Research on SOC balance strategy of STEKF battery based on MMC-BESS model

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Abstract. Under the condition of the battery current fluctuation and the uncertain initial value of the battery SOC in the MMC(Modular Multilevel Converter) battery energy storage system, there are relatively big errors in the prediction of SOC estimation values and there are poor results of the battery SOC balance, by using the ampere-hour integration method and the open-circuit voltage method. The method of model prediction was adopted to study the SOC balance strategy. Firstly, the power transfer function between each port is derived and the second-order Thevenin equivalent nonlinear model of the battery is established. On this foundation, the more accurate estimation results of the battery SOC are obtained employing the strong tracking extended Kalman filter algorithm, under the condition of the large fluctuation of the battery current and the uncertainty initial value of the battery SOC in the MMC-BESS model. In the end of the paper, the validity of the method introduced in the paper way was confirmed according to the simulation results of the simulation calculation based on the power transfer relationship between the battery SOC and each port, using the three-level SOC balance strategy to balance the battery SOC.

1. Introduction

With the continuous development of the renewable energy, it is a trend for the large-scale renewable energy to combine to the grid. For the characteristics of intermittence and randomness of the renewable energy, it is a negative impact on the power grid[1-3], which requires adding the BESS (Battery Energy Storage System) or other energy storage device to ensure the stability of power grid[4-6]. As an important link port in power grid, the MMC (Modular Multi level Converter) plays an important role in the medium and high voltage field, and the MMC-BESS (MMC-based battery energy storage system) can effectively improve the safety and stability of power grid, so as to provide necessary condition for large-scale power connection of renewable energy.

In the past more than one decade, due to high modularization of MMC topological structure, single sub-module has the characteristics of low voltage level, low switching frequency and small harmonic distortion rate of inverter output voltage, and it is generally applied in the fields of HVDC power transmission, AC-DC hybrid system and renewable energy power generation and grid connection[7-11]. In recent years, with the fast development of battery technology, the battery cost has declined in...
general. With the gradual increase in the number of decommissioning batteries, the cost for establishment of BESS has decreased sharply, and BESS has become a popular research subject. In addition, the MMC-BESS can effectively avoid the “buckets effect”, and it also has the AC and DC buses, which generally applies to the AC-DC hybrid medium and high voltage grid connection system.

In the MMC-BESS, the inconsistency of batteries and the difference between various sub-modules in power output will both result in different state of charge (SOC) between batteries. Furthermore, the utilization rate of MMC-BESS is affected by the sub-module with most extreme SOC, which is not beneficial to fully utilizing the capacity of BESS\(^{[18]}\), so it is necessary to balance the SOC of battery. In Literature \([12]\), they proposed a PWM modulation scheme which does not require computation decoupling, so that the adjacent sub-modules can realize voltage balance; Literature \([13]\) proposed an adaptive balance method for capacitor voltage under low switching frequency; in Literature \([14]\), a capacitor voltage balance strategy for minimum loop current was proposed, but they did not introduce the battery SOC, while only considered the balance of battery voltage; Literatures \([15-17]\) adopted the ampere-hour integration method to conduct SOC estimation of battery, conducted research on the SOC balance strategy and realized balance of battery SOC; based on that, the concept of droop control was integrated in Literature \([18]\), but they failed to formulate a method combining precise battery model with model prediction to balance the battery SOC more accurately.

Among current researches on MMC-BESS, the battery SOC estimation is conducted using the ampere-hour integration method and open-circuit voltage method. However, in reality, the battery current and voltage have significant fluctuations in the MMC-BESS, the ampere-hour integration method and open-circuit voltage method are sensitive to the collection of current and voltage, the error will be continuously accumulated, which will finally result in the SOC difference between batteries, and it cannot reach balance. In order to address this issue, a more reliable battery SOC estimation method is proposed in this paper. First, we analyze the power transfer relationship between each port of MMC-BESS; then, we build the second-order RC mathematical model of battery, and utilize the STEKF (strong tracking extended Kalman filter) algorithm to estimate the battery SOC; next, the three-level SOC balance strategy to realize SOC balance among all batteries; finally, the feasibility and effectiveness of this method are verified through simulation analysis.

2. Analysis of MMC-BESS principle

2.1. Topological structure of MMC-BESS

The topological structure of MMC-BESS is as shown in figure 1. The phases of MMC-BSS \((k=a\ (\text{phase} \ A), \ b\ (\text{phase} \ B) \ \text{and} \ c \ (\text{phase} \ C))\) consist of the upper bridge arm \((j=u)\) and lower bridge arm \((j=d)\); each bridge arms is composed of \(n\) SM; sub-modules \((i=1,2,3,\ldots, n)\); each sub-module consists of half-bridge, battery and capacitance \(C\). The upper and lower bridge arms connect the bridge arm inductance \(L\) in series, grid-connection filter inductance \(L_o\) in the middle point linked is connected to the AC bus, while the upper and lower bridge arms are directly connected to the DC bus.
In figure 1, the bridge arm inductance $L$ mainly plays the role of filtering and current limiting, $R$ is the equivalent series impedance of bridge arm, and $R_g$ is the grid connection equivalent impedance.

2.2. Operating mode of MMC-BESS sub-module

In MMC-BESS, the operating mode of SM sub-module includes three types, which are the charging/discharging mode, cut-off mode and by-pass mode, respectively. Among them, the first two states are normal operating modes, while the SM sub-module will enter the bypass mode when failure occurs.

Figures 2(a), 2(b), 2(c) and 2(d) show the working principle of sub-module under normal operating mode. Under the precondition of ignoring the dead time, the upper and lower switching tubes are always working in the complementary state. Figures 2(a) and (b) show the charging and discharging mode of battery. In this mode, the sub-module battery is put into operation, the output is the battery voltage $u_B$, the switching tube $S_1$ is on, the switching tube $S_2$ is off, and the bypass switch $K$ is open circuited. When the direction of current $i_{jk}$ is as shown in figure 2(a), the current passes the switching tube $S_1$, and the battery is at charging state. When the direction of current $i_{jk}$ is as shown in figure 2(b), the current passes the antiparallel diode of switching tube $S_1$, and the battery is at charging state. Figures 2(c) and (d) present the by-pass mode of battery. In this mode, the battery pack is cut off, the switching tube $S_1$ is off, the by-pass switching tube $S_2$ is on, and the by-pass switch $K$ is open circuited. The voltage of switching tube $S_1$ is the battery voltage, the output voltage of sub-module is 0, and current $i_{jk}$ flows through the switching tube $S_2$ or its antiparallel diode loop.

When MMC-BESS works normal, the relationship between the battery equivalent output voltage $u_{BE_{kji}}$ of this SM module and the duty cycle $d_{kji}$ is:

$$u_{BE_{kji}} = d_{kji}u_B$$

2.3. Power transfer relationship between each port of MMC-BESS

Because MMC-BESS has three-phase symmetrical topological structure, we only need to analyze a single phase. The selected current reference direction is as shown in figure 1. The bridge arm current
\( i_{k} \) consists of AC loop current \( i_{Zk} \), DC loop current \( i_{DCk} \) and AC grid current \( i_{gk} \). Among them, the AC loop current \( i_{Zk} \) is mainly generated by the difference between the upper/lower arm voltage and the DC bus voltage, while the interphase secondary loop current is mainly withstood by battery, so the secondary loop current component is very small, and we mainly analyze the primary loop current. Therefore, we can obtain the relationship between the upper arm current \( i_{ku} \) /lower arm current \( i_{kd} \) and various current components as:

\[
\begin{align*}
  i_{ku} &= i_{Zk} + i_{DCk} + i_{gk} \\
  i_{kd} &= i_{Zk} + i_{DCk} - i_{gk}
\end{align*}
\]

(2)

From formula (2), we can obtain:

\[
\frac{i_{ku} + i_{kd}}{2} = i_{Zk} + i_{DCk}
\]

(3)

The SM, sub-modules of the upper and lower bridge arms are equivalent to voltage sources, and then the voltage equations of the upper and lower bridge arms are established according to Kirchhoff voltage law:

The sub-module SM, of upper and lower arms can be equivalent to the voltage source, then the voltage equation of upper and lower arms is build according to the KVL (Kirchhoff voltage law), and we can obtain:

\[
\begin{align*}
  u_{ku} &= \frac{U_{DC}}{2} - u_{MNk} - i_{ku} R - L \frac{di_{ku}}{dt} \\
  u_{kd} &= \frac{U_{DC}}{2} + u_{MNk} - i_{kd} R - L \frac{di_{kd}}{dt}
\end{align*}
\]

(4)

where, \( u_{MN} \) is the voltage of the phase voltage of MMC-BESS relative to the neutral point, and \( U_{DC} \) is the DC bus voltage.

According to formula (2) and formula (4), we can obtain:

\[
\begin{align*}
  u_{ku} + u_{kd} = U_{DC} - 2 R (i_{gk} + i_{DCk}) - 2 L \frac{di_{Zk} + di_{DCk}}{dt} \\
  u_{kd} - u_{ku} = 2 u_{MNk}
\end{align*}
\]

(5)

By multiplying Formula (2) with Formula (4), we can obtain the power formula of upper and lower arms by multiplying various voltage and current components in pairs in the bridge arm. The average power of AC and DC coupling is 0, which can be finally simplified to obtain the average power of upper and lower arms as:

\[
\begin{align*}
  P_{ku} &= -\frac{i_{DCk} U_{DC}}{2} - \gamma_{gk, MNk} \cos \theta + \left( \frac{\gamma_{gk, MNk}}{2} \cos \phi \right) \cos \phi \cos \phi \\
  P_{kd} &= -\frac{i_{DCk} U_{DC}}{2} - \gamma_{gk, MNk} \cos \theta - \left( \frac{\gamma_{gk, MNk}}{2} \cos \phi \right) \cos \phi \cos \phi
\end{align*}
\]

(6)

where, \( \theta \) is the phase angle between \( i_{gk} \) and \( u_{MNk} \); \( \phi \) is the phase angle between \( i_{Zj} \) and \( u_{MNj} \); \( \varphi \) is the phase angle between \( i_{Zj} \) and \( u_{MNj} \).

In formula (6), the average powers of upper and lower arms can be added to obtain the power transfer relationship between the DC bus, AC bus and battery as:

\[
P_{bk} = - (P_{DCk} + P_{gk}) = -i_{DCk} U_{DC} - \gamma_{gk, ACK} \cos \theta
\]

(7)

From formula (3), we can obtain the sum of upper arm current \( i_{ku} \) and lower arm current \( i_{kd} \), including the information of DC component \( i_{DC} \) and loop current component \( i_{Zk} \); from formula (5), we find that when ignoring the equivalent series resistance \( R \) and equivalent inductance \( L \) of arm, the output phase voltage \( u_{MN} \) of MMC-BESS is related to the use of sub-module SM, of upper and lower arms, and the output voltage of MMC-BESS can be controlled by controlling the use of sub-module SM; according to formula (6), the interphase loop current can reallocate the upper and lower arm powers, resulting the power difference \( \Delta P_{ij} \) between the upper and lower arms, thus realizing power
reallocate the upper and lower arms; from formula (7), we can see that the overall battery power \( P_{Bk} \) of each phase is decided by the AC bus power and DC bus power, and in the three-phase symmetrical system, the AC bus has the same power in each phase, which can realize control of battery power of each phase by directly controlling the DC bus power of each phase. In phase shift pulse width modulation technology, each switching tube has the same switching time. For the same arm, the average current flowing through battery within a cycle is equal. The equivalent output voltage of single battery can be controlled through formula (1), so as to realize allocation of battery power in the arm.

3. Battery model and SOC estimation

3.1. Second-order Thevenin battery model

![Second-order RC Thevenin equivalent circuit model.](image)

Current MMC-BESS commonly adopts the ampere-hour integration method and open-circuit voltage method for estimation of SOC. In general, the low-pass filter is used to filter the battery current according to the upper and lower limits of voltage; then, the ampere-hour integration method is employed to estimate SOC, and the SOC estimation precision of this method is directly related to the current detection precision and the initial value of battery SOC. Furthermore, it will significantly lower the system response speed by using low-pass filter, and the error will be continuously accumulated as time goes by. The battery SOC estimation based on model prediction has the advantage of both short tracking time and high precision.

The second-order RC Thevenin equivalent circuit model as shown in figure 3 consists of the battery open-circuit voltage \( U_0 \), the internal resistance \( R_0 \) and two second-order RC links simulating the polarization effect of battery, in which, \( U_B \) is the output voltage of battery. The modeling process is as follows.

Assuming the second-order RC Thevenin equivalent circuit model of battery has the current direction as shown in figure 3, the voltage equation of this model is written according to the KVL (Kirchhoff voltage law), which is as follows:

\[
\begin{align*}
C_1 \frac{dU_1}{dt} & = I - \frac{U_1}{R_1} \\
C_2 \frac{dU_2}{dt} & = I - \frac{U_2}{R_2} \\
U_B & = U_0 - IR_0 - U_1 - U_2
\end{align*}
\]  

(8)

The SOC calculation formula of battery is:

\[
SOC(t) = SOC(0) + \int_0^t \frac{\eta \dot{Q}_B}{Q_B} dt
\]  

(9)

where, \( SOC(0) \) represents the initial SOC state of battery; \( SOC(t) \) represents the SOC state of battery at moment \( t \); \( \eta \) is the charging/discharging efficiency; \( Q_B \) is the battery capacity.

The mathematical model of battery is built by choosing the battery SOC and the voltages \( U_1 \) and \( U_2 \) of two RC links as the system state variables and the battery output voltage \( U_B \) as the system observation variable. After discretization, the state space expression is:
\[
\begin{aligned}
\begin{bmatrix}
\text{SOC}(t) \\
U_1(t) \\
U_2(t)
\end{bmatrix}
&= 
\begin{bmatrix}
1 & 0 & 0 \\
0 & e^{-\frac{\Delta t}{C_1R_1}} & 0 \\
0 & 0 & e^{-\frac{\Delta t}{C_2R_2}}
\end{bmatrix}
\begin{bmatrix}
\text{SOC}(t-1) \\
U_1(t-1) \\
U_2(t-1)
\end{bmatrix}

+ 
\begin{bmatrix}
-R_1 \left(1 - e^{-\frac{\Delta t}{C_1R_1}}\right) \\
-R_2 \left(1 - e^{-\frac{\Delta t}{C_2R_2}}\right)
\end{bmatrix} I(t-1)
\end{aligned}
\]

where, \(\Delta t\) is the sampling period; \(U_o(SOC(t))\) is the function relationship between the battery open-circuit voltage \(U_o\) and SOC.

3.2. STEKF algorithm
The mathematical model of battery is a nonlinear model. The EKF algorithm approximately linearizes the nonlinear equation, and then the Kalman algorithm is applied to the linear equation to further realize estimation of system state. Compared with the Kalman algorithm, this algorithm is more applicable to nonlinear discrete mathematical model.

The STEKF algorithm has introduced strong tracking algorithm on the basis of EKF algorithm, and the time-varying sub-optimal fading factor \(\lambda_t\) is introduced to the EKF algorithm to improve the robustness of algorithm.

The strong tracking algorithm has the following design principle:
\[
\begin{aligned}
&E[(x_t - \hat{x}_t)(x_t - \hat{x}_t)^T] = \min \\
&E[(z_t - \hat{z}_{t|t-1})(z_t - \hat{z}_{t|t-1})^T] = 0
\end{aligned}
\]

The extended Kalman filter algorithm satisfies the estimation of state minimum variance, i.e., the first condition of formula (11), and we only need to take measures to satisfy the second condition. The specific method is as follows: the time-varying sub-optimal fading factor \(\lambda_t\) is introduced to the prediction covariance matrix of EKF algorithm to ensure the residual sequences output by the system are orthogonal in real time. When the model is not sufficiently precise or when the state suddenly changes, the time-varying sub-optimal fading factor \(\lambda_t\) plays the role of adjusting the prediction covariance matrix in real time to realize adjustment of gain matrix, so as to improve the robustness of algorithm. When the system has a stable state, STEKF will degrade into EKF filter. The introduction of time-varying sub-optimal fading factor \(\lambda_t\) enables the system to obtain more information from the residual, and the filtering effect is more consistent with the actual situation, which has improved the reliability of algorithm.

After introducing the time-varying sub-optimal fading factor \(\lambda_t\), the system updates the prediction covariance matrix into:
\[
P_{t|t-1} = \lambda_{t-1} F_t P_{t-1} F_t^T + Q_t
\]

where, the solution to the time-varying sub-optimal fading factor \(\lambda_t\) is:
\[
\lambda_t = \begin{cases} 
1 & (e_t > 1) \\
\frac{e_t}{e_t > 1} & (e_t > 1)
\end{cases}
\]

\[
\begin{aligned}
\hat{x}_t &= t(N_t) / t(t(M_t)) \\
N_t &= V_t - \beta R_t - C_t Q_{t-1} C_t^T \\
M_t &= C_t A_t P_{t-1} A_t^T C_t^T
\end{aligned}
\]
where, \( tr(.) \) is the trace to solve the matrix; \( \beta \) is the softening factor, which makes the state estimation of this algorithm smoother, and generally \( \beta \geq 1 \). The solution to the residual covariance matrix \( V_t \) is:

\[
V_t = \begin{cases} 
\gamma_1 \gamma_1^T(t=1) \\
\frac{\rho V_t r_t r_t^T}{1+\rho}(t > 1)
\end{cases}
\]

(15)

where, \( \rho \) is the forgetting factor, which is used to adjust the ratio between current residuals and historical residuals, and generally \( 0 < \rho < 1 \).

Through continuous iterations of STEKF algorithm, we can obtain the state estimation value of battery at various moments.

The discrete nonlinear mathematical model of battery can be expressed as:

\[
\begin{align*}
\dot{x}_{k+1} & = f(x_k, u_k) + w_k \\
z_k & = h(x_k, u_k) + v_k
\end{align*}
\]

(16)

The specific iteration process of EKF filtering algorithm is:

1. State prediction:

\[
x_{\hat{t}t-1} = f(x_{t-1}, u_{t-1})
\]

(17)

2. Update the prediction covariance matrix:

\[
P_{\hat{t}t-1} = F_t P_{t-1} F_t^T + Q_t
\]

(18)

3. Update the gain coefficient matrix:

\[
K_t = P_{\hat{t}t-1} H_t \left( H_t P_{\hat{t}t-1} H_t^T + R_t \right)^{-1}
\]

(19)

4. Update the state:

\[
x_t = x_{\hat{t}t-1} + K_t (z_t - \hat{z}_{\hat{t}t-1})
\]

(20)

5. Update the covariance matrix:

\[
P_t = (I - K_t H_t) P_{\hat{t}t-1}
\]

(21)

where, \( Q_t \) is the process excitation noise covariance matrix; \( R_t \) is the measurement noise covariance matrix; \( F_t \) is the Jacobian matrix of matrix \( A \) of the mathematical model of battery; \( H_t \) is the Jacobian matrix of matrix \( C \) of the mathematical model of battery.

4. SOC balance strategy of MMC-BESS battery

In order to ensure the SOC difference of battery in each SM sub-module of MMC-BESS is maintained within a certain scope, and prevent over charging and over discharging of battery, so as to increase the battery service life and improve the overall system efficiency, the terminal voltage of battery is measured, and the current flowing through the battery is monitored in real time. The strong tracking algorithm is employed to obtain new information from voltage residual in real time, and then, the EKF algorithm is incorporated to predict the state of battery pack.

There is certain linear relationship between the battery SOC and battery power. The relationship between the battery SOC and battery power and the power transfer relationship between battery power and each port can be utilized to realize balanced SOC of battery. It mainly consists of the following three steps.

4.1. Interphase SOC balance strategy

According to formula (7), in the three-phase symmetrical system, the power distribution of each phase is realized by directly controlling the power of DC bus. The reference instruction of overall battery
power is obtained according to the AC bus active power instruction $P^*_g$ and DC bus power instruction $P^*_{DC}$, which is as follows:

$$P^*_B = -(P^*_g + P^*_{DC})$$  \hfill (22)

First, the average SOC value $SOC_{Ak}$ of battery in each phase and the SOC value $SOC_k$ of battery in each phase can be calculated; then, compare the difference, the battery power difference instruction $\Delta P^*_{Bk}$ for each phase through the proportional amplifier $K_{ph}$ can be obtained; next, through superposition of battery power instruction $P^*_B/3$ of each phase, the modified power instruction $P^*_{Bk}$ of battery for each phase is obtained, which is as follows:

$$P^*_{Bk} = K_{ph}(SOC_{Ak} - SOC_k) + P^*_B$$  \hfill (23)

Then, the interphase SOC balance of battery can be realized via power control at the DC bus, and its specific control block diagram is as shown in figure 4. The block diagram of power control at the DC bus is as shown in figure 5. Based on the sum of upper and lower arm current, the low-pass filter can be utilized to obtain the information of DC component in arm current to be compared with the reference current signal. After it flows through the PI controller and feed forward compensation, it can be superposed with the modulating signal to realize power control of battery in each phase.

4.2. SOC balance strategy between the upper and lower arms

According to formula (6), the battery SOC balance between the upper and lower arms can be realized as follows. The difference between the average SOC value $SOC_{Aku}$ of battery in upper arm for each phase and the average SOC value $SOC_{Akd}$ of battery in lower arm for each phase goes through the proportional amplifier $K_m$ to obtain the power difference instruction $\Delta P^*_{Bku}$ between the upper and lower arms as:

$$\Delta P^*_{Bku} = K_m(SOC_{Aku} - SOC_{Akd})$$  \hfill (24)

In this paper, we employ the loop current calculation method in Literature [19] to calculate $i^*_{zk}$. The battery SOC balance between the upper and lower arms can be realized through loop current control, and the control block diagram is as shown in figure 6.

The loop current control block diagram is as shown in figure 7. We collect the loop current information in the bridge arm current, and compare it with the provided reference value of loop current. After proportional resonant control, the control of loop current through superposition with the carrier signal can be realized.
4.3. SOC balance strategy of bridge arm SM<sub>i</sub> sub-module

The power reference value calculation method for bridge arm in each phase is:

\[
\begin{align*}
P_{ku}^* &= 0.5P_{bk}^* + 0.5\Delta P_{kd}^* \\
P_{kd}^* &= 0.5P_{bk}^* - 0.5\Delta P_{kd}^*
\end{align*}
\] (25)

The power of bridge arm sub-module SM<sub>i</sub> is obtained as follows. The difference between the SOC value \(SOC_{kj}\) of single battery of bridge arm in each phase and the average battery SOC value \(SOC_{kj}\) of bridge arm in each phase is amplified by the proportional amplifier \(K_B\), and then superposed to the reference power \(P_{kj}^*\) of each battery to obtain the power instruction \(P_{kji}^*\) of each battery as:

\[
P_{kji}^* = K_B(SOC_{kji} - SOC_{kj}) + P_{kj}^*/n
\] (26)

Then, the output voltage proportion \(K_{kji}\) can be calculated as:

\[
K_{kji} = \frac{P_{kji}^*}{P_{kj}^*/n}
\] (27)

By multiplying the output voltage proportion \(K_{kji}\) with corresponding modulating signal, the SOC balance of all batteries in the MMC model can be realized. Its control block diagram is as shown in figure 8.

In this balance strategy, the SOC balance speed of corresponding links can be adjusted by adjusting the proportionality coefficients \(K_{ph}\), \(K_m\) and \(K_B\) of various links.

5. Simulation and analysis

5.1. Battery SOC estimation of MMC-BESS model

In this paper, in order to verify the effectiveness and feasibility of the proposed method, a three-phase MMC-BESS simulation model was constructed in PLECS simulation software according to figure 1, and the parameters are as shown in table 1. An Intel Core i7-9700T CPU, 16 GB DDR4-2666 SDRAM memory, 200 Mbps connection to database were used in the case study, and the version of PLECS is 4.3.6. The battery is 18650 lithium battery. The electronic load device is used to conduct periodic impulsive discharging and constant-current discharging of lithium battery to obtain the
response curve of lithium battery; then, the SIGMAPLOT software is used to fit the response curve of lithium battery in each period, and the zero input response and zero output response are combined to finally identify the parameters of MMC-BESS battery model, as shown in Table 2.

Table 1. Simulation parameters of MMC-BESS model.

| Parameter                                      | Numerical value | Parameter                                      | Numerical value |
|-----------------------------------------------|-----------------|-----------------------------------------------|-----------------|
| Peak voltage \( u_{gp} \)/V of grid at AC bus | 311             | Voltage \( U_{DC} \)/V of grid at DC bus       | 800             |
| Rated voltage \( u_m \)/V of battery          | 200             | Rated capacity \( Q_s \)/Ah of battery         | 3               |
| Sub-module capacitance \( C \)/mF             | 2               | Sub-module number \( N \) in upper and lower bridge arms | 4               |
| Bridge arm filter inductance \( L \)/mH       | 1               | AC filter inductance \( L_g \)/mH              | 2               |
| Equivalent impedance \( R_e \)/Ω at power connection end | 0.1             | Equivalent series impedance \( R \)/Ω of bridge arm | 0.1             |
| Switching frequency /Hz                       | 2000            |                                               |                 |

Table 2. Simulation parameters of Battery model.

| Parameter                                      | Numerical value | Parameter                                      | Numerical value |
|-----------------------------------------------|-----------------|-----------------------------------------------|-----------------|
| Number of single lithium battery in series     | 20              | Number of single lithium battery in parallel  | 1               |
| Terminal voltage \( u_m \)/V of lithium battery in series | 200             | SOC of single lithium battery                 | 0.8             |
| Internal resistance \( R_0 \)/Ω               | 0.007           | Polarization resistance \( R_1 \)/Ω           | 0.006872        |
| Polarization resistance \( R_2 \)/Ω           | 0.026552        | Polarization resistance capacitance \( C_l \)/F | 695.92          |
| Polarization resistance capacitance \( C_2 \)/F | 2597.571        | Rated capacity \( Q_s \)/Ah of single battery | 3               |
| Relationship between the open-circuit voltage of lithium battery and SOC | Seventh-order fitting curve |                                               |                 |

![Graphs](image1.png)

(a) Battery current waveform  (b) Battery voltage waveform  (c) Battery voltage filtering  (d) Battery SOC estimation

Figure 9. STEKF algorithm based on MMC-BESS model.

In the MMC-BESS model, the DC bus power instruction is set as 3kW, the AC bus power instruction is set as 5kW, and the waveforms of current flowing through the battery and the battery terminal voltage are as shown in figure 9(a) and (b), respectively. Because the battery current consists of the DC component, AC bus current component and loop current component with significant fluctuations, if the ampere-hour integration method is employed, the initial value of battery SOC cannot be captured accurately. Furthermore, significant fluctuation of current makes it more difficult to collect current, which will continuously accumulate error, thus finally resulting in significant difference of SOC between batteries; when the open-circuit voltage method is adopted to determine the initial value of battery SOC, there is a nonlinear relationship between battery voltage and SOC, and slight change of voltage may cause significant difference of SOC between batteries, which will result in over high estimation error of battery SOC. As shown in 9(b), when STEKF is adopted to estimate the SOC of battery, the current and voltage sampling frequency is set as 1kHz, white Gaussian noise is injected into voltage and current during sampling, and the STEKF is put into use at
0.005s. The STEKF algorithm can immediately realize tracking of battery SOC with small fluctuation, as shown in figure 9(c), which also provides great filtering effects of battery voltage.

![Waveforms](image)

Figure 10. Waveforms of various port of MMC-BESS model.

### 5.2. Battery SOC estimation of MMC-BESS model

As shown in figure 10, the MMC-BESS model sets the DC bus power instruction as 3kW and the AC bus power instruction as 5kW. At 100s, the DC bus power instruction and AC bus power instruction simultaneously have sudden change to -3kW and -5kW.

In this paper, the three-level SOC balance strategy is adopted to realize SOC balance of battery. Figure 11(a) and (b) show the level-1 SOC balance, and the interphase battery SOC balance is realized according different average SOC value of battery in each phase and redistribution of power to each phase based on the proportion; Figure 11(c) and (d) show the level-2 SOC balance, the power difference between upper and lower arms is calculated according to the difference in average SOC value between upper and lower arms, and then the battery SOC balance between upper and lower arms is realized through loop current calculation and superposition of modulating wave; the level-3 SOC balance is shown figure 11(e) and (f), based on the SOC values of N batteries in upper and lower arms, and $K_{kji}$ is calculated in accordance with the control strategy and then multiplied with the modulating wave to realize the SOC balance of N batteries in upper and lower arms; Figure 11(g) shows how to realize the SOC balance of all 24 batteries by combining the level-1, level-2 and level-3 SOC balance.

![Three-level SOC balance](image)

Figure 11. Three-level SOC balance of MMC-BESS model.
6. Conclusion
In this paper, we find that the battery current in MMC-BESS structure has the characteristic of big fluctuation, and the common ampere-hour integration method and open-circuit voltage method cannot be used to accurately estimate the SOC of battery. In order to address this problem, we propose a more reliable MMC-BESS battery SOC estimation method, and derive the feasibility of MMC-BESS battery SOC estimation method in theory.

By inferring the power transfer relationship between the MMC-BESS battery and each port, we find the relation between the battery power and DC loop current, AC loop current, the bridge arm battery and proportionality coefficient $K_{kji}$, and propose the three-level SOC balance strategy. The power instructions of various batteries are adjusted according to the average interphase battery SOC value of various bridge arms, the average battery SOC value of upper and lower arms and the SOC value of each bridge arms, and the SOC balance strategy for MMC-BESS battery is established in theory.

By building the simulation model which combines the second-order RC lithium battery and MMC-BESS, the STEKF algorithm is employed to realize fast tracking of battery SOC in the MMC-BESS model when there are significant fluctuations of battery current and voltage. Furthermore, based on the power transfer relationship between battery and each port, the three-level SOC balance strategy is incorporated to realize the SOC balance among all batteries in the MMC-BESS model, which has proven the effectiveness and reliability of the battery SOC balance strategy proposed in this paper.

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