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Analysis and Control of Modular Multilevel Converter with Split Energy Storage for Railway Traction Power Conditioner

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Abstract—In this paper, a railway power conditioner (RPC) based on modular multilevel converter (MMC) with split supercapacitor energy storage system (SCESS) is studied. In this case, the MMC-SCESS based RPC could not only provide normal negative sequence currents (NSC) compensation but also could reduce the impact of power fluctuations caused by the locomotive braking or startup on the electric grid. Firstly, this paper analyzes the power flow patterns and deduces the reference circulating current under different operation modes of MMC-SCESS based RPC. Then, the control objectives of MMC-SCESS based RPC are divided into two categories including the balance control and the current tracking control. The balance control methods are developed for the submodules (SMs) capacitor voltages and the state of charge (SoC) of the supercapacitor, which are associated with the operation modes. To ensure the current tracking performance, a model predictive direct current control (MPDCC) method is proposed for MMC and bidirectional energy converter (BEC). Finally, the effectiveness of the proposed control methods is verified by the experimental results of a downscaled prototype.

Index Terms—Railway power conditioner (RPC), modular multilevel converter (MMC), split supercapacitor energy storage system (SCESS), power flow patterns, balance control, model predictive direct current control (MPDCC).

I. INTRODUCTION

O

VER the years, the high-speed electrified railway has been developed rapidly. Meanwhile, the traction system feature of the locomotives results in some power quality issues such as negative sequence currents (NSC), reactive power, harmonic currents, and fluctuant voltages [1]-[4]. Furthermore, the utilization of regenerative braking energy has been becoming a hot topic recently, particularly in China and Japan [5]. Therefore, how to regulate the power quality of the electrified railway and achieve the energy saving for recycling seems to be meaningful.

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With the growth of the electric load and the interconnection of the regional power system, the concept of the energy storage system (ESS) is initially proposed for dealing with the power quality and the power system stability problem [22]. Nowadays, with the penetration of the renewable source, the ESS is once again to cope with the power fluctuation resulted from the randomness and intermittent nature of renewable energy. So how to integrate the ESS into the power electronic converter effectively has been studied widely [23]. Among them, the structure of the MMC with split ESS has become a promising and emerging way [24]. In [25], the scholars make a discussion on the enhancement of performance, reliability, and flexibility of the modular multilevel cascaded converter (MMCC) with split battery energy storage system (BESS). The BESS can provide the MMCC with satisfactory performance on zero-voltage ride-through (ZVRT). In [26], an energy injection method is proposed to rebalance the ac voltage of grid asymmetries by utilizing the BESS. In [27], the operation modes of the MMC with integrated BESS are analyzed and the balance methods for the state of charge (SoC) are developed. A non-isolated dc-dc converter is utilized to link the split BESS to the SM when the direct connection to SM may decrease the battery lifetime. In [28], a novel balance control method based on the state of health of the recycled batteries is proposed to enhance the output capacity and lifetime of the MMC BESS. From the view of the system efficiency [29], the scholar makes a comparison for three kinds of classical MMC topologies with the split BESS. In [30], a hybrid modular multilevel converter (HMMC) with integrated BESS is proposed and the control strategies under normal modes and fault modes are studied. A decoupled power method based on the HMMC with hybrid energy storage system (HESS) is presented in [31]. In this configuration, the long-term fluctuant power is compensated by the battery energy while the short-term fluctuant power is compensated by the supercapacitor energy, which benefits for improving the reliability of the storage elements. Recently, the utilization of the regenerative braking energy of the traction locomotive is gradually attracting more attention when the traditional mechanical brakes and braking resistors may face the challenge of the environmental impact and energy saving. Due to the energy storage characteristic of high-power density, the supercapacitor is more applicable to the utilization of the regenerative braking energy compared to the battery storage [32]. In [33], a simplified mathematical model of the MMC integrated with supercapacitors energy system is presented and the control methods for traction motor and energy system balance are validated by the numerical simulations. Although many pieces of literature have been made studied on the MMC with split ESS, the MMC with split supercapacitors energy storage system (MMC-SCESS) based RPC is rarely studied and deserves to be further researched. For this reason, an MMC-SCESS based RPC is proposed to apply for the railway traction power conditioner with the ability to adapt different operation modes. In normal operation mode, the MMC-SCESS based RPC system could compensate the NSC. While in extended operation mode, the MMC-SCESS based RPC system could absorb the regenerative braking energy in the braking mode and supply the peak power in startup mode. The highlight of this paper includes 1) Analysis of the power flow patterns and reference circulating current under different operation modes, and 2) Research on control methods including the balance control and the current tracking control. This paper is organized as follows. In Section II, the system configuration and mathematical model of the MMC-SCESS based RPC are introduced. Afterward, the operation principle and the power flow of the MMC-SCESS based RPC under different operation modes are analyzed in Section III. Section IV mainly discusses the control methods of the MMC-SCESS based RPC. The experiments are carried out to demonstrate the effectiveness of the studied MMC-SCESS based RPC and the proposed control methods in section V and section VI draws the conclusion.

II. SYSTEM CONFIGURATION AND MODELING OF MMC-SCESS BASED RPC

The main topology of the MMC-SCESS based RPC to be discussed is shown in Fig. 2. It contains three phases and each phase contains two arms which are connected by inductor $L$ and its internal resistance $r$. Each arm consists of $N$ series SMs and each SM consists of the half-bridge converter (HBC) and the supercapacitor which are connected by bidirectional energy converter (BEC). $u_{ij}$ and $i_{ij}$ ($j=a, b, c$) denote the upper and lower arm voltage, respectively. $i_{ij}$ and $i_{ij}$ denote the upper and lower arm current, respectively. The midpoints of three phases are connected to the V/V transformer: the midpoint of phase $c$ is connected to the common point of V/V transformer while the midpoints of phase $a$ and phase $b$ are connected to the ends of V/V transformer. For convenient analysis, the mathematical model of MMC-SCESS based RPC could be divided into two parts incorporating the mathematical model of the MMC and the mathematical model of the BEC. A brief introduction is given in the following section:

Firstly, obeying the direction of voltages and currents shown in Fig. 2, the external dynamic characteristic equation of phase $j$ could be deduced as [34]-[35]:

$$\frac{L}{2} \frac{di_{jc}}{dt} = \frac{1}{2} u_{ij} - u_{ic} - u_{oc} - \frac{r}{2} i_{jc}$$

(1)

where $u_{jc}$ and $i_{jc}$ denote the traction feeder voltage and the
output current of phase $j$, respectively. $u_{co}$ denotes the common voltage measured between the midpoint of phase $c$ and the midpoint of the virtual dc-link which is supported by the inserted SMs capacitor voltages.

In spite of the asymmetric characteristic of MMC-SCESS based RPC, the external characteristic equations of three phases are symmetric, meaning that the common voltage $u_{co}$ could be obtained by summing the external characteristic equations of three phases yields:

$$u_{co} = \frac{1}{3} \sum_{j=1}^{3} u_{jc} = -\frac{1}{3}(u_{sc} + u_{pc})$$

(2)

Assuming that the SMs capacitor voltages are well-balanced, the internal dynamic characteristic equation of phase $j$ could be deduced as [34]-[35]:

$$L \frac{di_{ij}}{dt} = \frac{U_{dc}}{2} - \frac{u_{ij} + u_{cj}}{2} - r_{ij}$$

(3)

where $U_{dc}$ and $i_{ij}$ denote the virtual dc-link voltage and the circulating current of phase $j$. In addition, the arm voltage of phase $j$ could also be given approximately as follows:

$$u_{ij} = \sum_{k=1}^{N} s_{pj} u_{pkj} \approx \frac{N}{N_u} u_{pkj}$$

(4)

where $s_{pj}$ and $s_{pkj}$ denote the upper and lower arm SMs switching states, respectively. $u_{pkj}$ and $u_{pkc}$ denote the upper and lower arm SMs capacitor voltage, respectively. $u_{sc}$ and $u_{pc}$ denote the summation of the upper and lower arm SMs capacitor voltages, respectively. $N_p$ and $N_u$ indicate the upper and lower arm inserted SMs numbers, respectively.

To ensure the energy bidirectional flow with the characteristic of the reliability, it utilizes a bidirectional buck/boost converter to decouple the supercapacitor from the dc-link voltage of HBC in this paper. Assuming that the converter is always operating in continuous current mode, the current paths of BEC under different operation modes are shown in Fig. 3.

There are two kinds of operations including energy storage and energy release mode, as shown in Fig. 3(a) and Fig. 3(b), respectively. When BEC is in energy storage mode, as shown in Fig. 3(a), i.e., the energy could flow from the HBC dc-link to the supercapacitor, $Q_1$ is set to the PWM state and $Q_2$ is set to the off state. Inversely, when BEC is operating in energy release mode, as shown in Fig. 3(b), i.e., the energy flows from the supercapacitor to the HBC dc-link, $Q_1$ is set to the off state and $Q_2$ is set to the PWM state. It is worth to mention that the current paths of Fig. 3(a)(i) and Fig. 3(a)(ii) are identical to those of Fig. 3(b)(i) and Fig. 3(b)(ii), respectively, so the mathematical models of the converter in two modes could be given in a unified expression as:

$$\begin{cases} \frac{dc}{dt} = \frac{1}{C_{sm}} (i_e - Q_i_L) \\ \frac{di}{dt} = \frac{1}{L_s} (Q u_{c} - u_{sup} - r i) \end{cases}$$

(5)

where $i_e$ and $i$ denote the input current and inductor current, respectively. $u_{c}$ and $u_{sup}$ denote the SM capacitor voltage and the supercapacitor voltage. In unified expressions, when $i_t \geq 0$, $Q_1=Q$ and $Q_2=0$, while $i_t < 0$, $Q_1=(1-Q)$ and $Q_2=0$.

III. OPERATION PRINCIPLE AND POWER FLOW ANALYSIS OF MMC-SCESS BASED RPC

For MMC-SCESS based RPC, the power flow is closely related to its operation modes which incorporate: 1) the normal operation mode, and 2) the extended operation mode. In general, the power flow based on the former mode occurs between the electric grid and the traction locomotive, while the power flow based on the latter mode occurs between the supercapacitor and the traction locomotive. Since the operation modes are associated with the control objectives of the MMC-SCESS based RPC detailed in IV, it is worthwhile first to analyze the power flow. The corresponding processes are presented as follows:

A. Normal Operation Mode

If MMC-SCESS based RPC is operating in normal mode, i.e., the supercapacitor does not work and the MMC system takes responsibility for NSC compensation. In this case, the power flow is depicted in Fig. 4. When the active power required by traction feeder A is lower than that by traction feeder B, the power flow is shown in Fig. 4(a) and the MMC transfers half of the active power difference from the left traction arm to the right one; Conversely, when the active power required by traction feeder A is more than that by traction feeder B, the power flow is shown in Fig. 4(b) and the MMC transfers half of the active power difference from the right traction arm to the left one.

For convenient analysis, we assume that phase b is in full load while phase a is in no load. According to the compensation
principle of the V/V traction system [36], the compensation phasor diagram is depicted in Fig. 5. In this case, the traction feeder voltage and the reference compensation currents could be defined as follows:

\[
\begin{align*}
    u_{ac} &= U_s \sin(\omega t + \theta_{ac}) \\
    u_{bc} &= U_s \sin(\omega t + \theta_{bc}) \\
    i_{ac0} &= I_Q \sin(\omega t + \theta_{ac} + \frac{\pi}{2}) - I_p \sin(\omega t + \theta_{ac}) \\
    i_{bc0} &= I_Q \sin(\omega t + \theta_{bc} - \frac{\pi}{2}) + I_p \sin(\omega t + \theta_{bc})
\end{align*}
\]  

(6)

(7)

where \(U_s\) denotes the amplitude of the traction feeder voltage. \(I_p\) and \(I_Q\) denote the amplitudes of the reference active current and the reactive current, respectively. The amplitudes and the phase angles in (6) and (7) should satisfy the following conditions:

\[
\begin{align*}
    I_Q &= I_p / \sqrt{3} \\
    \theta_{ac} - \theta_{bc} &= \pi / 3
\end{align*}
\]  

(8)

Ignoring the loss of the inductance and resistance in each arm, the instantaneous power expressions of the upper and the lower arm in phase \(j\) are given as:

\[
\begin{align*}
    P_p &= u_{aj} i_{aj} = \left( U_{ac} / 2 - (u_{ac} + u_{nc}) \right) \left( i_{jc} / 2 + i_{jy} \right) \\
    P_q &= u_{aj} i_{aj} = \left( U_{ac} / 2 + (u_{ac} + u_{nc}) \right) \left( -i_{jc} / 2 + i_{jy} \right)
\end{align*}
\]  

(9)

To simplify the deduction, the total instantaneous power of the phase \(j\) could be deduced by summing these relations in (9):

\[
P_j = U_{ac} i_{aj} = \left( u_{jc} + u_{nc} \right) i_{jc}
\]  

(10)

with:

\[
\begin{align*}
    \alpha &= \sin(2\omega t + 2\theta_{ac}) \\
    \alpha_2 &= \sin(2\omega t + 2\theta_{bc}) \\
    \alpha_3 &= \sin(2\omega t + \theta_{ac} + \theta_{bc}) \\
    \beta &= \cos(2\omega t + 2\theta_{ac}) \\
    \beta_2 &= \cos(2\omega t + 2\theta_{bc}) \\
    \beta_3 &= \cos(2\omega t + \theta_{ac} + \theta_{bc})
\end{align*}
\]
Substituting (2), (6), (7), and (8) into (10). After a series of the mathematical operations, the three-phase instantaneous power expressions could be deduced shown in (11), (12), and (13). In order to ensure stable operation of MMC system, the dc component of the total instantaneous power on each phase should be kept as zero, which benefits for balancing the SMs capacitor voltages. Hence, the reference circulating currents in normal operation mode could be deduced as follows:

\[
\begin{align*}
    i_{a_{\text{ref}}} & = \frac{1}{U_{\text{dc}}} \left( -\frac{1}{4} U_s I_p + \frac{\sqrt{3}}{12} U_s I_Q \right) \\
    i_{b_{\text{ref}}} & = \frac{1}{U_{\text{dc}}} \left( \frac{1}{4} U_s I_p + \frac{\sqrt{3}}{12} U_s I_Q \right) \\
    i_{c_{\text{ref}}} & = \frac{1}{U_{\text{dc}}} \left( -\frac{\sqrt{3}}{6} U_s I_Q \right)
\end{align*}
\]

According to (14), the three-phase circulating currents are composed of active circulating current and reactive circulating current components. The former is stimulated by transferring the active power and flows only between phase a and phase b, as shown by the blue dotted line in Fig. 6, while the latter is stimulated by compensating the reactive power and flows among three phases, as shown by the pink dotted line in Fig. 6.

**B. Extended Operation Mode**

If MMC-SCESS based RPC is operating in extended mode, such as the braking or startup mode of the traction locomotive, then the supercapacitor could be assessed to reduce the impact of power fluctuations on the electrical grid by energy storage or energy release. In this case, the power flow is depicted in Fig. 7. When the locomotive is operating in startup mode, the instan-
taneous launch energy could be provided by the supercapacitor, as shown in Fig. 7(a). When the locomotive is operating in braking mode, the regenerative braking energy could be feedback to the supercapacitor, as shown in Fig. 7(b).

To simplify the analysis, we assume that only one locomotive is in the braking mode and the regenerative braking power remains constant. According to (7), the reference compensation currents could be defined as follows:

\[
\begin{align*}
    i_{a_{\text{ref}}} & = 0 \\
    i_{b_{\text{ref}}} & = -I_p \sin(\omega t + \theta_{i_{b_{\text{ref}}}})
\end{align*}
\]

Taking the braking mode as an example, because the phase a does not participate in the transfer of active power, as shown in Fig. 8(a), the regenerative braking energy will be fully absorbed by the supercapacitor of phase b and phase c, which consequently results in a significant difference in SoC between phase b (phase c) and phase a. In order to make full use of the storage capacity of the supercapacitor, the circulating current injection method should be introduced to reduce the phase SoC difference.

Firstly, we define a virtual circulating current \( i_{v_{zb}} \), which is utilized for charging supercapacitor but cannot be measured. In order to deduce the expression of \( i_{v_{zb}} \), the total instantaneous power expressions of phase b and phase c could be given as follows:

\[
\begin{align*}
    P_b & = -U_{dc} i_{v_{zb}} - \frac{1}{2} u_{bc} i_{bc} \\
    P_c & = -U_{dc} i_{v_{zc}} - \frac{1}{2} u_{bc} i_{bc}
\end{align*}
\]

Substituting (6) and (15) into (16) yields:

\[
\begin{align*}
    P_b & = -U_{dc} i_{v_{zb}} - \frac{1}{4} U_s I_p - \frac{1}{4} U_s I_p \cos(2\omega t + \theta_{i_{bc}}) \\
    P_c & = -U_{dc} i_{v_{zc}} - \frac{1}{4} U_s I_p - \frac{1}{4} U_s I_p \cos(2\omega t + \theta_{i_{bc}})
\end{align*}
\]

For the stable operation of the MMC, the expression for the virtual circulating currents should satisfy the following relations:

\[
\begin{align*}
    i_{v_{zb}} & = i_{v_{zc}} = \frac{U_s I_p}{4U_{dc}}
\end{align*}
\]

Actually, the virtual circulating currents could be decomposed into two terms:

\[
\begin{align*}
    i_{v_{zb}} & = i_{b_{\text{ref}}} + \tilde{i}_{v_{zb}} \\
    i_{v_{zc}} & = i_{c_{\text{ref}}} + \tilde{i}_{v_{zc}}
\end{align*}
\]

where \( i_{b_{\text{ref}}} \) and \( i_{c_{\text{ref}}} \) denote the injected circulating currents while \( \tilde{i}_{v_{zb}} \) and \( \tilde{i}_{v_{zc}} \) denote the corrected virtual circulating currents. To reduce the phase difference of SoC, the regenerative braking energy should be distributed symmetrically on the three phases, as shown in Fig. 8(b), that is:

\[
\tilde{i}_{v_{zb}} = \tilde{i}_{v_{zc}} = i_{v_{za}}
\]
According to (18), (19) and (20), the reference injected circulating currents are deduced as follows:

\[
\begin{align*}
    i_{za_{\text{ext}}} &= \frac{U_L I_p}{6 U_d} \\
    i_{zb_{\text{ext}}} &= \frac{U_L I_p}{12 U_d} \\
    i_{zc_{\text{ext}}} &= \frac{U_L I_p}{24 U_d}
\end{align*}
\]  

(21)

Similarly, when the traction locomotive is operating in startup mode, the reference injected circulating currents for reducing the difference in SoC between phase b (phase c) and phase a could be deduced similarly and do not cover again. Actually, the expressions of the reference injected circulating currents in startup mode are the same as that in braking mode, but the sign of the reference amplitude of the active current \( I_p \) should be reversed.

IV. CONTROL METHODS OF MMC-SCCESS BASED RPC

A. Control Objectives of MMC-SCCESS based RPC

The main control objectives of the MMC-SCCESS system are associated with the operation modes. On the one hand, when MMC-SCCESS based RPC is operating in normal mode, i.e., for the NSC compensation, the control objectives contain three parts: 1) Reference compensation current tracking, 2) Reference circulating current tracking, and 3) SMs capacitor voltages balancing. On the other hand, when MMC-SCCESS based RPC is operating in extended mode, i.e., for energy storage or energy balancing. On the other hand, when MMC-SCCESS based RPC is operating in extended mode, the reference injected circulating currents for reducing the difference in SoC between phase b (phase c) and phase a could be deduced similarly and do not cover again. Actually, the expressions of the reference injected circulating currents in startup mode are the same as that in braking mode, but the sign of the reference amplitude of the active current \( I_p \) should be reversed. FTC

B. Balance Control for MMC-SCCESS based RPC

When MMC-SCCESS based RPC is operating in normal compensation mode, the purpose of the balance control is to prevent the SMs capacitor voltages from divergence due to the unavoidable power difference of the SMs. The detailed voltage balance methods are discussed as follows:

1) Total Power Balance Control

Define \( P_{xy} \) and \( P_y \) to represent the power of the upper arm and the lower arm, respectively. The expressions are given as follows:

\[
\begin{align*}
    P_{xy} &= \frac{1}{2} \sum_{k=1}^{N} u_{xy}^2 \\
    P_y &= \frac{1}{2} \sum_{k=1}^{N} u_{x}^2
\end{align*}
\]  

(22)

As presented in (23), the reference active power for total power balance control could be obtained via the PI controller, giving as:

\[
P_{\text{ref}} = k_p \left( \frac{1}{2} N U_{\text{ref}}^2 - \frac{1}{6} \sum_{j=a,b,c} \left( P_{xy} + P_y \right) \right) + k_i \int \left( \frac{1}{2} N U_{\text{ref}}^2 - \frac{1}{6} \sum_{j=a,b,c} \left( P_{xy} + P_y \right) \right)
\]

(23)

where \( U_{\text{ref}} \) represents the reference SM capacitor voltage. Hence, the amplitude of reference fundamental current is deduced as follows:

\[
P_{\text{ref}} = \frac{2 p_{\text{ref}} U_s}{U_d}
\]

(24)
2) Phase Power Balance Control

According to (9), the summation of the upper and lower arm voltage only contains the dc components, i.e., the imbalance of phase power could be eliminated by injecting the dc circulating current. Because the total power balance is ensured by (24), the control degrees of freedom of phase power control are actually only two, i.e., as long as the arbitrary two-phase circulating current is controlled, the three-phase power deviation could be eliminated. So the reference phase power deviations are given as:

\[
p_{\text{ref sum}} = k_p \left( P_u - NU_c^2 \right) + k_z \left( P_u - NU_c^2 \right)
\]

where \( P_j \) denotes the summation of \( P_{jp} \) and \( P_{jy} \). The reference dc circulating currents for phase power balance control are calculated correspondingly as:

\[
p_{\text{ref sum}} = \frac{P_{\text{ref sum}}}{U_{dc}}
\]

(26)

3) Arm Power Balance Control

According to (9), the difference between the upper and lower arm voltage only contains the fundamental components, i.e., the imbalance of the arm power could be eliminated by injecting the fundamental circulating current. The reference arm power deviations are given as:

\[
p_{\text{ref diff}} = k_p \left( P_{ua} - P_{pa} \right) + k_z \left( P_{ua} - P_{pa} \right)
\]

\[
p_{\text{ref diff}} = k_p \left( P_{ub} - P_{pb} \right) + k_z \left( P_{ub} - P_{pb} \right)
\]

\[
p_{\text{ref diff}} = k_p \left( P_{uc} - P_{pc} \right) + k_z \left( P_{uc} - P_{pc} \right)
\]

(27)

Because the control degrees of freedom of arm power control are three, fundamental positive-sequence circulating currents and fundamental negative-sequence circulating currents are needed to be injected simultaneously, as shown in (28), which contains four controllable states including positive-sequence amplitude \( I_{p+,} \), positive-sequence phase angle \( \theta_s, \) negative-sequence amplitude \( I_{p-,} \) and negative-sequence phase angle \( \theta_. \)

\[
i_{\text{ref diff}} = I_{p+,} \sin (\omega t + \theta_s) + I_{p-,} \sin (\omega t + \theta_-.)
\]

\[
i_{\text{ref diff}} = I_{p+,} \sin (\omega t + 2 \pi / 3) + I_{p-,} \sin (\omega t + 2 \pi / 3)
\]

\[
i_{\text{ref diff}} = I_{p+,} \sin (\omega t + 4 \pi / 3) + I_{p-,} \sin (\omega t + 4 \pi / 3)
\]

(28)

The arm power deviations introduced by injecting the circulating current are shown in (29) and the derivation in detail is listed in appendix I.

\[
p_{\text{diff}} = U_{I} I_{p+,} \cos \theta_s + U_{I} I_{p-,} \cos \theta_-
\]

\[
p_{\text{diff}} = U_{I} I_{p+,} \cos \theta_s + U_{I} I_{p-,} \cos (\theta_s - 2 \pi / 3)
\]

\[
p_{\text{diff}} = U_{I} I_{p+,} \cos \theta_s + U_{I} I_{p-,} \cos (\theta_s - 4 \pi / 3)
\]

(29)

Setting \( \theta \) to be zero and substituting reference arm power deviations into (29), the value of \( I_{p+,}, I_{p-,}, \) and \( \theta \) could be deduced as follows:

\[
I_{p+,} = \sqrt{3} \left( P_{\text{diff ref}} / U_{i} \right)
\]

\[
I_{p-,} = \sqrt{3} \left( P_{\text{diff ref}} / U_{i} \right)
\]

\[
\cos \theta_s = d_1 / \sqrt{d_1^2 + d_2^2}
\]

\[
\sin \theta_s = d_2 / \sqrt{d_1^2 + d_2^2}
\]

(30)

4) Individual SMs Power Balance Control

The difference among the individual SMs power in the same arm could be eliminated by the independent PI controller or sorting algorithm [37]. As the former method may increase the design complexity of the distributed controller, the latter method is utilized to balance the individual SMs power and determines the final switching states in this paper.

When MMC-SCESS based RPC is operating in extended mode, the above balance control methods are also suitable for supercapacitor SoC balance including phase SoC balance and arm SoC balance and do not cover again. It is noted that the SMs capacitor voltages balance in extended mode is ensured by BEC controller (introduced in section C), the individual SoC balance in the same arm could be achieved indirectly by sorting the corrected SMs capacitor voltages expressed in (31).

\[
u_{\text{pdcj correct}} = u_{\text{pdcj}} + \lambda \left( \text{SoC}_{pj} - \frac{1}{N} \sum_{k=1}^{N} \text{SoC}_{pj} \right)
\]

(31)

where \( u_{\text{pdcj correct}} \) and \( u_{\text{pdcj correct}} \) denote the upper and lower arm corrected SMs capacitor voltages. \( \lambda \) denotes the correction coefficient.

Therefore, the diagram of the balance control methods under different operations modes is shown in Fig. 9.

C. Model Predictive Direct Current Control for MMC-SCESS based RPC

In this paper, a model predictive direct current control (MPDCC) method is utilized for the current tracking of the MMC-SCESS based RPC. Since the MMC-SCESS based RPC incorporates two independent parts of MMC and BEC, the MPDCC method is designed separately for a reduced computation and the detailed implementation process is as follows:

Firstly, according to (1)-(5), the continuous mathematical model of the MMC in phase \( j \) and the arbitrary BEC could be organized as follows:

\[
\begin{bmatrix}
\dot{x} \\
\dot{\theta}_s
\end{bmatrix} =
\begin{bmatrix}
A & 0 \\
0 & -B
\end{bmatrix}
\begin{bmatrix}
x \\
\theta_s
\end{bmatrix}
\]

(32)

The state variables \( x \in \{i_s, i_a \} \) are used to describe the MMC and consist of the output current and the circulating current, while the state variables \( x_c \in \{u_c, i_c \} \) are used to describe the
izing currents mode, the reference compensation current associated with the output current, the circulating current, and II. 

where the matrices $A$, $B$, $A'$, and $B'$ are listed in appendix II. 

Assuming that the slope of state variables keeps constant in one control period, an approximate discrete method, known as forward Euler method, could be introduced to discretize (32) yields:

$$
\begin{align*}
\left[ \begin{array}{c}
x(k + 1) \\
x_c(k + 1)
\end{array} \right] &= \left[ \begin{array}{c}
Gx(k) \\
Gx_c(k)
\end{array} \right] + 
\left[ \begin{array}{c}
H \\
H_c
\end{array} \right]
\end{align*}
$$

(33)

where the matrices $G$, $H$, $G'$, and $H'$ are also listed in appendix II.

Then the control objectives of MMC-SCESS based RPC associated with the output current, the circulating current, and the inductor current are mapped into the cost functions $J$ and $J_c$, respectively, given as follows:

$$
\begin{align*}
J &= \left\| x^{ref} (k + 1) - x(k + 1) \right\|_2 \\
J_c &= \left\| x_c^{ref} (k + 1) - x_c(k + 1) \right\|_2
\end{align*}
$$

(34)

For MMC, $x(k+1)^T=[i_d(k+1) \ i_q(k+1)]^T$ denotes the prediction value of state variables and is calculated by (33). $x^{ref}(k+1)^T=[i_d^{ref}(k+1) \ i_q^{ref}(k+1)]^T$ denotes the reference value of state variables. The matrix $W=\text{diag}(\{w_1,w_2\})$ is utilized to penalize the tracking error of the output current and the circulating current. The design method for weighting matrix could be referred to [38]. When MMC-SCESS based RPC is operating in normal compensation mode, the reference compensation current $i_d^{ref}(k+1)$ could be given by synthesize (7) and (24) while the reference circulating currents $i_c^{ref}(k+1)$ could be given by (14), (26), and (28). When MMC-SCESS based RPC is operating in extended mode, the reference compensation current $i_d^{ref}(k+1)$ could be given by (21), (26), and (28).

For BEC, $i_d^{ref}(k+1)$ and $i_q^{ref}(k+1)$ denote the prediction and reference of the inductor current, respectively. To improve the steady performance and anti-disturbance, the outer voltage controller is introduced to fine-tuning the reference inductor current as expressed in (35).

$$
I_d^{ref} = \frac{P_s}{6N_{\text{sup}}} + \sigma(U_{\text{ref}} - u_e)
$$

(35)

where $P_s$ denotes the reference power for energy storage or energy release and $\sigma$ denotes the fine-tuning coefficient.

Due to the continuity of the state variables, the current search field of the MMC could be limited to the set in which the elements are adjacent to the previous optimal inserted number [39]-[41]. So in this paper, the concept of adjacent search is also applied to reduce the computation. The flowchart of the update method for the current search field is shown in Fig. 10(a). Noting that the number for the current inserted number $N_p$, to be evaluated is at most three, i.e., nine inserted number combinations $[N_p N_s]$ for the MMC and each switching states $Q$ for the BEC, the state variables at instant $k+1$ are predicted by using the discrete model (33). Then the cost functions are calculated according to (34). Finally, the optimal inserted number $[N_p^{\text{opt}} N_s^{\text{opt}}]$ that minimizes the cost function $J$ could be obtained and further transferred into the optimal switching states $[s_p^{\text{opt}} s_s^{\text{opt}}]$ for the MMC via sorting algorithm, while the optimal switching states $Q^{\text{opt}}$ that minimizes the cost function $J_c$ could also be selected to apply for the BEC.
In order to test experimentally the basic functionalities of the MMC-SCESS base RPC and verify the effectiveness of the proposed control methods, experiments of the downscaled prototype are designed and constructed in the lab, as shown in Fig. 12. The main parameters are listed in Table I. The design principle of parameters could refer to [21] and [42].

The main circuit consists of MMC-SCESS, simulated load, and V/V traction transformer. Firstly, the MMC-SCESS converter is used to simulate the different operation modes of the locomotive. The V/V traction transformer consists of two single-phase transformers and draws the power from the electric grid to the simulated load.

The control system mainly consists of master controller and slave controller. Firstly, with the features of high-speed parallel computing for FPGA and high-level algorithm tasks for DSP, a dual-core controller with DSP and FPGA are jointly together as master controller to share computation and execute sophisticated control algorithm. In master controller, DSP is mainly responsible for executing the model predictive control (MPC) method of the MMC while the FPGA not only executes the balance control methods for SMs capacitor voltages and supercapacitor SoC, but also distributes the multiplex pulse signals to control the switching states of SMs. Then, a back-to-back three-phase to two-phase two-level converter is used to simulate the different operation modes of the locomotive. The V/V traction transformer consists of two single-phase transformers and draws the power from the electric grid to the simulated load.

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Combining the balance control methods in different operation modes and the MPDCC methods for the current tracking, the overall control block diagram of the MMC-SCESS based RPC is shown in Fig. 11.

V. EXPERIMENTAL RESULTS

In order to test experimentally the basic functionalities of the studied MMC-SCESS base RPC and verify the effectiveness of the proposed control methods, experiments of the downscaled prototype are designed and constructed in the lab, as shown in Fig. 12. The main parameters are listed in Table I. The design principle of parameters could refer to [21] and [42].

The main circuit consists of MMC-SCESS, simulated load, and V/V traction transformer. Firstly, the MMC-SCESS contains three phases and each phase contains two arms. Each arm is equipped with two SMs and each SM consists of HBC, BEC, and supercapacitor. In general, the supercapacitor has low cell voltage, typical 2.7 V, so the supercapacitors are connected in series to demand the relatively high voltage (such as 72 V in this paper) and an additional balance circuit is used to ensure the balance among the supercapacitors connected in series.

The control system mainly consists of master controller and slave controller. Firstly, with the features of high-speed parallel computing for FPGA and high-level algorithm tasks for DSP, a dual-core controller with DSP and FPGA are jointly together as master controller to share computation and execute sophisticated control algorithm. In master controller, DSP is mainly responsible for executing the model predictive control (MPC) method of the MMC while the FPGA not only executes the balance control methods for SMs capacitor voltages and supercapacitor SoC, but also distributes the multiplex pulse signals to control the switching states of SMs. Then, an additional balance circuit is used to ensure the balance among the supercapacitors connected in series.
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Fig. 11. The overall control block diagram of the MMC-SCESS based RPC.

Fig. 12. Experimental setup of the MMC-SCESS based RPC. (a) Schematic of the downscaled prototype system. (b) Picture of the downscaled prototype system.

TABLE I

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Locomotive capacity $P$</td>
<td>5 kW</td>
<td>Arm inductance $L$</td>
<td>1 mH</td>
</tr>
<tr>
<td>Traction supply voltage $u_{ac}$, $u_{bc}$</td>
<td>110 V</td>
<td>Supercapacitor $C_{sup}$</td>
<td>6 F</td>
</tr>
<tr>
<td>Braking/Startup Power $P_{bs}$</td>
<td>2.5 kW</td>
<td>Filter inductance $L_{s}$</td>
<td>10 mH</td>
</tr>
<tr>
<td>Rated SMs capacitor voltage $U_{int}$</td>
<td>90 V</td>
<td>Initial Supercapacitor SoC</td>
<td>50 %</td>
</tr>
<tr>
<td>Number of SMs per arm $N$</td>
<td>2</td>
<td>Sampling time $T_s$</td>
<td>100 μs</td>
</tr>
<tr>
<td>SM capacitance $C_{sm}$</td>
<td>10 mF</td>
<td>Operation frequency $f$</td>
<td>50 Hz</td>
</tr>
</tbody>
</table>
voltages and supercapacitor voltage/current for SoC estimation. Furthermore, the distributed FPGA also ensures the SMs protection to prevent over-current and over-voltage of supercapacitor. Both communication data transmit among the controllers and switching signal distribution for SMs are realized through the optical fiber.

The experiments of MMC-SCESS based RPC in normal operation mode are carried out and the corresponding results are shown in Fig. 13. The load of 5 kW is located at phase b traction power arm while phase a works on a no-load operation. Firstly, phase b traction locomotive turns into normal operation mode at $t=50$ ms without enabling NSC compensation. Three-phase grid currents are seriously asymmetrical and contain a large number of NSC, as shown in Fig. 13(a)(i). Then, the NSC compensation is enabled at $t=100$ ms. According to the NSC compensation principle, the reference amplitudes of the active current $I_P$ and the reactive current $I_Q$ are set to 32.14 and -18.56 A, respectively. According to (14), the reference three-phase circulating currents are -9.26, 4.63, and 4.63 A, respectively. The experimental waveforms of the compensation currents and the circulating currents are shown in Fig. 13(a)(ii) and Fig. 13(a)(iii), respectively. After NSC compensation, three-phase grid currents tend to be symmetrical and the unbalance level is reduced greatly. Considering that the SMs capacitor voltages of the same arm have been balanced by sorting algorithm, it only displays the first SM capacitor voltage of each arm, as shown in Fig. 13(b). It can be seen that the SMs capacitor voltages appear to the fundamental and second frequencies fluctuations and tend to become divergent in different arms due to the unavoidable power difference. Then, the balance control methods for SMs capacitor voltages are applied at $t=300$ ms. It can be seen that the three-phase circulating currents contain the obvious fundamental components to eliminate the difference between the upper and lower arm voltage, as shown in Fig. R13(a)(iii). The SMs capacitor voltages are re-balanced around the reference value of 90 V and the maximum ripple values of each phase SMs capacitor voltages are 4.87, 5.67, and 5.87 V, respectively. Fig. 13(c) shows the three-phase output multilevel voltages. The output voltage level of each phase is up to its maximum value of five. It is worth to mention that the MPC method usually does not require a modulator, so the output multilevel voltage of each phase seems to be irregular. Furthermore, the three-phase output multilevel voltages are also not completely symmetrical. This is due to the characteristic of the asymmetry on MMC-SCESS based RPC. The experimental results verify that the MMC-SCESS based RPC could generate the reference active current and reactive power to compensate the NSC in the normal operation mode and maintain the SMs capacitor voltage balance with the balance control methods.

The experiments of MMC-SCESS based RPC in extended operation mode are carried out and the corresponding results are shown in Fig. 14 and Fig. 15, respectively. We assume that phase b traction locomotive firstly turns into startup mode at $t=10$ ms with a constant power of 2.5 kW, then turns into normal operation mode at $t=170$ ms with a constant power of 5 kW, and finally turns into braking mode at $t=330$ ms with a constant power of 2.5 kW.

When the supercapacitor does not work, the startup energy is completely provided by electric grid while the regenerative
braking energy has to be feedback to the electric grid. In these cases, the NSC compensation has to be enabled to reduce the unbalance of three-phase grid currents, as shown in Fig. 14(a)(i). When the locomotive is operating in startup mode, the reference amplitudes of the active current $I_P$ and the reactive current $I_Q$ are set to 16.07 and -9.28 A, respectively. According to (14), the reference three-phase circulating currents are -4.63, 2.32, and 2.32 A, respectively. When the locomotive is operating in braking mode, the reference amplitudes of the active current $I_P$ and the reactive current $I_Q$ are set to -16.07 and 9.28 A, respectively. Also, according to (14), the reference three-phase circulating currents are -4.63, 2.32, and 2.32 A, respectively. The experimental waveforms of the compensation currents and the circulating currents are shown in Fig. 14(a)(ii) and Fig. 14(a)(iii), respectively. Due to the use of balance control method, the SMs capacitor voltages of the different arms are well balanced around its reference value of 90 V, as shown in Fig. 14(b). It is worth to mention that the SMs capacitor voltages fluctuation under extended operation is smaller than that under normal operation, this is because SMs capacitor voltages fluctuation is proportional to the magnitude of the transmission power of converter [34]. The three-phase output multilevel voltages in extended mode are not uniformly distributed, which are the same as those in normal mode, as shown in Fig. 14(c).

When the supercapacitor is access to the dc-side of the SM, the startup energy is completely provided by the supercapacitor while the regenerative braking energy could flow to the supercapacitor via the BEC. In these cases, the effect of the startup mode and braking mode on grid current can be neglected, as shown in Fig. 15(a)(i). When the locomotive is operating in startup mode, the reference amplitude of the active current $I_P$ is set to 32.14 A provided by phase b and phase c together while the reactive current is not required. To balance the supercapacitor SoC between phase b (phase c) and phase a, additional dc circulating currents are required to be injected in three phases. According to (21), the three-phase reference circulating currents are set to -4.63, 2.32, and 2.32 A, respectively. Similarly, when the locomotive is operating in braking mode, the reference amplitude of the active current $I_P$ is set to -32.14 A and the three-phase reference circulating currents are set to 4.63, -2.32, and -2.32 A, respectively. The experimental waveforms of the compensation currents and three-phase circulating currents are shown in Fig. 15(a)(ii) and Fig. 15(a)(iii), respectively. It is obvious that the BEC could not only provide the bidirectional power flow, but also keep the SMs capacitor voltages balanced around the reference value of 90 V. The maximum ripple values of each phase SMs capacitor voltages are 2.56, 5.93, and 6.20 V, respectively in the startup mode and 2.24, 5.53, and 5.66 V, respectively in the braking mode. It is noted that when MMC-SCESS based RPC is operating in extended mode, the SMs capacitor voltages fluctuations of phase b and phase c are significantly larger than those of phase a, as shown in Fig. 15(b), this is because whether the MMC-SCESS is operating in startup mode or braking mode, the power interaction occurs among phase b, phase c, and the locomotive directly. The three-phase output multilevel voltages are also not uniformly distributed, as shown in Fig. 15(c). Fig. 16 shows the variation curves of all supercapacitor SoC of three-phase under different operation modes. To verify the SoC balance control
methods in extended mode, the initial imbalance of each supercapacitor is achieved by charging or discharging supercapacitor independently before experiments. When the locomotive is operating in startup mode, SoC would be decreased; while the locomotive is operating in braking mode, SoC would be increased. Furthermore, all supercapacitor SoCs gradually tend to the same level with the balance control methods. It is worth to mention that when the locomotive is operating in normal mode, i.e., the supercapacitor does not work, the supercapacitor SoCs still show a slight decrease due to self-discharge.

The experiments of MMC-SCESS based RPC in different operation modes at the same time (mixed mode) are carried out and the corresponding results are shown in Fig. 17 and Fig. 18, respectively. We assume that both locomotive A and locomotive B turn into normal mode at $t=10$ ms with a constant power of 5 kW. Then, locomotive B turns into braking mode at $t=170$ ms with a constant power of 2.5 kW, of which 40% flows to locomotive A for power supply and 60% flows to supercapacitor for energy storage. Finally, locomotive B stops operating at $t=330$ ms.

When locomotive B is operating in normal mode or stop mode, the MMC-SCESS based RPC is mainly responsible for NSC compensation to reduce the unbalance of three-phase grid currents, as shown in Fig. 17(a)(i). When locomotive B is operating in normal mode, the reference amplitudes of the active current $I_P$ and the reactive current $I_Q$ are set to 0 and -37.11 A, respectively. According to (14), the reference three-phase circulating currents are -4.63, -4.63, and 9.26 A, respectively.

When locomotive B is operating in braking mode, the MMC-SCESS based RPC is responsible for not only NSC compensation but also regenerative braking energy utilization at the same time. Considering that 40% of braking power (i.e., 1 kW) flows to locomotive A for power supply, the reference amplitudes of the active current $I_P$ and the reactive current $I_Q$ are set to -32.14 and -18.56 A, respectively. According to (14), the reference three-phase circulating currents are 4.63, -9.26, and 4.63 A, respectively.

When locomotive B is operating in stop mode, the reference amplitudes of the active current $I_P$ and the reactive current $I_Q$ are set to -38.57 and -14.85 A, respectively. According to (14), the reference three-phase circulating currents are 6.48, -10.19, and 3.70 A, respectively. Considering that 60% of braking power (i.e., 1.5 kW) flows to supercapacitor for energy storage, the reference amplitude of the active current $I_P$ is set to -19.28 A provided by phase b and phase c.
together. According to (21), the three-phase reference circulating currents are set to 2.78, -1.39, and -1.39 A, respectively. Therefore, after synthesizing the reference values of the above two considerations, the final reference amplitudes of the active current \( I_P \) and the reactive current \( I_Q \) provided by phase a and phase c together are -38.57 and -14.85 A, respectively, and those provided by phase b and phase c together are -57.85 and -14.85 A, respectively. The final three-phase reference circulating currents are set to 9.26, -11.58, and 2.31 A, respectively. The experimental waveforms of the compensation currents and the circulating currents are shown in Fig. 17(a)(ii) and Fig. 17(a)(iii), respectively. The SMs capacitor voltages are well balanced around its reference value of 90 V, as shown in Fig. 17(b). It is worth to mention that the SMs capacitor voltages balance in mixed mode is ensured by BEC controller. The three-phase output multilevel voltages are also not uniformly distributed, as shown in Fig. 17(c). Fig. 18 shows the variation curves of all supercapacitor SoCs of three-phase under different operation modes. Due to a part of the braking power flowing to the supercapacitor in the mixed mode, all supercapacitor SoCs are increased and tend to the same level with the balance control method.

All the above experimental results verify the effectiveness of the proposed current tracking control methods and SoC balance control methods in extended (or mixed) operation mode.

VI. CONCLUSIONS

This paper has investigated an MMC-SCESS for RPC. In this case, the MMC-SCESS based RPC could not only provide the ability of NSC compensation, but also achieve the energy storage or energy release for the regenerative braking energy or startup energy of the traction locomotive. Firstly, the mathematical models of MMC-SCESS based RPC incorporating the MMC and bidirectional energy converter are studied. Then, the power flow and the reference circulating current are analyzed and deduced under different operation modes. The balance control methods are presented for the SMs capacitor voltages balance and the supercapacitors SoC balance, which are associated with the operation modes. Furthermore, an MPDCC method is also presented for MMC-SCESS based RPC to ensure the current tracking performance. Finally, the effectiveness of the investigated MMC-SCESS based RPC and the proposed control methods are verified by experimental results of a downscaled prototype.
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APPENDIX

I.

Assuming that the initial phase angle of phase a of grid-side transformer is zero, the initial phase angles of secondary voltages of V/V transformer are:

\[
\begin{align*}
\theta_{sa} &= -\frac{\pi}{6} \\
\theta_{sb} &= -\frac{\pi}{2} 
\end{align*}
\]

(a)

According to (9), the fundamental components of the arm voltage are:

\[
\begin{align*}
\tilde{u}_a &= \frac{1}{\sqrt{3}} U_i \sin(\omega t) \\
\tilde{u}_b &= \frac{1}{\sqrt{3}} U_i \sin(\omega t - \frac{2}{3}\pi) \\
\tilde{u}_c &= \frac{1}{\sqrt{3}} U_i \sin(\omega t - \frac{4}{3}\pi)
\end{align*}
\]

(b)

The positive-sequence circulating current and the negative circulating current are expressed in (c) and (d).

\[
\begin{align*}
i_{sa} &= I_{sa} \sin(\omega t + \theta_s) \\
i_{sb} &= I_{sa} \sin(\omega t + \theta_s - 2\pi/3) \\
i_{sc} &= I_{sa} \sin(\omega t + \theta_s - 4\pi/3) \\
i_{sa} &= I_{sa} \sin(\omega t + \theta_s) \\
i_{sb} &= I_{sa} \sin(\omega t + \theta_s - 2\pi/3) \\
i_{sc} &= I_{sa} \sin(\omega t + \theta_s - 4\pi/3)
\end{align*}
\]

(c)

(d)

The deviations of arm instantaneous power introduced by injecting the circulating currents are shown in (e) and (f).

\[
\begin{align*}
\Delta P_{sa} &= 2\tilde{u}_a i_{sa} = -\frac{1}{\sqrt{3}} U_i I_{sa} \cos(2\omega t + \theta_s) - \cos \theta_s \\
\Delta P_{sb} &= 2\tilde{u}_a i_{sb} = -\frac{1}{\sqrt{3}} U_i I_{sa} \cos(2\omega t + \theta_s - 2\pi/3) - \cos \theta_s \\
\Delta P_{sc} &= 2\tilde{u}_a i_{sc} = -\frac{1}{\sqrt{3}} U_i I_{sa} \cos(2\omega t + \theta_s - 4\pi/3) - \cos \theta_s \\
\Delta P_{sa} &= \tilde{u}_a i_{sa} = -\frac{1}{\sqrt{3}} U_i I_{sa} \cos(2\omega t + \theta_s) - \cos \theta_s \\
\Delta P_{sb} &= \tilde{u}_a i_{sb} = -\frac{1}{\sqrt{3}} U_i I_{sa} \cos(2\omega t + \theta_s - 2\pi/3) - \cos \theta_s \\
\Delta P_{sc} &= \tilde{u}_a i_{sc} = -\frac{1}{\sqrt{3}} U_i I_{sa} \cos(2\omega t + \theta_s - 4\pi/3) - \cos \theta_s
\end{align*}
\]

(e)

(f)

According to (e) and (f), the deviations of arm active power introduced by injecting the circulating currents are given as:

\[
\begin{align*}
P_{\text{diffa}} = \Delta P_{sa} + \Delta P_{sa} &= \frac{1}{\sqrt{3}} U_i I_{sa} \cos \theta_s + \frac{1}{\sqrt{3}} U_i I_{sa} \cos \theta_s \\
P_{\text{diffb}} = \Delta P_{sb} + \Delta P_{sa} &= \frac{1}{\sqrt{3}} U_i I_{sa} \cos \theta_s + \frac{1}{\sqrt{3}} U_i I_{sa} \cos(\theta - 2\pi/3) \\
P_{\text{diffc}} = \Delta P_{sc} + \Delta P_{sa} &= \frac{1}{\sqrt{3}} U_i I_{sa} \cos \theta_s + \frac{1}{\sqrt{3}} U_i I_{sa} \cos(\theta - 4\pi/3)
\end{align*}
\]

(g)

REFERENCES


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