An Adaptive Rapid Balancing Control for Clustered SoC of Cascaded Battery Energy Storage Converter

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Abstract

Accelerating the balancing speed of the cascaded battery energy storage converter can improve the output performance, utilization rate and battery life of the energy storage unit in response to the problem of clustered SoC imbalance. On the basis of analyzing the principle of system power redistribution caused by injecting zero sequence voltage during clustered imbalance, the relationship between the variable power injection and the battery SoC was explored; Secondly, considering the modulation constraints of each power unit and the charging and discharging limitations of each battery, the boundary of the superimposed zero sequence voltage required for clustered balanced is analyzed. Based on the above analysis, an adaptive rapid balancing control for clustered SoC is proposed. When the degree of SoC imbalance is large, the maximum zero sequence voltage is continuously injected to improve the speed of clustered SoC balanced. Contrarily, a PI controller is used to ensure that the system achieves zero difference balanced while taking into account system stability. Finally, the effectiveness of the proposed control strategy is verified through simulation analysis.

Keywords

Cascaded Battery Energy Storage Converter; Clustered SoC Balancing; Zero Sequence Voltage; Variable Power; Modulation Constraints; Rapid Balancing; Adaptive Control.

1. Introduction

The rapid development of centralized new energy development and distributed power generation has led to increasingly prominent issues of large-scale new energy consumption[1, 2].In order to reduce the rate of wind and light abandonment, suppress fluctuations in new energy output, and enhance the ability of the power grid to absorb new energy, large-capacity energy storage technology has been vigorously promoted[3, 4].The existing battery module grouping technology limits the capacity of batteries. Currently, MMC topology and H-bridge cascaded topology are commonly used to expand the capacity of energy storage systems [5].The H-bridge cascaded topology has the advantages of low loss, fast dynamic response speed, high conversion efficiency, and high capacity utilization, which better meets the technological development needs of future power grids for electrochemical energy storage with high power, capacity, and efficiency [6-7].

Due to factors such as the initial battery capacity of the H-bridge cascaded battery pack and the difference in losses of various power devices, there are differences in the SoC between phases in the energy storage system, which can easily lead to a "short board" effect [8]. That is, during the charging process, the SoC of a certain battery pack reaches 100%, or during the discharge process, the SoC of a certain battery pack first reaches 0, forcing the module in the energy storage system to exit, reducing the utilization rate of battery energy storage capacity, Therefore, it is necessary to perform balanced control on the H-bridge cascaded energy storage converter [9,10].

In response to the problem of clustered voltage imbalance in the H-bridge cascaded reactive power compensator, reference [11] adopts a three-layer control, with different control objectives at each level and decoupling from each other. Realize the total power setting of the three-phase first layer control system, thereby determining the total capacitance voltage of the three-phase module; The second layer of interphase power balance control distributes interphase power to achieve voltage balanced of interphase DC capacitors; The third layer of power balance control within the phase allocates the active power of each module within the phase, achieving DC voltage balance between cascaded modules. Analogous to the DC voltage balance problem, for the phase to phase SoC imbalance problem of H-bridge cascaded energy storage systems, the balance methods are mainly divided into hardware balance and software balance. Hardware balance mostly uses additional circuits to absorb or release energy to achieve SoC balance between battery packs, which is simple to control but inevitably increases costs, and is rarely applied in practical engineering [12]. In practical applications, software balancing is mostly used. Reference [13] uses the method of injecting zero sequence voltage to achieve clustered SoC balancing control. This method does not affect the system output performance and is easy to implement, and is widely used. When there is a significant difference in clustered SoC, this method may cause the power module to overshoot and lose the balancing effect; Reference [14] improves the clustered balance ability by injecting negative sequence voltage. When there is a significant difference in SoC between phases, it can achieve clustered SoC balance while ensuring that the power module does not overshoot, but to some extent, it affects the system output performance and has limitations in practical applications; In order to balance the system output performance and balancing ability, reference [15] combines zero sequence voltage injection control strategy with negative sequence voltage injection control strategy, that is, zero sequence voltage injection strategy is adopted when the system imbalance is small, and vice versa, negative sequence voltage injection strategy is adopted to make the system more stable in complex imbalance conditions. According to the analysis of negative sequence voltage injection control strategy, This composite balanced control strategy also has a significant impact of negative sequence current on the power quality of the energy storage system; Reference [16] improved the composite balancing control strategy by introducing a series of parameters m and m respectively for zero sequence voltage and negative sequence voltage, which not only alleviated the impact of negative sequence current on the output performance of energy storage systems but also solved the problem of smooth transition between different balancing modes. Currently, it is in the engineering practice stage. Although the injection of negative sequence voltage has a strong ability to regulate clustered balance, it also introduces negative sequence current into the power grid, causing pollution to the power grid. Due to the star shaped topology, the injection of zero sequence voltage does not introduce zero sequence current into the power grid. Therefore, the zero sequence voltage injection method does not have any impact on power quality. Based on this, this article adopts the zero sequence voltage injection method to achieve clustered SoC balance.

The rapid balancing of clustered SoC helps to improve the capacity utilization rate of the system and ensure the safety of the battery [17]. This article further analyzes the balance control method of injecting zero sequence voltage based on reference [13], explores the relationship between variable power caused by injecting zero sequence voltage and battery pack SoC, and proposes an adaptive balance control method for clustered SoC, which can change the amplitude and phase of injected zero sequence voltage in real-time according to the difference in clustered SoC, achieving balance between the three phases of the energy storage system SoC and improving the balance speed.

2. Cascade H-bridge Energy Storage System

2.1 Topology

The topology diagram of the cascaded H-bridge energy storage converter is shown in Figure 1. Each phase is composed of n H-bridge power units in series, and capacitors are connected in parallel at both ends of the DC side battery pack of each module to reduce ripple. The energy storage converter adopts a star connection method and is connected to the medium and high voltage power grid through the grid connected reactor L. In Figure 1, usa, usb, usc respectively represent the three-phase AC voltages of grid A, B, and C; uao, ubo, uco represent the three-phase output voltage of the converter, and ia, ib, icrepresent the grid connected current of each phase.

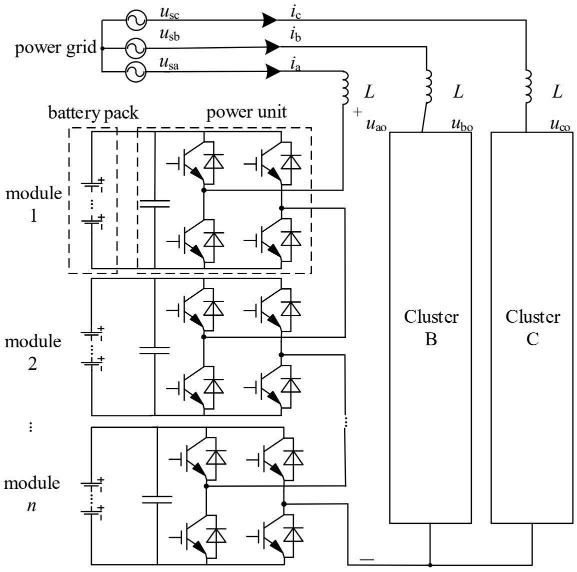


Figure 1. Topology diagram of cascaded H-bridge energy storage converter

2.2 Page Numbers

The control strategy of energy storage converters mainly includes two aspects: system power control and balance control. The power control diagram of the energy storage converter system based on instantaneous power theory is shown in Figure 2.

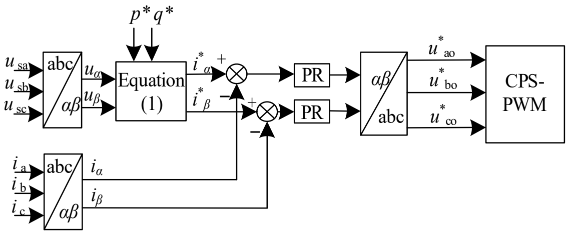


Figure 2. Control strategy of cascaded H-bridge energy storage converter

In a $\alpha\beta$ two-phase stationary coordinate system, according to the instantaneous power theory[18], the grid connection command current i_α^* , i_β^* can be derived by:

$$\begin{cases} i_\alpha^* = \dfrac{u_\alpha}{u_\alpha^2 + u_\beta^2} p^* + \dfrac{u_\beta}{u_\alpha^2 + u_\beta^2} q^* \\ i_\beta^* = \dfrac{u_\beta}{u_\alpha^2 + u_\beta^2} p^* - \dfrac{u_\alpha}{u_\alpha^2 + u_\beta^2} q^* \end{cases} \tag{1}$$

Where u_α is the grid voltage component α in $\alpha\beta$ coordinate system, u_β is the grid voltage component β in $\alpha\beta$ coordinate system; p^* is active power command for the system, q^* is reactive power command for the system.

The current inner loop uses a Proportional Resonant (PR) regulator to track the command current without error, and then obtains u^*_{ao}, u^*_{bo}, u^*_{co} which the modulation reference voltage of each phase through coordinate transformation.

3. Clusterd Balance Control

The clustered SoC balance control of the cascaded H-bridge energy storage converter is to control the SoC value of each phase to be equal to the average of the sum of the three phase SoC values. Unbalanced power grid voltage or different losses of each phase and module can lead to inconsistent clustered SoC in the cascaded H-bridge energy storage converter.Therefore, it is necessary to balance the clustered SoC. This article studies and improves the phase to phase SoC balanced based on the zero sequence voltage injection method in reference [13].

3.1 The Balance Principle of Injecting Zero Sequence Voltage

The clustered SoC balance should meet the following requirements: (1) Under charging conditions, the lower average SoC value phase should allocate more active power to accelerate charging speed, while the higher average SoC value phase should reduce the allocation of active power and slow down charging speed. (2) Under discharge conditions, the lower average SoC value phase reduces active output and slows down discharge speed, while the higher average SoC value phase increases its active output and accelerates discharge speed. Essentially, it is the redistribution of active power between different phases. Therefore, the power corresponding analysis should be conducted first.

The output voltage and grid connected current of the energy storage converter can be assumed as:

$$\begin{cases} u_{\mathrm{ao}} = U_1\cos(\omega t) + U_2\cos(\omega t+\theta_2) + U_0\cos(\omega t+\theta_0) \\ u_{\mathrm{bo}} = U_1\cos(\omega t - \dfrac{2\pi}{3}) + U_2\cos(\omega t+\theta_2+\dfrac{2\pi}{3}) + U_0\cos(\omega t+\theta_0) \\ u_{\mathrm{co}} = U_1\cos(\omega t + \dfrac{2\pi}{3}) + U_2\cos(\omega t+\theta_2-\dfrac{2\pi}{3}) + U_0\cos(\omega t+\theta_0) \end{cases} \tag{2}$$

$$\begin{cases} i_a = I_1\cos(\omega t-\phi_1) + I_2\cos(\omega t-\phi_2) \\ i_b = I_1\cos(\omega t-\phi_1-\dfrac{2\pi}{3}) + I_2\cos(\omega t-\phi_2-\dfrac{2\pi}{3}) \\ i_c = I_1\cos(\omega t-\phi_1+\dfrac{2\pi}{3}) + I_2\cos(\omega t-\phi_2+\dfrac{2\pi}{3}) \end{cases} \tag{3}$$

Where U_1 is the positive sequence component's amplitude of the output fundamental voltage, U_2 and U_0 are the negative and zero sequence component's amplitude of the output fundamental voltage respectively; θ_2 and θ_0 are the negative sequence and zero sequence component's phase angles of the output fundamental voltage of the energy storage converter; I_1, I_2 and I_0 respectively are the positive sequence, negative sequence and zero sequence component's amplitude of the output fundamental current; ϕ_1, ϕ_2 are the positive sequenc, negative sequence component's phase angle of the output fundamental current.

Only injecting zero sequence voltage, by combining equations (2) and (3) and simplifying, the output active power of each phase of the energy storage converter can be expressed as:

$$\begin{cases} P_{\mathrm{ao}}=\frac{1}{2}[U_1I_1\cos\phi_1+U_0I_1\cos(\theta_0+\phi_1)]=P+\Delta P_{\mathrm{ao}} \\ P_{\mathrm{bo}}=\frac{1}{2}[U_1I_1\cos\phi_1+U_0I_1\cos(\theta_0+\phi_1+\frac{2\pi}{3})]=P+\Delta P_{\mathrm{bo}} \\ P_{\mathrm{co}}=\frac{1}{2}[U_1I_1\cos\phi_1+U_0I_1\cos(\theta_0+\phi_1-\frac{2\pi}{3})]=P+\Delta P_{\mathrm{co}} \end{cases} \tag{4}$$

Where the first part on the right of each equation is the constant active power component output by the phase, and the second part on the right of each equation is the variable active power component generated by injecting zero sequence into the phase. Due to the symmetry of the three phases in the system, the sum of the variable active power components ΔPao+ΔPbo+ΔPco is 0, indicating that injecting zero sequence voltage will not change the system output characteristics.

Analysis equation (4), choosing to inject a zero sequence voltage with appropriate amplitude and phase can change the variable active power component of the energy storage converter, thereby changing the system power distribution to achieve clustered SoC balance.

Define the SoC of the battery pack corresponding to the *j*th power unit of phase *k* as $S_{k,j}$(k=a,b,c;j=1,2,..n), S_a, S_b and S_c are respective the SoC mean value of each phase DC side energy storage battery. The system average SoC value S_o between the three phases can be expressed as:

$$S_\mathrm{o}=(S_\mathrm{a}+S_\mathrm{b}+S_\mathrm{c})/3 \tag{5}$$

The clustered imbalance of each phase can be expressed as:

$$\Delta S_k=S_k-S_\mathrm{o} \tag{6}$$

According to the analysis of clustered SoC balance, the balanced active power required to be allocated for each phase of the energy storage converter should be proportional to the clustered imbalance of each phase, and a proportional coefficient λ should be introduced. The relationship between the required balanced power of each phase and the degree of imbalance is satisfied:

$$\Delta P_{k\mathrm{o}}=\lambda\Delta S_k \tag{7}$$

Combining equations (4) and (7):

$$\begin{aligned} \Delta P_{\mathrm{ao}}&=\lambda\Delta S_\mathrm{a}=\frac{1}{2}U_0I_1\cos(\theta_0+\phi_1) \\ \Delta P_{\mathrm{bo}}&=\lambda\Delta S_\mathrm{b}=\frac{1}{2}U_0I_1\cos\left(\theta_0+\phi_1+\frac{2\pi}{3}\right) \\ \Delta P_{\mathrm{co}}&=\lambda\Delta S_\mathrm{c}=\frac{1}{2}U_0I_1\cos\left(\theta_0+\phi_1-\frac{2\pi}{3}\right) \end{aligned} \tag{8}$$

Equation (8) performs Clark transformation:

$$\begin{bmatrix} \Delta P_{\alpha o} \\ \Delta P_{\beta o} \end{bmatrix} = \lambda \begin{bmatrix} \sqrt{\frac{3}{2}} \quad \Delta S_a \\ \sqrt{\frac{1}{2}} \left(\Delta S_b - \Delta S_c \right) \end{bmatrix} = \begin{bmatrix} \sqrt{\frac{3}{8}} U_0 I_1 \cos\left(\theta_0 + \phi_1\right) \\ -\sqrt{\frac{3}{8}} U_0 I_1 \sin\left(\theta_0 + \phi_1\right) \end{bmatrix} \tag{9}$$

According to equation (9), the amplitude and phase angle of the injected zero sequence voltage can calculated as:

$$\begin{cases} U_0 = \sqrt{\frac{2}{3}} \frac{\lambda \Delta S_x}{I_1} \\ \theta_0 = \phi_1 + \gamma \end{cases} \tag{10}$$

Where:

$$\Delta S_x = \sqrt{\Delta S_a^2 + \Delta S_b^2 + \Delta S_c^2}$$
$$\gamma = \begin{cases} -\tan^{-1} \frac{\Delta S_b - \Delta S_c}{\Delta S_a} & \Delta S_a \neq 0 \\ -\frac{\pi}{2} & \Delta S_a = 0 \,\&\, \Delta S_b - \Delta S_c > 0 \\ \frac{\pi}{2} & \Delta S_a = 0 \,\&\, \Delta S_b - \Delta S_c < 0 \end{cases} \tag{11}$$

The clustered SoC balance control strategy for injecting zero sequence voltage is shown in Figure. 3, where u*0 is the zero sequence modulation reference voltage for clustered SoC balance injection.

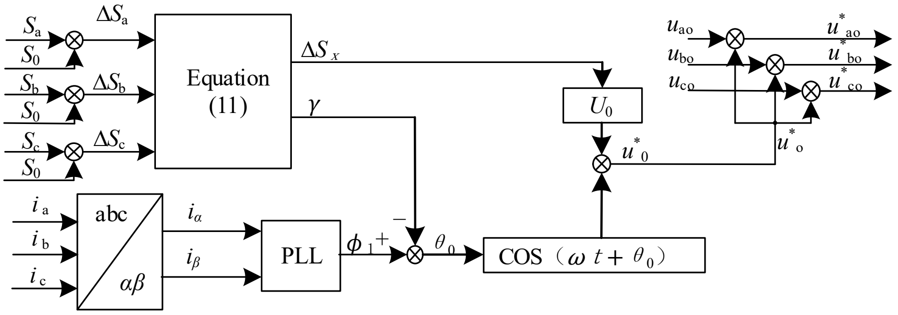


Figure 3. Clustered SoC balance control strategy for injecting zero sequence voltage

3.2 The Specific Relationship between Injected Variable Active Power and SoC Variation

The specific relationship between the injected variable active power ΔPao and the variation of battery pack's SoC is analyzed by taking the a-phase of the energy storage converter as an example. The equivalent circuit diagram of the converter A-phase is shown in Figure 4, where idca is the DC side current of the storage converter a-phase; Vdca is the voltage at both ends of the battery pack, which does not fluctuate much in consideration of the battery characteristics; and Sa is the average value of the real-time SoC of the battery pack of the A-phase, which is obtained by the amperage time integration method.

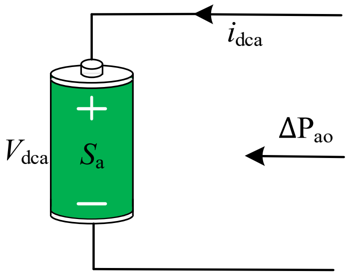


Figure 4. Equivalent circuit diagram of phase A of storage converter

From Figure 4 and the method of integrating the ampere time, we have:

$$\begin{gathered}(S_t - S_0)Q_{\text{nom}} = \int_0^t i_{\text{dca}}dt = \int_0^t \frac{\Delta P_{\text{ao}}}{V_{\text{dca}}}dt \\ \Rightarrow S_t - S_0 = \frac{\Delta P_{\text{ao}} * t}{Q_{\text{nom}}V_{\text{dca}}}\end{gathered} \tag{12}$$

Where St is the charging state of A-phase battery at time t; S0 is the charging state of A-phase battery at the initial moment; Qnom is the rated capacity of A-phase battery.

Analyzing Equation (12), it can be seen that the change of SoC of a-phase battery pack is proportional to the product of injected variable active power ΔPao and time t. Combined with Equation (4), it can be analyzed that the injected variable active power ΔPao is proportional to the magnitude of injected zero-sequence voltage.The larger the injected variable active power ΔPao, the smaller balance time t. That is, the larger the injected zero-sequence voltage magnitude U0, the faster the balance. Then the clustered SoC rapid balance problem is transformed into injecting the maximum magnitude of zero-sequence voltage in each power unit of the energy storage converter without modulation.

4. Improved Adaptive Rapid Balancing Control for Clustered SoC

4.1 Boundary Analysis of Injected Zero-sequence Voltage Magnitude

In clustered balance control, it is known from equation (10) that the proportionality coefficient λ determines the magnitude of the injected zero-sequence voltage, the larger value of λ, the larger the injected variable active power ΔPao, and the faster the clustered SoC balance. When the clustered unbalance ΔSa, ΔSb, ΔSc is large, the active power to be balanced increases, and the amplitude of the injected zero-sequence voltage increases. In order to avoid overshooting of each power unit in the battery energy system, the injected zero-sequence voltage should satisfy:

$$u_{ko} + u_0^* \le nm_{ko}V_{\text{dc}} \tag{13}$$

Where mko is a modulated wave with amplitude 1.

Neglecting the inductive voltage drop, the upper bound on the allowed amplitude of the injected zero-sequence voltage of the system can be obtained from the Equation (13) as:

$$U_{0\max}=\min\left\{\begin{array}{l}\sqrt{(nV_{\mathrm{dc}})^2-U_{\mathrm{sa}}^2\sin^2\varphi_{\mathrm{a}}}-U_{\mathrm{sa}}\cos\varphi_{\mathrm{a}},\\ \sqrt{(nV_{\mathrm{dc}})^2-U_{\mathrm{sb}}^2\sin^2\varphi_{\mathrm{b}}}-U_{\mathrm{sb}}\cos\varphi_{\mathrm{b}},\\ \sqrt{(nV_{\mathrm{dc}})^2-U_{\mathrm{sc}}^2\sin^2\varphi_{\mathrm{c}}}-U_{\mathrm{sc}}\cos\varphi_{\mathrm{c}}\end{array}\right\} \tag{14}$$

Where U0max is the maximum value of zero sequence voltage amplitude allowed to be injected, Uao, Ubo and Uco are the amplitudes of the three-phase voltage of the converter, φa, φb and φc are the angle between the phase angle of each phase of the output voltage of the converter and the zero sequence current.

To ensure that the clustered balance can be completed when the SoC of all modules in a phase reaches 100% or 0, a minimum value of the injected zero-sequence voltage exists. Under the charging critical condition, the ratio of the active component of the inverter voltage between the phases is (1-Sa):(1-Sb):(1-Sc); under the discharging critical condition, the ratio of the active component of the inverter voltage between the phases is Sa:Sb:Sc. Thus, under the charging condition, the lower bound of the permissible amplitude of the injected zero-sequence voltage in the system is:

$$U_{0\min\mathrm{cha}}=\max\left\{\begin{array}{l}U_{\mathrm{ao}}\left(\sqrt{\left(\frac{1-S_{\mathrm{a}}}{1-S_0}\right)^2-\sin^2\varphi_{\mathrm{a}}}-\cos\varphi_{\mathrm{a}}\right),\\ U_{\mathrm{bo}}\left(\sqrt{\left(\frac{1-S_{\mathrm{b}}}{1-S_0}\right)^2-\sin^2\varphi_{\mathrm{b}}}-\cos\varphi_{\mathrm{b}}\right),\\ U_{\mathrm{co}}\left(\sqrt{\left(\frac{1-S_{\mathrm{c}}}{1-S_0}\right)^2-\sin^2\varphi_{\mathrm{c}}}-\cos\varphi_{\mathrm{c}}\right)\end{array}\right\} \tag{15}$$

Similarly, the lower bound on the allowable amplitude of the injected zero-sequence voltage of the system under the discharge condition is:

$$U_{0\min disc}=\max\left\{\begin{array}{l}U_{\mathrm{ao}}\left(\sqrt{\left(\frac{S_{\mathrm{a}}}{S_0}\right)^2-\sin^2\varphi_{\mathrm{a}}}-\cos\varphi_{\mathrm{a}}\right),\\ U_{\mathrm{bo}}\left(\sqrt{\left(\frac{S_{\mathrm{b}}}{S_0}\right)^2-\sin^2\varphi_{\mathrm{b}}}-\cos\varphi_{\mathrm{b}}\right),\\ U_{\mathrm{co}}\left(\sqrt{\left(\frac{S_{\mathrm{c}}}{S_0}\right)^2-\sin^2\varphi_{\mathrm{c}}}-\cos\varphi_{\mathrm{c}}\right)\end{array}\right\} \tag{16}$$

In summary, when the energy storage converter system parameters are certain, the amplitude of the injected zero-sequence voltage exists upper and lower limits. Adaptive balance control is used to accelerate the clustered balance control based on the above analysis. when the clustered SoC imbalance is large, utilizes power module balanced capability as much as possible by superimposing the largest value of zero-sequence voltage to accelerate clustered SoC balance; when the clustered SoC imbalance is smaller, considering the dynamic stability of the system, a PI controller is used for clustered SoC balance control.

4.2 Improved Adaptive Rapid Balancing Control for Clustered SoC

An improved clustered SoC adaptive rapid balance control is proposed on the basis of the clustered balance control strategy in Fig. 3, and the injected zero-sequence voltage is expressed as:

$$U_0=\begin{cases} K_0\Delta S_x\cos(\omega t+\theta_0) & i_{\mathrm{dc}}>0 \\ -K_0\Delta S_x\cos(\omega t+\theta_0) & i_{\mathrm{dc}}<0 \end{cases} \tag{17}$$

where the balanced coefficient K0 is:

$$K_0=\frac{\sqrt{2/3}\lambda}{I_1} \tag{18}$$

In order to take into account the system stability and clustered SoC balance speed, balance coefficient K0 adopts a segmented design, when the degree of clustered SoC imbalance |ΔSmax| is larger, the need to avoid over-modulation of the power unit under the premise of the SoC balance on speed as much as possible to accelerate the speed of the phase, focusing on the rapid realization of the phase equilibrium, the balanced coefficient K0 is dependent on the upper limit of the amplitude of the injected zero-sequence voltage; when the degree of inter-phase SoC imbalance |ΔSmax| is smaller, the focus on considering the stability of the system, at this time, balanced coefficient K0 is obtained from the PI controller to achieve the balanced of the balance coefficient of the expression as follows:

$$K_0=\begin{cases} \dfrac{U_{0\max}}{\Delta S_x}, & |\Delta S_{\max}|>w \\ k_p(\Delta S_x+k_i\int\Delta S_x dt), & |\Delta S_{\max}|<w \end{cases} \tag{19}$$

The specific implementation steps of the improved clustered SoC adaptive rapid balance control strategy are as follows:

1) Judge the converter charging and discharging state, the charging and discharging state |ΔSmax| are:

$$|\Delta S_{\max}|=\begin{cases} \mathrm{Max}\{\Delta S_a,\ \Delta S_b,\ \Delta S_c\}, & \text{charging state} \\ \mathrm{Min}\{\Delta S_a,\ \Delta S_b,\ \Delta S_c\}, & \text{discharging state} \end{cases} \tag{20}$$

2) By judging the charging and discharging state and associated equation (14), (15),(16) to obtain this converter imbalance degree corresponding to the injected zero-sequence voltage amplitude boundaries. if U0min<U0max, indicates that only the injection of zero-sequence voltage can not be maximized under the premise of the use of the stored energy to achieve balanced, it is necessary to consider with the method of injecting the negative-sequence voltage to cooperate with the method, the paper does not go into detail; if U0min<U0max, indicates that the method is effective, to carry out the next step.

3) Judge the relationship between |ΔSmax| and the segmentation threshold w. Where the selection of the w should be a suitable choice. The threshold value is taken too large, reducing the utilization of the system balanced margin and thus reducing the speed of inter-phase balanced; too small a value reduces the stability of the system. In this paper, w is taken as 0.02. Then the value of balanced coefficient can be known from equation (19).

4) When |ΔSmax| is in the segmentation interval of |ΔSmax|>w, the dynamic balanced coefficient K0 is obtained through the system parameters and the calculation module to realize the inter-phase SoC balanced at the maximum speed; when |ΔSmax| is in the segmentation interval of |ΔSmax|<w, the balanced coefficient K0 of the moment before the segmentation as well as the system stability requirements are adjusted in the parameters of PI controllers, which ensures that the power of the

phases will not drop suddenly and at the same time realizes the system inter-phase SoC balanced quickly and without any difference.

5. Simulation Analysis

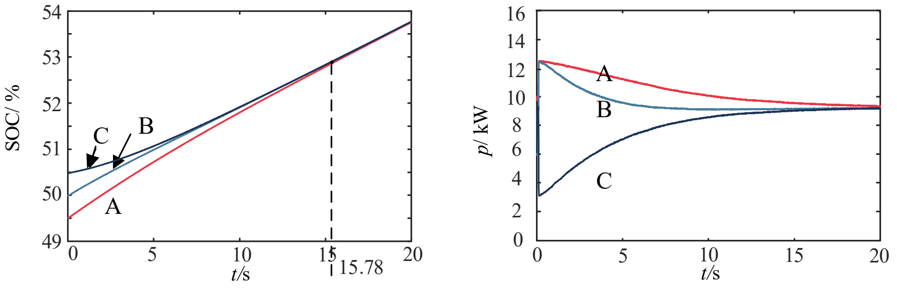
In order to verify the effectiveness of improved adaptive rapid balancing control for clustered SoC, build a cascaded H-bridge type energy storage converter simulation model in Matlab/Simulink. The parameters of the cascaded H-bridge type energy storage converter system are shown in Table 1.

Table 1. Cascaded H-bridge power conversion system parameters

parameter	Value
Effective value of grid phase voltage U_{sk}/V	220
Number of cascading modules n	3
Filter reactor reactance L/mH	1
Battery pack voltag U_{dc}/V	120
Rated capacity of battery pack Q_{nom}/A·h	3
DC side capacitance C_s/mF	3
Device switching frequency f_s/kHz	1
System active power command p^*/kW	30
System reactive power command q^*/kvar	0
Initial SoC of each phase battery pack /%	49.5, 50,50.5

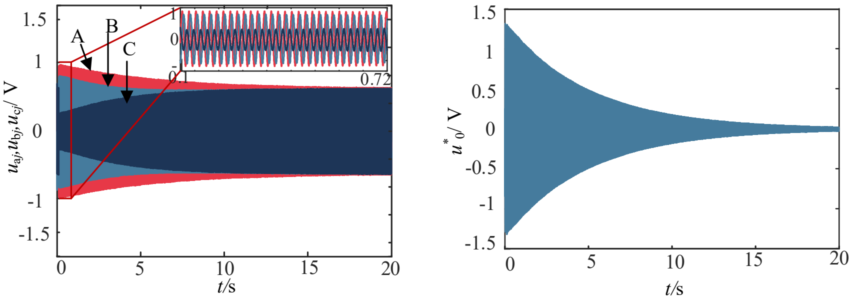
5.1 Simulation Analysis of Clustered Control with Zero-sequence Voltage Injection

The clustered SoC balanced with injected zero-sequence voltage is added after 0.1s, at which time the simulation waveform is shown in Figure. 5.



(a) Three-phase SoC average state diagram under clustered SoC balanced

(b) Simulated waveforms of three-phase output power Pko



(c) Simulated waveforms of modulated reference voltage of each phase power unit

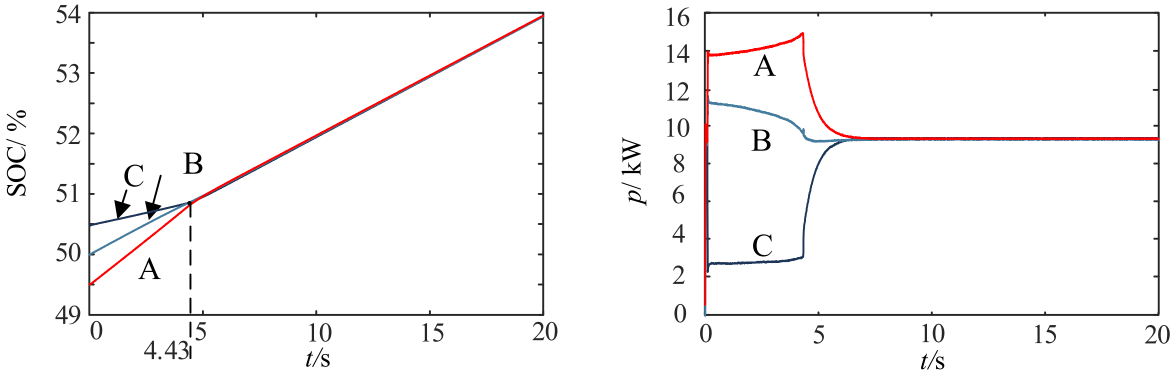
(d) Simulated waveforms of zero sequence voltage injected by the system

Figure 5. Simulation waveforms of injected zero sequence voltage clustered balance

Figure. 5(a) shows the three-phase SoC average state diagram after performing clustered SoC balanced, and the three-phase SoC reaches balanced at 15.78s, indicating the effectiveness of clustered SoC balanced. Fig. 5(b) shows the waveforms of three-phase output power Pko after the clustered SoC balanced, in which the A-phase SoC is the lowest and the charging power is the largest, the C-phase SoC is the highest and the charging power is the smallest accordingly, and with the gradual equalization of the clustered SoC, the power is gradually equalized between the phases, which verifies the correctness of the principle of clustered SoC balanced. Figure 5(c) shows the simulated waveforms of the modulated reference voltage of the power unit of each phase of the energy storage converter after the clustered SoC balanced, and the amplitude of the modulated reference voltage of each power unit of the A-phase is the largest and the charging speed is the fastest, with a modulation ratio of 0.99, which is close to 1, indicating that the amplitude of the injected zero-sequence voltage is close to the maximum at this time, and the modulated reference voltage of the power unit of the C-phase has the smallest amplitude and the slowest charging speed. Figure 5(d) shows the simulation waveforms of the zero-sequence voltage modulation reference voltage injected after clustered SoC balanced, the zero-sequence voltage is injected at 0.1s, and K0 takes the value of 72 in the simulation, and the theoretical value of K0 is 72.75 by Equation (10) and (11), ignoring simulation control errors, the actual value is basically in line with the theoretical value, and it verifies the correctness of its boundary analysis.

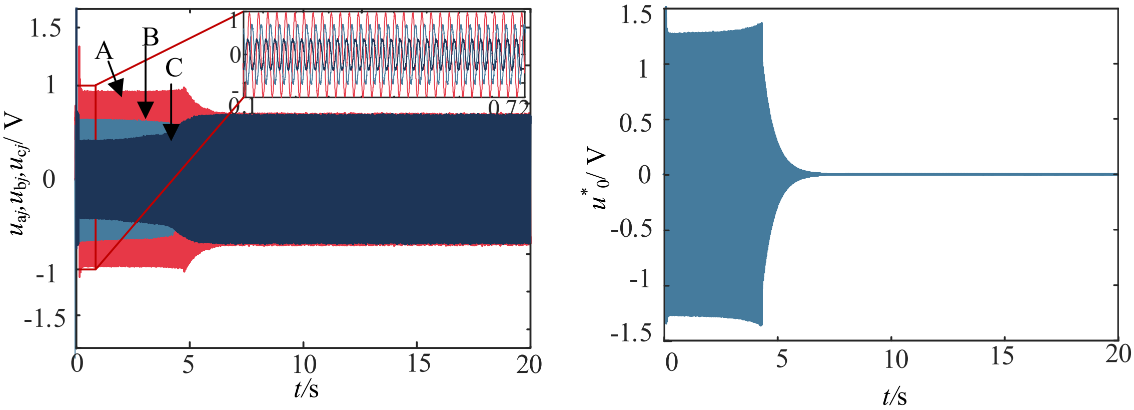
5.2 Simulation and Analysis of Improved Clustered SoC Adaptive Rapid Balanced Control

The improved clustered SoC adaptive rapid balanced control is added after 0.1 s. At this time, the simulation waveform is shown in Figure 6.



(a) Three-phase SoC average state diagram under clustered SoC balanced

(b) Simulated waveforms of three-phase output power Pko



(c) Simulated waveforms of modulated reference voltage of each phase power unit

(d) Simulated waveforms of zero sequence voltage injected by the system

Figure 6. Simulation waveforms of clustered SoC adaptive rapid balanced control

In Fig. 6(a) the three-phase SoC reaches balance in 4.43s, which reduces the balance time by 11.43s compared with the zero-sequence voltage injection method, demonstrating the effectiveness of the improved clustered SoC adaptive rapid balance. Compared with Figure 5 (b), the module with lower SoC in Figure 6 (b) has an increase in charging power, which fully utilizes the power balancing ability of each power unit. In Figure 6 (c), the modulation reference voltage amplitude of each power unit in phase A is the largest, with a modulation ratio of 0.99, close to 1, indicating that the amplitude of the injected zero sequence voltage is maintained at a state close to the maximum value under this method, increasing the charging power of phase A and accelerating inter phase equalization. Compared to Figure 5 (d), the amplitude of the injected zero sequence voltage in Figure 6 (d) remains unchanged at the maximum zero sequence voltage value, increasing the transmission of phase A charging power.

6. Conclusion

This paper proposes an adaptive rapid balancing method for clustered SoC based on the analysis of the injected zero-sequence voltage boundary when the clustered SoC is not balanced and performs a simulation study. Simulation results show that this method can maximize the utilization of the equalization capacity of each power unit, improve the charging and discharging power of the unbalanced module, and realize the rapid balancing of clustered SoC under the premise of system stability.

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