An Improved Droop Control Method for Energy Storage Module of DC Microgrid

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Abstract. This paper proposes an improved droop control method with state of charge (SOC) balance function for energy storage module of DC microgrid. The average SOC of all energy storage modules is obtained by low bandwidth network. The SOC balance controller calculates the difference between each module’s SOC and average SOC and then adjust the droop coefficients according to the difference. As the coefficient changes, the output power of module is allocated according to its SOC and eventually achieve balance. Besides, secondary voltage controller is employed to compensate DC bus voltage drop. Also, the stability of the proposed method is studied by small-signal analysis. The effectiveness of the proposed method is finally verified by MATLAB/Simulink simulation.

1. Introduction

With the continuous development of renewable energy, the concept of microgrid came into being[1]. Since DC microgrid does not have the problems of phase synchronization, reactive power loss, harmonics, etc. that often occur in ac microgrid, the research and application of DC microgrid has received more and more attention worldwide [2-4]. A DC microgrid system is shown in Figure 1. In order to stabilize the energy fluctuation of renewable energy, energy storage devices are usually added to the DC microgrid[5]. As implication, multiple energy storage modules are typically distributed in the microgrid to meet the needs of large-capacity systems [6, 7]. It is important for energy storage module to allocate the energy properly, which helps to prevent overdischarge and extend its life.

![Figure 1. DC microgrid schematic with distributed energy storage modules](image)

In this paper, an improved droop control method with state of charge (SOC) balance function is proposed. SOC balance controller and secondary voltage controller are employed, and SOC information is exchanged via low bandwidth network. The SOC balance controller is used to regulate the droop coefficient based on the difference between each parallel energy storage module’s SOC and...
the average SOC, which adjusts the output power module so that the SOC tends to be equal. The secondary voltage controller compensates for bus voltage drop.

The rest of the paper is organized as follows. In section 2, the improved droop control is introduced and the stability of the method is studied with small-signal analysis. Section 3 shows the results and discussions of MATLAB/Simulink simulation. Section 4 finally summarizes the paper and draws the conclusions.

2. Principle of improved droop control method

Droop control is a common method for energy management in DC microgrid [8-10]. In this paper, we improve the traditional droop control by changing the droop coefficient to achieve SOC balance among different energy storage modules. The details of the method are discussed as follows.

2.1. SOC balance controller

The decrease rate of SOC is positively correlated with the output power. Consider two parallel energy storage modules with the same specification but different initial SOC. To equalize the SOC of two modules, the droop coefficient of the module with higher SOC should be increased, thus output power increases and SOC decreases faster. Whereas, the droop coefficient of the module with lower SOC should be decreased. When SOC of two modules are the same, the droop coefficients will remain unchanged so that the parallel modules maintain both SOC and output power balance. The modules’ SOC are exchanged via low bandwidth network and the average SOC is calculated.

The adjustment of droop coefficient is expressed as follows:

\[
m_i = m_0 - m_0 (SOC_i - SOC_{avg}) = m_0 - m_0 (SOC_i - \sum_{i=1}^{N} \frac{SOC_i}{N}) = m_0 - m_0 \Delta SOC_i
\]

where \(m_i\) is the calculated droop coefficient of module \(i\), \(m_0\) is the given initial value of droop coefficient, \(m_0\) is the scale factor, \(SOC_i\) is the SOC of module \(i\), \(N\) is the number of all modules put into operation, \(SOC_{avg}\) is the average SOC of all \(N\) parallel modules.

It can be seen from (1) that, \(m_i\) will be smaller than \(m_0\) if \(SOC_i\) is bigger than \(SOC_{avg}\) and conversely \(m_i\) will be bigger than \(m_0\) if \(SOC_i\) is smaller than \(SOC_{avg}\), which leads to increase or decrease in output power of each module. As \(\Delta SOC_i\) gradually drops to zero, \(m_i\) tends to \(m_0\) so that the output power of each module will not change anymore and the SOC is balanced.

\(m_0\) can not be too large in case \(m_0\) is too small or even below zero, which will cause instability of the system. Normally, the values of \(m_0\) are the same in all modules. It should also be noticed that both the parameters \(m_0\) and \(m_i\) should be given approximately to ensure that the output power of each module is within limit.

2.2. Stability analysis of SOC balance controller

To analyse the stability of SOC balance controller, we take a DC microgrid with two parallel energy storage modules as an example without loss of generality. Assume that two modules have the same capacity and rated voltage but different SOC. The reference voltage of two modules can be express as

\[
u_{dc1} = u^{*}_{dc} - [m_0 - m_0 (soc_1 - soc_{avg})]p_1
\]
\[
u_{dc2} = u^{*}_{dc} - [m_0 - m_0 (soc_2 - soc_{avg})]p_2
\]

where \(u_{dc1}\) and \(u_{dc2}\) are the reference voltage, \(u^{*}_{dc}\) is the no-load voltage, \(soc_1\) and \(soc_2\) are the SOC from low bandwidth network, \(soc_{avg}\) is the average SOC of two modules, \(p_1\) and \(p_2\) are the measured output power.

Since \(soc_{avg}\) can be derived as

\[
soc_{avg} = (soc_1 + soc_2) / 2 = soc_1 - \Delta soc = soc_2 + \Delta soc
\]

The \(\Delta soc\), \(p_1\) and \(p_2\) can be reached as

\[
\Delta soc = (soc_1 - soc_2) / 2 = G_d \Delta SOC = [1/(\tau s + 1)]\Delta SOC
\]
\[
p_1 = G_{fP} \frac{\omega_c}{\omega_c + s} p_1
\]
$p_s = G_{lpf}P_2 = \left( \omega_c / (\omega_c + s) \right)P_2$

where $SOC_{avg}$ is the actual average SOC, $P_1$ and $P_2$ are the actual output power, $G_d$ indicates the delay of low bandwidth network, $\tau$ is the time constant of delay link, $G_{lpf}$ is the transfer function of lowpass filter, $\omega_c$ is the cut-off frequency of lowpass filter.

Substituting (4)–(7) into (2) and (3), it yields

$$u_{dc1} = u_{dc} - [m_0 - m_1 G_d \Delta SOC] G_{lpf} P_1$$

$$u_{dc2} = u_{dc} - [m_0 + m_1 G_d \Delta SOC] G_{lpf} P_2$$

Performing the small-signal analysis for (8) and (9), it yields

$$\hat{u}_{dc1} = (m_0 G_d \Delta SOC - m_0) G_{lpf} \hat{P}_1 + m_1 G_d G_{lpf} P_1 \Delta SOC$$

$$\hat{u}_{dc2} = (-m_0 G_d \Delta SOC - m_0) G_{lpf} \hat{P}_2 - m_1 G_d G_{lpf} P_2 \Delta SOC$$

At point of common coupling, the following equation is satisfied.

$$P_1 + P_2 = U_{dc}^2 / R_{load}$$

where $U_{dc}$ is the DC bus voltage and $R_{load}$ represents the load resistance.

Because the response speed of the inner current loop is much faster than droop control, the closed loop transfer function of voltage can be considered as 1[11]. The approximate relation is shown as

$$U_{dc} \approx u_{dc1} \approx u_{dc2}$$

Combining (10), (11), (13) and (14), the following closed loop transfer functions are obtained

$$G_{U_{dc}/\Delta SOC}(s) = \hat{U}_{dc} / \Delta SOC = a(\tau^2 s^2 + (\omega_c \tau + 1)s + \omega_c^2)/(bs^3 + cs^2 + ds + e)$$

where

$a = -m_0^2 \Delta SOC(P_1 + P_2)R$, $b = -2m_0 \tau$, $c = -2m_0\tau(2R + \omega_c \tau - U_{dc}m_0 \omega_c \tau)$,

d $= -2m_0\tau(2R \omega_c \tau + 2U_{dc} m_0 \omega_c \tau)$, $e = -2\omega_c(m_0 R - U_{dc} m_0^2 - m_1^2 U_{dc} \Delta SOC^2)$.

$$G_{U_{dc}/P_1}(s) = \hat{U}_{dc} / \hat{P}_1 = (A s + B) / (C s^3 + D s + E)$$

where

$A = (P_1 - P_2) R m_0 \omega_c \tau$, $B = R \omega_c [m_0 (P_1 - P_2) + m_1 (P_1 + P_2) \Delta SOC]$, $C = (P_1 + P_2) R \tau$, $D = (P_1 + P_2)(R \omega_c \tau + 1) + 2P_1 U_{dc} m_0 \omega_c \tau$, $E = (P_1 + P_2) R \omega_c + 2P_1 U_{dc} \omega_c m_0 + m_1 \Delta SOC$.

Solve the dominant poles of (15) and (16) by using MATLAB and the results are shown in figure 2 and figure 3. When $\Delta SOC$ varies over a wide range, the dominant poles locate in the left half of $s$ domain, which guarantees the stability of SOC balance controller.

![Figure 2. Dominant poles map of $G_{U_{dc}/\Delta SOC}(s)$](image1)

![Figure 3. Dominant poles map of $G_{U_{dc}/P_1}(s)$](image2)

2.3. Secondary voltage controller

In this paper, secondary control is introduced to prevent voltage drop caused by droop control. The stability of the system needs to be verified. The control scheme is shown in Figure 4, the dotted line part indicates the droop control which can be regarded as a disturbance to the secondary control[12].

The secondary control diagram can be expressed as

$$u_{dc1} = u_{dc} - [m_0 - m_1 G_d \Delta SOC] G_{lpf} P_1 + G_{lpf} (u_{dc} - u_{dc1})$$

Rewrite (17) as
\[ u_{dc}^* = u_{dc} = \frac{m_0 - m_i G_p \Delta SOC_i}{1 + G_{pi}} G_{pf} P_{\text{ref}} = u_{dc}^* = \frac{m_0 - m_i G_p \Delta SOC_i}{1 + (K_p + K_i / s)} P_1 \]

where \( G_{pi} \) is the PI control transfer function, \( K_p \) and \( K_i \) are proportion and integral coefficient.

Figure 5 shows the frequency response of secondary controller with the change of \( \Delta SOC_1 \). As \( \Delta SOC \) changes over a wide range, the amplitude is far below zero which means that \( P_1 \) has little effect on the output of secondary controller. Hence, the stability of secondary voltage controller is guaranteed.

3. Case Study and Simulation Test

In order to validate the feasibility of the proposed method, we use MATLAB/Simulink to set up the simulation model. Super capacitor is used as energy storage module and the rated capacity is 100F and rated voltage is 60V. The load power is 800W and DC bus rating is 200V. The SOC balance controller parameters \( m_0 = 0.0375 \), \( m_i = 0.03 \). The PID parameters \( K_p \) and \( K_i \) are 1 and 5, respectively.

Firstly, consider the case of two modules. The initial values of \( SOC_1 \) and \( SOC_2 \) are set to 100% and 99%, respectively. As shown in the Figure 6 and Figure 7, \( P_1 \) is larger than \( P_2 \) under the control of the proposed method, which makes \( SOC_1 \) decreases faster than \( SOC_2 \). As the difference between \( SOC_1 \) and \( SOC_2 \) diminishes, \( P_1 \) and \( P_2 \) tends to be equal. And eventually, SOC balance is reached. It can also be seen from Figure 8 that the DC bus voltage can maintain the rating.

Also, the case of three modules is considered. The initial values of \( SOC_1 \), \( SOC_2 \) and \( SOC_3 \) are 100%, 99.3% and 99%, respectively. As the Figure 9 shown, before module 2 is removed, \( SOC_1 \), \( SOC_2 \) and \( SOC_3 \) have different falling speeds to reach the average. After module 2 is removed, which is a normal operation in practical applications, \( SOC_{\text{avg}} \) changes immediately since module 2 cannot be taken into account in the calculation of the average value anymore. \( SOC_2 \) and \( SOC_3 \) keep reaching balance gradually which means the proposed method still works after the disturbance. The stability of the proposed method is verified.

4. Conclusions
In this paper, an improved droop control method is proposed to achieve SOC balance of different energy storage modules. The improved method introduces the low bandwidth network to measure the average SOC, which is used to regulate the droop coefficients. Under the control of the SOC balance controller, the SOC of different modules tend to be balanced and the output power will also be equal. The secondary voltage controller is also introduced to ensure the DC bus voltage maintains rating. MATLAB/Simulink simulation verifies the effectiveness of the proposed method.

5. References
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