Improved Droop Control Strategy with Fast Equalization for SOC Based on Power Balance in Energy Storage System

Heng Zhang¹, Shiyu Sun¹, Gaohui Feng², Bingqing Shi³

¹Army Engineering University, Shijiazhuang, Hebei, 050003, China
²Beijing Qingsheng Electrical Science and Technology Research Institute Co., Ltd., Beijing, 100084, China
³Department of Electrical Engineering, Tsinghua University, Beijing, 100084, China

*Corresponding author’s e-mail: 1343235018@qq.com

Abstract. In parallel operation of energy storage units, the droop control based on voltage and current tends to neglect the difference of SOC in energy storage unit, which leads to the withdrawal of some energy storage units from the system due to overcharge or overdischarge, thus causing the voltage fluctuation of DC micro-grid bus. To solve this problem, an improved droop control strategy with fast equalization for SOC is proposed. With the SOC of energy storage batteries, the acceleration factor can be calculated in real time, so as to improve the speed of SOC equalization and power distribution. Finally, the validity of the control strategy is verified by simulation results with MATLAB/Simulink.

1. Introduction

In DC micro-grid (DM), the access of various distributed generation units bring great challenge to the stable operation of DM, especially the uncertainty and randomness of new energy generation. In DM, the power balance of the system is usually regulated by adding a certain capacity of energy storage unit, which absorbs the excess energy on the bus and supplements the insufficient energy. When multiple energy storage units are connected to the micro-grid at the same time, how to make good use of the limited capacity of energy storage to maintain power balance of the DM is the key problem. Based on this, the coordinated control of multiple energy storage units based on SOC droop is studied in this paper.

For energy storage units, reasonable coordinated control requires "more energy and more work", that is, the magnitude of output and absorption power is directly related to their own charging and discharging capacity. Although the traditional method based on voltage and current droop control can achieve power distribution among energy storage units, it does not fully consider the actual charging and discharging capacity of each energy storage unit, leading to some energy storage units withdrawing from the micro-grid system ahead of schedule, resulting in "short board effect". In order to solve this problem, scholars at home and abroad have made some explorations on the rational distribution and coordinated control of power among energy storage units. In reference [1] SOC of energy storage unit is introduced into droop coefficient in the form of reciprocal power in AC micro-grid, so that the energy storage unit can distribute power reasonably according to the value of SOC, and based on this method, a small signal model of the system is established to verify its stability. In [2], SOC is brought into droop coefficient in logarithmic form, and acceleration factor is optimized to solve the limitation of fixed acceleration factor in AC micro-grid. [3] introduces SOC into droop...
coefficient based on power exponential function, and verifies the stability of the system by Routh Criterion; [4] proposes a method of distributed droop control to achieve SOC balance, which solves the charging and discharging problems of batteries with different capacities. [5] fully considers SOC and discharge efficiency of energy storage unit, and effectively solves the power allocation problem when SOC and discharge efficiency are different. In reference [6], SOC is added to droop control in the form of power exponent, and voltage compensator is added to reduce bus voltage variations caused by droop control.

To improve the equalization speed of SOC, an improved droop control method based on SOC is proposed, and the acceleration factor of SOC equalization is optimized. What’s more, Contrast simulations were carried out with fixed and optimized acceleration factors in this paper. The Simulation results verify the effectiveness and feasibility of the control strategy.

2. Improved SOC droop control

2.1. Determination of droop control function based on SOC

The SOC of energy storage battery is estimated by charge accumulation method. The calculation formula of SOC of energy storage battery is as follows:

$$\text{SOC}_i = \text{SOC}_{i-0} - \frac{1}{C_{\text{bat}}} \int i_{\text{bat}} dt$$

(1)

\(\text{SOC}_i\) and \(\text{SOC}_{i-0}\) represent the current SOC and the initial SOC of the \(i\)th energy storage battery, \(i_{\text{bat}}\) is the output current of the battery, and \(C_{\text{bat}}\) is the capacity of the energy storage battery.

Formula (1) shows that SOC of energy storage battery is directly related to the output current. Therefore, SOC can be introduced into the control terminal to change the droop coefficient, so that it can follow the change of SOC value, realize the reasonable distribution of current and achieve the effect of SOC balance. The charging process is opposite to the discharging process. However, the droop coefficient associated with SOC is limited by the voltage stability condition of DC bus, which will affect the current sharing effect.

In this paper, the exponential form of droop function is used, which can satisfy the constraints and has a good discrimination.

The droop function is

$$R(\text{SOC}) = \frac{s}{e^{m\text{SOC}}},$$

(2)

\(m=4, s=10,\) and the effect of parameter \(m\) on the sag function is not discussed.

2.2. Optimum Design of Acceleration Factor

Ignoring the power loss of DC/DC converter unit, we can consider that the power of DC/DC converter unit remains unchanged, and the specific expression is as follows (3)

$$V_{\text{bati}} \cdot i_{\text{bati}} = V_{\text{basi}} \cdot i_{\text{basi}} = P_{\text{outi}}$$

(3)

\(V_{\text{bati}}, i_{\text{bati}}, V_{\text{basi}}, i_{\text{basi}}\) are represented respectively the output voltage of the \(i\)th energy storage battery, the output current of the energy storage battery, the DC bus voltage and the output current of the converter.
In order to verify the SOC balance ability between energy storage batteries under this droop coefficient, Formula (5) is established.

\[
\dot{e}_{SOC} = SOC_1 - SOC_2
\]  

(5)

SOC_1, SOC_2, e_{SOC} represent respectively the SOC of the 1st energy storage battery, the SOC of the 2nd energy storage battery and the difference between two energy storage batteries.

\[
SOC_i = \frac{P_{Load}}{V_{bat}C_{bat}} \sum_{j=1}^{2} e^{mSOC_j^n} dt
\]

(6)

\[
\dot{e}_{SOC} = \frac{P_{Load}}{V_{bat}C_{bat}} \sum_{j=1}^{2} e^{mSOC_j^n} - e^{mSOC_i^n}
\]

(7)

On the premise that \(SOC_1 > SOC_2\), \(\dot{e}_{SOC} \leq 0\) can be got.

\[
\dot{e}_{SOC} = \frac{P_{Load}}{V_{bat}C_{bat}} (1 - \frac{2}{e^{mSOC_2^n - mSOC_1^n} + 1})
\]

(8)

In order to find the minimum value of \(\dot{e}_{SOC}\), the formula (9)(10) are established.

\[
\dot{e}_{SOC} = \frac{P_{Load}}{V_{bat}C_{bat}} (1 - \frac{2}{e^{my} + 1})
\]

(9)

\[
y = SOC_2^n - SOC_1^n
\]

(10)

In this case, the objective is to take the minimum value of function y.

\[
\frac{\partial y}{\partial n} = SOC_2^n \ln SOC_2 - SOC_1^n \ln SOC_1
\]

(11)

When y is the minimum value, the expression of n is

\[
n = \frac{\ln[\ln(SOC_1)/\ln(SOC_2)]}{\ln(SOC_2) - \ln(SOC_1)}
\]

(12)

That is to say, under any given \(SOC_1\) and \(SOC_2\), the optimal n can be found. The optimized n schematic diagram is shown in Figure 1.
But based on this objective function, \( \text{SOC}_1 = \text{SOC}_2 \) cannot be obtained; and for the purpose of fast equalization, the equalization speed will be too fast when SOC deviation is very small, resulting in the two energy storage devices not reaching the optimal equilibrium state. Therefore, when the SOC deviation is small, \( n \) remains unchanged to stabilize the SOC equalization speed, thus avoiding the problem of excessive equalization.

### 3. Simulation analysis

The same specification lithium-ion batteries are chosen to establish simulation experiments. The DC bus voltage is 700V and the bus voltage is allowed to range. The specific parameters are shown in Table 1.

| Parameter                      | Value | Parameter                      | Value |
|--------------------------------|-------|--------------------------------|-------|
| Voltage of Energy Storage Unit 1(V) | 80    | SOC of energy storage unit 1(%) | 90    |
| Voltage of Energy Storage Unit 2(V) | 80    | SOC of energy storage unit 2(%) | 85    |
| Capacity of Energy Storage Unit 1(Ah) | 20    | DC Bus Voltage(V)             | 700   |
| Capacity of Energy Storage Unit 2(Ah) | 20    | Total Load Power(KW)          | 6     |

**Experiment 1: SOC droop control experiment with fixed acceleration factor**

The simulation results in figure 2 and figure 3 show that the droop control method based SOC can match the output power of the energy storage battery with SOC, that is to say, the energy storage battery with large capacity discharges more, and the value of SOC decreases faster; while the energy storage battery with small capacity discharges less, and the value of SOC decreases slowly, which eventually achieves the effect of SOC equalization and power sharing.

In the process of SOC equalization, fixed \( n \) has its limitations that can not meet the requirements of fast equalization in the whole process. Therefore, the acceleration factor \( n \) needs to be further optimized.

**Experiment 2: SOC droop control experiment with optimized acceleration factor**
Figure 4. Schematic diagram of Optimizing Acceleration Factor with Time

![Figure 4](image)

Figure 5. SOC equalization schematic under optimized $n$.  

Figure 6. Schematic diagram of power balance under optimized $n$.

Figure 5 and figure 6 show that compared with the fixed acceleration factor equalization method, the optimized acceleration factor greatly improves the equalization speed of SOC. At the same time, the power allocation can be adjusted according to the value of SOC. Figure 4 shows that when the SOC deviation is large, the acceleration factor $n$ adjusts with the change of SOC in real time to ensure the fast balancing under different SOC; when the SOC deviation is small, the acceleration factor remains unchanged to avoid excessive balancing caused by too fast balancing speed; besides, the acceleration factor $n$ decreases gradually over time, which Satisfies basic conditions that the high charge state corresponds to the large acceleration factor, and the low charge state corresponds to the low acceleration factor.

4. conclusion
In order to improve the equalization speed of SOC and achieve the goal of SOC equalization, the improved droop control based on SOC is proposed in this paper, and the calculation method of optimal acceleration factor is deduced. With the value of $SOC_1$ and $SOC_2$, the optimal acceleration factor can be calculated in real time. The strategy effectively solves the prominent problem of unreasonable power distribution caused by traditional droop control. The Simulations can fully verify feasibility and validity of the control strategy.

References
[1] Lu, X. , Sun, K. , Huang, L. (2013) Improved droop control method in distributed energy storage systems for autonomous operation of AC microgrid. automation of electric power systems, 37(1): 180-185.
[2] Wang, W. , Duan, J. , Zhang, R. , Guo, H. , Sun, L. (2015) Optimal state-of-charge balancing control for paralleled battery energy storage devices in islanded microgrid. Transactions of China Electrotechnical Society. 30(23): 126-135
[3] Li, P. , Zhang, C. , Yuan, R. , Kang, Z. , Chen, Y. (2017) Load current sharing method of distributed energy storage systems by improved soc drooping control. Proceedings of the Csee. 37(13): 86-94
[4] Wu, Q. , Guan, R. , Sun, X. , Wang, Y. , Xin, L. (2018) Soc balancing strategy for multiple
energy storage units with different capacities in islanded microgrids based on droop control. IEEE Journal of Emerging & Selected Topics in Power Electronics, PP(99), 1-1.

[5] WEI, Z. , Chen, M. , Li, J. , Chen, T. , Li, Q. , Chen, F. , Ling, W. (2018) Balancing control strategy of SOC and efficiency for distributed energy storage in islanded microgrid. Electric Power Automation Equipment, 38(4): 169-177

[6] Xu, P. (2018) Research on Energy Storage System Based on SOC Balancing Control for DC Microgrid. Anhui University of Technology, Anhui.