage stable. When the SOCs are too low due to the continuous discharge of storages, SLs will be cut off through loads management, and the rest PLs will be powered entirely by PVs, which can prevent storages from over-discharged. Simulation based on Matlab successfully verifies the proposed control strategy.

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