Hierarchical Energy Balance Control Method for M³C based on Injecting Output Frequency Circulating Currents

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Abstract—This paper presents a simplified hierarchical energy balance control method for a modular multilevel matrix converter (M³C) operating as a frequency changer (50Hz to 50/3Hz) for Low Frequency AC (LFAC) transmission system. The proposed method employs an independent energy balance control for each sub-converter of M³C with only injecting the output frequency circulating current, aiming at balancing the energy among the three arms of the sub-converter. Then the modulation technique is redesigned to balance the energy among n sub-modules within each arm. The proposed method simplifies the computational complexity of M³C by considering the sub-converter independently, enabling an easy and efficient way to control M³C. The feasibility of the proposed method is evaluated with normal and dynamic operation, which includes step changes in the output frequency and voltage. The performance and effectiveness of the proposed control strategy is demonstrated by extensive simulation studies and experimentally validated using a scaled-down laboratory prototype.

Keywords— *Modular multilevel matrix converter (M³C); Low Frequency AC (LFAC) transmission system; independent sub-converter control; circulating currents control.*

I. INTRODUCTION

The ever growing demand for renewable energy due to environmental and economic concerns has resulted in huge investments in wind energy in general and large offshore wind farms in particular. The low frequency AC (LFAC) transmission system has shown promising benefits for transmitting offshore energy over medium distances (30km to 150km) when compared with high-voltage DC (HVDC) and high-voltage AC (HVAC) system [1]. LFAC was first proposed as Fractional Frequency Transmission System (FFTS) in [2], 1994 and then its feasibility evaluated by interconnecting two frequency systems for hydro-power plant [3]. In [4] the preliminary experiments further indicated that the transmission capacity of LFAC increases by 2.5 times when compared with HVAC. Furthermore, the authors in [5] presented a thorough comparison between HVDC and LFAC systems. While HVDC shows a favourable performance over a long distance compared to other transmission systems, however the lack of reliable DC/DC circuit breakers has imposed challenging constraints on such a system when realizing a multi-terminal network. A case study in [6] elaborated that the LFAC has a promising potential for

practical implementation within an offshore wind farm. Thereby, the LFAC is chosen for the offshore wind farm.

The backbone of LFAC is the power converter, which works as a frequency changer. Different converters have been considered and discussed in the literature and the 6-pulse cyclo-converter was attempted to triple the frequency in LFAC, from 50/3 Hz to 50 Hz in [4]. Experimental results confirmed its usability but the high total harmonic distortion (THD) makes it inefficient. A different variation was then presented in [7] where the 6-pulse cycloconverter is replaced by a 12-pulse cycloconverter aiming to reduce the THD. However, as confirmed by [8], the 12-pulse cycloconverter still requires large filters to suppress the lower-order harmonics. Therefore, back-to-back AC-DC-AC converters are considered as an alternative by researchers instead of the conventional AC-AC converter [5]. The Modular Multilevel Converter (MMC) is a mature technology in VSC-HVDC, which apparently the back-to-back arrangement is a good candidate for LFAC system. Reference [9] highlighted that the modular design of MMC provides capability to meet any voltage level requirements. Meanwhile, compared with the cycloconverter, it has a superior harmonic performance [10]. However, as discussed in [4] the structure of the half-bridge sub-module in MMC does not allow clearing the dc bus short circuit fault, which is a major limitation.

The modular multilevel matrix converter, M³C, is recognized as the next generation AC-AC converter for LFAC. The concept and operation of M³C was first introduced in [11]. Later on, the space vector control was adapted to control this converter in [12]-[14]. These works also confirm the ability of M³C to overcome the dominated matrix converters' limitation of low voltage conversion ratio (i.e. $V_{out}/V_{in} = 0.866$). A new structure of M³C with arm inductors was later proposed in [15] where each of the nine converter arms functions as a current source, aiming at overcoming the short circuit problem. This structure utilizes the feedforward control method and the simulation results showed its steady-state operation. Furthermore, [16] introduced nine circulating current paths of the M³C builds on the results of [15] and utilized the four of nine circulating currents to balance capacitor voltages of the sub-modules. The commonly used mathematical model of the M³C is based on the 'double $\alpha\beta$ transformation' control method which was proposed in [17]-[20] where the control

algorithm is designed based on the sophisticated mathematical calculation which requires multiple $\alpha\beta$ transformations to decouple the input current, output current and circulating current. It results in a very complex analysis of the mathematical relationship between the arm power and the capacitor voltage. According to that mathematical relationship, the circulating current which contains both input and output frequency components is used to balance the capacitor voltage. Reference [21] applied this ‘double $\alpha\beta$ transformation’ control method into a MW wind energy conversion system. Reference [22] proposed the ‘dq transformation’ control method based on [20] where the current is transformed to dq axis dc signals for a better performance. The capacitor voltage fluctuations of M³C is significant when the input/output frequency get close to each other. In order to solve this problem, reference [23] reallocates the arm currents by only using inner circulating currents. However, this control method is also developed from [20]. A generalized control method for Modular Multilevel Converter topologies (MMC, M³C etc.) is proposed in [24]. It presents a current control based on the state-space representation and an optimized arm energy balancing control which has been applied to M³C as an example. It concluded that references [20] are boundary cases of their proposed control method and their method has better performance. However, these two methods both need a very complex control algorithm and associated mathematical calculation. Reference [25] proposed the method which decouples the sub-converter currents into positive, negative and zero sequences in order to control the input current, circulating current and output current independently. It uses the negative sequence circulating current, which is running at the input frequency, to balance the inter-arm dc-link voltages within each sub-converter. This idea is similar to the commonly used “negative sequence current injection” methods in the star-connected cascaded H-bridge converters (CHBC) [26]. Several predictive control methods are also developed for M³C in [27]-[30]. However, predictive control method needs accurate system parameters and a huge amount of real time calculation which makes it less practical.

The arm current contains both input and output frequency components, which makes the control of M³C challenging. In this paper the injection of the output frequency circulating current is proposed to resolve this problem. The M³C is divided into three sub-converters with each sub-converter being controlled independently. Three arms in each sub-converter share the same output phase, where the phase angle of the corresponding output voltage is set as the reference phase angle for the circulating current to balance the capacitor voltage. Meanwhile, the selective voltage mapping modulation technique (SVMM) has been developed to balance the energy between n sub-modules (SM) within each arm. The complexity and associated mathematical calculation has been dramatically reduced compared with earlier methods proposed in the literature. Experimental results confirm the simulation results and further demonstrated a comparable performance with other relevant papers presented in the literature.

The rest of the paper is organized as follows: Section II presents the circuit topology and the mathematical model of the proposed M³C. Section III discusses the proposed control strategy in detail. Section IV highlights representative simulation results for a medium voltage system model. The experimental validation based on a small laboratory prototype has proven the viability of the proposed simplified control method under different operating conditions as presented in Section V. Finally, the work is concluded in Section VI.

II. THE MODULAR MULTILEVEL MATRIX CONVERTER (M³C)

A. The Circuit configuration of the proposed M³C

Fig. 1 shows the circuit diagram of the M³C, which is functioning as an interface between two power systems with different frequencies. In this work, the input of M³C is connected to the offshore wind farm (50/3Hz), where the three-phase voltages and currents are annotated as uppercase letter: e_A and i_A ; e_B and i_B ; e_C and i_C respectively. (E_A , E_B and E_C are the RMS value of the input voltages while I_A , I_B and I_C are the RMS value of the input current). On the other hand, the output of M³C is connected to the on-shore grid (50Hz), where the three-phase output voltages and currents are presented as lowercase letter: e_a and i_a ; e_b and i_b ; e_c and i_c respectively. (E_a , E_b and E_c are the RMS value of the output voltages while I_a , I_b and I_c are the RMS value of the input current).

The analysis of the proposed M³C is based on dividing the converter into three sub-converters and each sub-converter consists of three arms. Each arm is numbered consecutively according to the three phases of the input and output sides. The input side of each arm is denoted as x (i.e. $x=A,B,C$) according to phase A, B and C, respectively. Similarly, the output side of each arm is denoted as y (i.e. $y=a,b,c$) according to phase a, b and c, respectively. Therefore, each arm in M³C is represented as: arm_{xy} and the output current of the corresponding arm is: i_{xy} while the output voltage of the corresponding arm is: u_{xy} . In each arm, there are n sub-modules (SMs) connected in series with an arm inductor. Each SM is constructed by a full bridge converter cell using four IGBT switches with their associated antiparallel diodes and one dc capacitor. The dc capacitor is denoted by C_{xyz} (i.e. $z=1,2,\dots,n$). The output voltage of each SM: u_{xyz} has three different possible voltage levels, i.e. u_{xyz} , 0 and $-u_{xyz}$, determined by the states of the four IGBT switches. Consequently, the dc capacitor of each SM has three states, i.e. charging, discharging and bypassed, according to the

Table I Switching states of SM

Status	S_1	S_2	S_3	S_4	i_{xy}	u_{xyz}	Capacitor
1	0	1	1	0	<0	$-u_{Cxyz}$	Charging
2	0	1	1	0	>0	$-u_{Cxyz}$	Discharging
3	1	0	0	1	<0	u_{Cxyz}	Discharging
4	1	0	0	1	>0	u_{Cxyz}	Charging
5	0	1	0	1	/	0	Bypassed
6	1	0	1	0	/	0	Bypassed

Fig. 1 Circuit diagram of the Modular Multilevel Matrix Converter (M³C)

switching states of the IGBT switch and the direction of the arm current as shown in Table I.

B. Mathematical modeling of sub-converter a

As illustrated in Fig. 1, the M³C is divided into three identical sub-converters. For simplicity and owing to the symmetry properties, only sub-converter a is considered for deriving the mathematical model in this section. However, this can be equally applied to the other sub-converters of the M³C.

As injecting the output frequency circulating current, each arm current contains three current components: input current component, output current component and circulating current component. For better presentation and discussion in the following sections, the input is represented by abbreviated letter: *i* and the output is represented by abbreviated letter: *o*, while the circulating current is represented by: *cir*. Therefore, the arm current in sub-converter a is given by (1) as follows:

$$\begin{cases} i_{Aa} = i_{Aa_i} + i_{Aa_o} + i_{Aa_cir} \\ i_{Ba} = i_{Ba_i} + i_{Ba_o} + i_{Ba_cir} \\ i_{Ca} = i_{Ca_i} + i_{Ca_o} + i_{Ca_cir} \end{cases} \quad (1)$$

where, i_{Aa_i} , i_{Ba_i} and i_{Ca_i} are the input current components and i_{Aa_o} , i_{Ba_o} and i_{Ca_o} are the output current components while i_{Aa_cir} , i_{Ba_cir} and i_{Ca_cir} are circulating currents.

It is worth noting that the circulating current flows within the sub-converter and does not contribute to the input and

output currents and the sum of the three circulating currents equals to zero.

$$i_{Aa_cir} + i_{Ba_cir} + i_{Ca_cir} = 0 \quad (2)$$

Due to the symmetry property of the proposed M³C, the output current components are one third of the output currents. Therefore, (1) can be further represented by (3) as follows:

$$\begin{cases} i_{Aa} = i_{Aa_i} + \frac{i_a}{3} + i_{Aa_cir} \\ i_{Ba} = i_{Ba_i} + \frac{i_a}{3} + i_{Ba_cir} \\ i_{Ca} = i_{Ca_i} + \frac{i_a}{3} + i_{Ca_cir} \end{cases} \quad (3)$$

Hence, the arm voltage of sub-converter a can be calculated as:

$$\begin{cases} u_{Aa} = e_A - (3L_i + L) \frac{di_{Aa_i}}{dt} - (3L_o + L) \frac{di_{Aa_o}}{dt} - L \frac{di_{Aa_cir}}{dt} - e_a \\ u_{Ba} = e_B - (3L_i + L) \frac{di_{Ba_i}}{dt} - (3L_o + L) \frac{di_{Ba_o}}{dt} - L \frac{di_{Ba_cir}}{dt} - e_a \\ u_{Ca} = e_C - (3L_i + L) \frac{di_{Ca_i}}{dt} - (3L_o + L) \frac{di_{Ca_o}}{dt} - L \frac{di_{Ca_cir}}{dt} - e_a \end{cases} \quad (4)$$

Fig. 2 The block diagram of the proposed control method in sub-converter a

III. THE PROPOSED CONTROL STRATEGY

This section utilizes the developed mathematical model presented in Section II and discusses in detail the proposed control method for M³C. The control block diagram of the proposed control method is illustrated in Fig. 2, where it is divided into three control levels as discussed in following subsections. It is worth noting that again sub-converter a is considered here for the analysis while similar analysis can be applied for the other two sub-converters.

A. Sub-converter Energy Balance Control

The energy balance control of M³C requires that the sum of all capacitor voltages within a sub-converter, which is defined as $\sum u_{Cy}$, to be maintained constant.

Taking sub-converter a as an example, the sum of all capacitor voltages is $\sum u_{Ca}$. Furthermore, the sum of capacitor voltages of n SMs of each of the three arms in each sub-converter is defined as $\sum u_{Cxy}$ ($x \in \{A, B, C\}$, $y \in \{a, b, c\}$). Hence, the sum of all capacitor voltages in arm_{Aa} , arm_{Ba} and arm_{Ca} are $\sum u_{CAa}$, $\sum u_{CBa}$ and $\sum u_{CCa}$, respectively:

$$\sum u_{Ca} = \sum u_{CAa} + \sum u_{CBa} + \sum u_{CCa} \quad (5)$$

where, $\sum u_{CAa}$, $\sum u_{CBa}$ and $\sum u_{CCa}$ are calculated by (6):

$$\begin{cases} \sum u_{CAa} = u_{CAa1} + u_{CAa2} + \dots + u_{CAan} \\ \sum u_{CBa} = u_{CBa1} + u_{CBa2} + \dots + u_{CBan} \\ \sum u_{CCa} = u_{CCa1} + u_{CCa2} + \dots + u_{CCan} \end{cases} \quad (6)$$

The arm current consists of input and output current components as given by (1), where any changes in these currents will influence the $\sum u_{Ca}$ and vice versa. Hence

Fig. 3 Active and reactive power control block diagram

controlling $\sum u_{Ca}$ is the key to achieve the required energy balance.

a. Active and Reactive Power Control

In Fig. 3, P^* and Q^* are reference values of the required active and reactive power, respectively, which are dependent on the demand from the output side.

The output voltages are transferred to dq frame (i.e. e_d and e_q) using (7):

$$T_{abc/dq} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \theta & \cos\left(\theta - \frac{2}{3}\pi\right) & \cos\left(\theta + \frac{2}{3}\pi\right) \\ -\sin \theta & -\sin\left(\theta - \frac{2}{3}\pi\right) & -\sin\left(\theta + \frac{2}{3}\pi\right) \end{bmatrix} \quad (7)$$

Then the reference values, $i_{d_o}^*$ and $i_{q_o}^*$ of the output currents, can be obtained from (8):

$$\begin{cases} P^* = e_d \cdot i_{d_o}^* \\ Q^* = -i_{q_o}^* \cdot e_d \end{cases} \quad (8)$$

Therefore, the reference values of the output currents i_a^* , i_b^* and i_c^* can then be calculated by transforming $i_{d_o}^*$ and $i_{q_o}^*$ back to abc frame using (9).

$$T_{dq/abc} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \sin\theta \\ \cos(\theta - \frac{2}{3}\pi) & -\sin(\theta - \frac{2}{3}\pi) \\ \cos(\theta + \frac{2}{3}\pi) & -\sin(\theta + \frac{2}{3}\pi) \end{bmatrix} \quad (9)$$

With reference to (3), in each sub-converter the output current components within the arm current is equal to one third of the output current. Therefore, the reference value of output current components $i_{xa_o}^*$, $i_{xb_o}^*$ and $i_{xc_o}^*$ of the nine arms currents of three sub-converters in M³C have been calculated as shown in Fig. 3.

where:

$$i_{xy_o}^* = \frac{i_y^*}{3} \quad (10)$$

b. Overall capacitor voltage control

In Fig. 4, the low pass filter functions as filtering out the ac fluctuation of $\sum u_{Ca}$. After passing through the filter, the DC capacitor voltage of $\sum u_{Ca}$ is defined as $\sum U_{Ca}$. $\sum U_{Ca}^*$ is the reference value of $\sum U_{Ca}$. When $\sum U_{Ca}$ is bigger than $\sum U_{Ca}^*$ it means there is an extra energy that is stored within the sub-converter a. Therefore, the input side must decrease the energy that is provided to this sub-converter. Conversely, when $\sum U_{Ca}$ is smaller than $\sum U_{Ca}^*$, it means the energy provided to the sub-converter a is insufficient. Therefore, the input side must increase the energy provided to sub-converter a. The ultimate goal of this control block is to keep $\sum U_{Ca}$ equal to $\sum U_{Ca}^*$ which means the input side meets the required energy demand.

Fig. 4 The block diagram of the overall capacitor voltage control

In Fig. 4, $i_{d_i}^*$ and $i_{q_i}^*$ are reference values of the direct and quadrature axis components of the input current components i_{Aa_i} , i_{Ba_i} and i_{Ca_i} , respectively. Furthermore, $i_{q_i}^*$ is set to zero to achieve a unity power factor. Therefore, the reference values of the input current components: $i_{Aa_i}^*$, $i_{Ba_i}^*$ and $i_{Ca_i}^*$ in Fig. 4 have been calculated according to transformation matrix (9).

It is important to mention that the amplitude of three arm currents i_{Aa_i} , i_{Ba_i} , i_{Ca_i} in sub-converters a, b, c, respectively are not necessary equalled with each other. When there is an unbalanced condition at the grid, the proposed control method is able to self-balance the energy between sub-converters.

B. Energy Balance Control between the three arms of the sub-converter (Capacitor voltage balancing control)

Although the overall energy of the sub-converter is controlled as discussed in section A, however it is not necessarily means that the energy between the three arms of the sub-converter is balanced. Therefore, another control level is required, which utilizes the circulating current. With the circulating current control, the arm with bigger energy compensates the arm with smaller energy, to realize the dynamic energy balance within each sub-converter.

Fig. 5 illustrates the proposed circulating current control, which equally balances the energy across the three arms of the sub-converter. The sum of all capacitor voltages in arm_{Aa} , arm_{Ba} and arm_{Ca} are $\sum u_{CAa}$, $\sum u_{CBa}$ and $\sum u_{CCa}$, respectively. The low pass filter functions as filtering out the ac fluctuation of $\sum u_{CAa}$, $\sum u_{CBa}$ and $\sum u_{CCa}$. After passing through the filter, these three DC capacitor voltages are defined as $\sum U_{CAa}$, $\sum U_{CBa}$ and $\sum U_{CCa}$. Then, these three values are averaged as in (11):

$$\overline{\sum U_{Ca}} = (\sum U_{CAa} + \sum U_{CBa} + \sum U_{CCa}) / 3 \quad (11)$$

After $\sum U_{CAa}$ and $\sum U_{CBa}$ are compared with the mean value and the error is processed the PI controller, the RMS value of the circulating currents: $I_{Aa_cir}^*$, $I_{Ba_cir}^*$ are then calculated as portrayed in Fig. 5.

In sub-converter a, three arms are connected with output

Fig. 5 The block diagram of the capacitor voltage balancing control in sub-converter a

phase a and the initial phase angle of e_a is θ_a . In order to realize the independent control of each sub-converter, the frequency and initial phase angle of the respective output voltage is set as the reference phase angle of three circulating currents. Meanwhile, in order to ensure that three circulating currents in each sub-converter do not affect the respective output current, the sum of the three circulating currents is zero. The circulating current is calculated as:

$$\begin{cases} i_{Aa_cir}^* = \sqrt{2}I_{Aa_cir}^* \cos(\omega_o t) \\ i_{Ba_cir}^* = \sqrt{2}I_{Ba_cir}^* \cos(\omega_o t) \\ i_{Ca_cir}^* = -i_{Aa_cir}^* - i_{Ba_cir}^* \end{cases} \quad (12)$$

The energy difference between three arms of sub-converter a is caused by the active power that are generated by circulating currents are defined by: P_{Aa_cir} , P_{Ba_cir} and P_{Ca_cir} which can be calculated as follows:

$$\begin{cases} P_{Aa_cir} = i_{Aa_cir}^* \cdot u_{Aa} \\ P_{Ba_cir} = i_{Ba_cir}^* \cdot u_{Ba} \\ P_{Ca_cir} = i_{Ca_cir}^* \cdot u_{Ca} \end{cases} \quad (13)$$

Fig. 6 shows one possible power exchange path between the three arms in sub-converter a, which is further discussed in details in the remaining of this section.

When:

$$\begin{cases} \sum U_{CAa} - \sum U_{Ca} > 0 \\ \sum U_{CBa} - \sum U_{Ca} < 0 \\ \sum U_{CCa} - \sum U_{Ca} < 0 \end{cases} \quad (14)$$

After PI controller, the direction of the three circulating currents are determined as given:

Fig. 6 One possible power exchange path

$$\begin{cases} I_{Aa_cir}^* > 0 \\ I_{Ba_cir}^* < 0 \\ I_{Ca_cir}^* < 0 \end{cases} \quad (15)$$

According to (13), therefore:

$$\begin{cases} P_{Aa_cir} > 0 \\ P_{Ba_cir} < 0 \\ P_{Ca_cir} < 0 \end{cases} \quad (16)$$

For this condition, the arm_{Aa} should supply P_{Aa_cir} to the output phase a while arm_{Ba} and arm_{Ca} should absorb P_{Ba_cir} and P_{Ca_cir} from the output phase a. Meanwhile, when the voltage's frequency and the current's frequency are different, there is no active power generation and since the sum of three circulating currents is equal to zero as given by (2). Therefore:

$$P_{Aa_cir} + P_{Ba_cir} + P_{Ca_cir} = 0 \quad (17)$$

Therefore, P_{Aa_cir} , P_{Ba_cir} and P_{Ca_cir} only exchange between the three arms to compensate with each other in sub-converter a.

C. The arm current control

Fig. 7 shows the arm current control according to (4) in sub-converter a. The reference value of the arm current i_{xa}^* consists of three current components: $i_{xa_i}^*$, $i_{xa_o}^*$ and $i_{xa_cir}^*$ that have been calculated in the previous sections.

The difference between the i_{xa} and i_{xa}^* are calculated at first, after which the PI controller along with a feedforward term as per (4) is used to calculate the reference value of three arm voltages (noted by u_{xa}^*). Then, the selective voltage mapping modulation technique (SVMM), as discussed in the following section, is designed to generate the PWM signals of each SM.

D. Energy balance control between n SMs of each arm (Selective Voltage Mapping Modulation)

In each arm, each SM's energy should be balanced which indicates the balance of the capacitor voltage. Therefore, a third control level is required to control the SM's capacitors voltage. The selective voltage mapping modulation (SVMM) is designed based on the phase disposition modulation method (PDPWM) but the sorting algorithm is specifically designed

Fig. 7 Arm current control block diagram

Fig. 8 (a) Full bridge SM (b) PWM signals of five SMs

for the M³C. The voltages of all SM's capacitors are being measured and sorted according to their values. Then based on the arm current's direction these capacitors are mapped according to the sorting algorithm to realize the goal of balancing energy between the n SMs. The details of the control strategy is further explained below.

The instantaneous power of each SM is defined as: p_{Cxyz} . The dc capacitor voltage of the SM is defined as: U_{Cxyz} as discussed in the previous section. The reference value of the dc capacitor voltage is defined as: U_{Cxyz}^* . Each SM needs two switching signals which can be presented as S_{CAaz1} , S_{CAaz2} in sub-converter a as shown in Fig. 8(a). Assuming there are five SMs in arm_{Aa} of sub-converter a, then two switching signals are S_{CAa1} , S_{CAa2} . Therefore, the output voltage of the SM in arm_{Aa} is determined from:

$$u_{CAaz} = S_{CAaz1} \cdot U_{CAaz} - (1 - S_{CAaz2}) \cdot U_{CAaz} \quad (18)$$

Whereas, the instantaneous power of each SM is calculated as:

$$p_{CAaz} = u_{CAaz} \cdot i_{Aa} = (S_{CAaz1} + S_{CAaz2} - 1) \cdot U_{CAaz} \cdot i_{Aa} \quad (19)$$

Hence:

$$\begin{cases} p_{CAa1} = u_{CAa1} \cdot i_{Aa} = (S_{CAa11} + S_{CAa12} - 1) \cdot U_{CAa1} \cdot i_{Aa} \\ p_{CAa2} = u_{CAa2} \cdot i_{Aa} = (S_{CAa21} + S_{CAa22} - 1) \cdot U_{CAa2} \cdot i_{Aa} \\ \vdots \\ p_{CAa5} = u_{CAa5} \cdot i_{Aa} = (S_{CAa51} + S_{CAa52} - 1) \cdot U_{CAa5} \cdot i_{Aa} \end{cases} \quad (20)$$

In Fig. 8(b), the reference value of arm voltage: u_{Aa}^* is the reference signal and there are ten carrier signals in terms of five SMs. It generates ten PWM signals that defined as: PWM_1 , $PWM_2 \dots PWM_{10}$. For example, when $i_{Aa} > 0$, each SM's instantaneous power could be sorted descending in (21):

$$\begin{cases} (PWM_5 + PWM_{10} - 1) \cdot U_{Cxyz}^* \cdot i_{Aa} > (PWM_4 + PWM_9 - 1) \cdot U_{Cxyz}^* \cdot i_{Aa} \\ (PWM_4 + PWM_9 - 1) \cdot U_{Cxyz}^* \cdot i_{Aa} > (PWM_3 + PWM_8 - 1) \cdot U_{Cxyz}^* \cdot i_{Aa} \\ (PWM_3 + PWM_8 - 1) \cdot U_{Cxyz}^* \cdot i_{Aa} > (PWM_2 + PWM_7 - 1) \cdot U_{Cxyz}^* \cdot i_{Aa} \\ (PWM_2 + PWM_7 - 1) \cdot U_{Cxyz}^* \cdot i_{Aa} > (PWM_1 + PWM_6 - 1) \cdot U_{Cxyz}^* \cdot i_{Aa} \end{cases} \quad (21)$$

Then the capacitor voltages should be sorted ascending in order to balance the energy between five SMs in arm_{Aa} . Assuming $U_{CAa1} < U_{CAa2} < U_{CAa3} < U_{CAa4} < U_{CAa5}$, then PWM signals should be mapped to the certain switching signals of

Fig. 9 PWM signals mapping of SVM

each SM as shown in Fig. 9, which enables the balancing of the capacitors voltage within each arm.

IV. SIMULATION RESULTS

The simulation model of M³C for LFAC is developed using MATLAB/SIMULINK software. The input side of the M³C is

Table II Simulation parameters

Description	Parameters	Value
Rated Active Power	P	10 MW
Input RMS line voltage	E_i	11 kV
Input frequency	f_i	50/3 Hz
Input inductance	L_i	4 mH (3.4%)
Output RMS line voltage	E_o	11 kV
Output frequency	f_o	50 Hz
Output inductance	L_o	4 mH (3.4%)
Arm inductance	L	5 mH (4.3%)
Capacitance of SM's capacitor	C_{xyz}	5.1 mF
Rated dc capacitor voltage	U_{Cxyz}^*	5 kV
Number of SMs per arm	n	5
Switching frequency	f_s	5 kHz
Carrier frequency	f_c	5 kHz

connected to the offshore wind farm (50/3Hz) while the output side is connected with the on-shore power grid (50Hz). The simulation parameters is shown in Table II. There are five capacitors in each arm. The standard 6.6 kV 1.5 kA IGBT module such as the product from Infineon is considered as the power switch to build the SM. The proposed system is tested

under different operating conditions to validate the effectiveness and the performance of the proposed control strategy.

A. Case I: Steady-state operation

Fig. 10 shows the simulation results under steady-state operation, where Fig. 10(a) and (b) are the input voltage and input current with no phase shift, demonstrating the unity power operation. The arm current contains two frequency components as illustrated in Fig. 10(c). The capacitor voltages of arm_{Aa} in sub-converter a is illustrated in Fig. 10(e), where all five capacitor voltages are tightly balanced around 5 kV. Furthermore, Fig. 10(f) shows the sum of capacitor voltages of all SMs in sub-converter a, which are perfectly controlled around 25kV.

B. Case II: Dynamic output power operation

Fig. 11 shows the simulation results under dynamic output power operation. Specifically, Fig. 11(a) demonstrates the case when the active power supplied by the input side increases from 10MW to 11MW at 0.5s, where the reactive power maintain as zero for the unity power operation. It is worth noting that the capacitor voltages in Fig. 11(e) and (f) slightly decreased to compensate the active power to the grid from 0.5s and the proposed control strategy successfully managed to maintain the voltage balance at 0.8s.

C. Case III: Unbalanced grid voltage condition

The 5% negative sequence component has been added in the input side of the M³C which cause the unbalanced grid voltage condition as shown in Fig. 12(a), the proposed control

strategy illustrated the good performance under this condition. From 0.5s to 0.8s, the capacitor voltage balancing control has been deactivated to illustrate the effect of the circulating

Fig. 11 Simulation results under a dynamic output power operation

current. As it can be noticed, from 0s to 0.5s, the circulating

Fig. 10 Simulation results under steady-state operation

Fig. 12 Simulation results under unbalanced grid voltage condition

current control is deactivated, which causing the five capacitors voltages in arm_{Aa} in sub-converter a deviating (i.e. gradually increasing) from the reference voltage. This has also influenced the sum of capacitor voltages of arm_{Aa} (increasing) and arm_{Ba} , arm_{Ca} (decreasing) as shown in Fig. 12. On the other hand, the effect of the circulating current can be obviously observed when it is activated at 0.8s, where the capacitor voltages are quickly re-balanced around 5kV.

V. EXPERIMENTAL RESULTS

A. Experimental Setup

Table III Experimental parameters

Description	Parameters	Value
Rated active power	P	0.63 kW
Input phase RMS voltage	E_i	60 V
Input frequency	f_i	50 Hz
Input inductance	L_i	1 mH (1.8%)
Output phase RMS voltage	E_o	56 V
Output frequency	f_o	50/3 Hz
Output inductance	L_o	1 mH (1.8%)
Capacitance of SM's capacitor	C_{xyz}	1 mF
Rated dc capacitor voltage	U_{Cxyz}^*	70 V
Arm inductance	L	4 mH (7.3%)
Load Resistance	R_o	16 Ω
Load Inductance	L_o	1 mH (1.8%)
Number of SMs per arm	n	3

Fig. 13 Experimental setup of M³C

Fig. 13 depicts a scaled-down laboratory prototype of the M³C has been developed with the parameters tabulated in Table III to validate the effectiveness of the proposed control strategy. It should be noted that with the limited resources, the system demonstrated by an input voltage of 50Hz obtained from a three phase programmable AC source, while the output side of 50/3Hz is connected to a three phase inductive load. There are three sub-converters within the M³C. Each sub-converter has three arms of which is connected in series with an arm inductor. Furthermore, there are three full-bridge SMs with a dc capacitor within each arm.

The experimental setup is realized by using a distributed

Fig. 14 Experimental results under steady-state operation

control network, which consists of a total of ten controllers (TMS320F2837xS). One master controller for the whole M³C system and one controller for each arm. The communication is realized by CAN system.

For completeness, the proposed system is tested experimentally under different operating conditions to verify its performance and effectiveness as discussed in the following subsections.

B. Experimental Results

Fig. 14 shows the experimental results of M^3C under steady-state operation condition. Specifically, Fig. 14(b) shows the input current is in-phase with the input voltage, which demonstrates the unity power factor operation achieved by the proposed control method. The output current has been controlled well with the desired low frequency of 50/3 Hz as can be seen from Fig. 14(d).

As expected, the arm current contains two frequency components, which is experimentally shown in Fig. 14(c). once again, the circulating current has no effect on the either the input or the output currents as demonstrated experimentally in Fig. 14(b), (c) and (d). Three capacitor voltages are presented in Fig. 14(e) where the zoomed figure shows the voltage fluctuates by only $\pm 2V$ from the desired voltage of 70V, which again confirms the effectiveness of the proposed control technique. Finally, the output voltage of arm_{Aa} is shown in Fig. 14(f).

Fig. 15 Experimental results under output voltage step change operation

Furthermore, the performance of the proposed system is experimentally validated with two step change operating conditions. Fig. 15 illustrates the step change in the output frequency, i.e. 50/3 to 5Hz. The lower the output frequency

the higher ac voltage ripple of the capacitor voltage. This test aims to demonstrate the performance of the proposed control technique with a very low output frequency. However, the measured capacitor voltages shows only $\pm 2V$ variation from the 70V reference voltage as shown in Fig. 15(d), which again proves the robustness of the control method.

Step change in the output voltage is also demonstrated experimentally, where the voltage changed from 43V to 56V as portrayed in Fig. 16. As the demand on the output side increased as shown in Fig. 16(c), the input current increases accordingly as depicted in Fig. 16(a). Three capacitor voltages damped for compensating the increasing power demand from the output side, but well balanced at 70V.

Fig. 16 Experimental results under output frequency step change operation

C. Comparison between 'double $\alpha\beta 0$ transformation' control method and the proposed control method

In terms of the complexity of the voltage balancing control, the comparison between two control methods has been given in Fig. 17. The complexity of the mathematical calculation is determined by how many accumulator, multiplier, sin and cos in the coding of these three methods based on the CCS platform. Obviously, the amount of

Fig. 17 Comparison between the 'double $\alpha\beta 0$ transformation' and the proposed control method

accumulator, multiplier, sin and cos of the 'double $\alpha\beta 0$ transformation' control method are much more than the proposed control method. The operation time of 'double $\alpha\beta 0$ transformation' control method is 4117 CPU period and the proposed control method only take half of the time, 2553 CPU period (CPU frequency is 200MHz). Therefore, the proposed control method effectively reduced the control complexity and the associated mathematical calculation with reduced operation time. It is important to mention that all the data are based on the coding of the author to achieve the fairest results.

VI. CONCLUSION

The proposed control method achieved the fully independent control of each sub-converter. The injection of output frequency circulating current has been designed easily and accurately for the purpose of compensating the energy difference between the three arms of the sub-converter. The selective voltage mapping modulation technique is designed that balances the energy between n sub-modules within each arm. The experimental results from a scaled down laboratory prototype proved the performance of the proposed control method under steady-state and different dynamic operating conditions.

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