

Fully Decoupled Branch Energy Balancing Control Method for Modular Multilevel Matrix Converter Based on Sequence Circulating Components

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Abstract—The modular multilevel matrix converter (M3C) is a potential frequency converter for low-frequency AC transmission. However, capacitor voltage control of high-voltage and large-capacity M3C is more difficult, especially for voltage balancing between branches. To solve this problem, this paper defines sequence circulating components and theoretically analyzes the influence mechanism of different sequence circulating components on branch capacitor voltage. A fully decoupled branch energy balancing control method based on four groups of sequence circulating components is proposed. This method can control capacitor voltages of nine branches in horizontal, vertical and diagonal directions. Considering influences of both circulating current and voltage, a cross decoupled control is designed to improve control precision. Simulation results are taken from a low-frequency transmission system based on PSCAD/EMTDC, and effectiveness and precision of the proposed branch energy balancing control method are verified in the case of nonuniform parameters and an unbalanced power system.

Index Terms—Branch energy balancing control, decoupled control, low-frequency AC transmission, modular multilevel matrix converter (M3C), sequence circulating components.

NOMENCLATURE

u_a, u_b, u_c	Grid side voltages.
i_a, i_b, i_c	Grid side currents.
u_u, u_v, u_w	Low frequency side voltages.
i_u, i_v, i_w	Low frequency side currents.
i_{xy}, u_{xy}	Branch currents and voltages.
$(x = a, b, c;$ $y = u, v, w)$	
L	Branch inductance.

u_{on}	Voltage difference between neutral point O and N.
u_{Cxy}	Average capacitor voltage of branch xy .
n	Module number of a branch.
C	Module capacitance.
U_C	Average value of all the capacitance voltage.
p_{xy}	Instantaneous power of branch xy .
i_{xycir}	Circulating current of branch xy .
u_{xycir}	Circulating voltage of branch xy .
U_{scirp}, U_{scirn}	Amplitude of positive-sequence and negative-sequence circulating voltage and current of low frequency.
I_{scirp}, I_{scirn}	
$\varphi_{scirp}, \varphi_{scirn}$	Phase angle of positive-sequence and negative-sequence circulating voltage of low frequency.
ω_s	Angular frequency of low frequency.
U_{mcirp}, U_{mcirn}	Amplitude of positive-sequence and negative-sequence circulating voltage and current of grid side frequency.
I_{mcirp}, I_{mcirn}	
$\varphi_{mcirp}, \varphi_{mcirn}$	Phase angle of positive-sequence and negative-sequence circulating voltage of grid side frequency.
ω_m	Angular frequency of grid side frequency.
U_s, I_s	Amplitude of low frequency side voltage and current.
φ_s	Angle between the voltage and current of low frequency side.
U_m, I_m	Amplitude of grid side voltage and current.
φ_m	Angle between the voltage and current of grid side.
$\Delta \bar{p}_{sau}, \Delta \bar{p}_{mau}$	DC components of instantaneous power which generated by the circulating components of low frequency and grid side frequency.
U_{scirp_d}, U_{scirp_q}	Positive-sequence and negative-sequence circulating voltage components of grid side frequency in the dq frame.
U_{scirn_d}, U_{scirn_q}	
U_{mcirp_d}, U_{mcirp_q}	Positive-sequence and negative-sequence circulating voltage components of low frequency in the dq frame.
U_{mcirn_d}, U_{mcirn_q}	

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$u_{sd}, u_{sq}, i_{sq}, i_{sq}$	Voltage and current of grid side system in the dq frame.
$u_{md}, u_{mq}, i_{mq}, i_{mq}$	Voltage and current of low frequency side system in the dq frame.

I. INTRODUCTION

THE low-frequency AC transmission is a promising technology applicable for offshore wind power transmission [1]–[3], power grid interconnection [4] and integration of large scale renewable generation [5]. Low frequency can increase static stability limit power of transmission system and permissible current rating of cable [6], and it is easy to change voltage and break current compared with DC transmission [7]. In addition, the voltage source converter (VSC) provides the low-frequency AC transmission system with a flexible control similar to VSC based high voltage direct current transmission (VSC-HVDC) [8], [9]. These technical characteristics rely on high-voltage and large-capacity frequency converters which are core equipment of low-frequency AC transmission system. As a family member of modular multilevel cascaded converters (MMCCs), the modular multilevel matrix converter (M3C) is recognized as preferred choice. M3C converts AC to AC directly with smaller magnitudes of submodule capacitor voltage ripple and branch circulating current than back-to-back modular multilevel converter (MMC) [10]–[13].

M3C contains a large number of capacitors in submodules of each branch. Maintaining voltage or energy balancing of these capacitors is the premise for proper and safe operation of M3C [14]. Energy balancing control of M3C is divided into three hierarchies: total energy balancing, branch energy balancing, and submodule energy balancing of each branch [15]. Among them, branch energy balancing control plays an important role as the second hierarchy of energy balancing control. On the basis of total energy balancing all nine branches must get an equal share of energy in M3C, which allows for further energy balancing control of each submodule. Branch energy balancing is affected by operation status on both sides system and M3C parameters [16]. Therefore, branch energy balancing control of M3C is the focus and difficulty of research.

To avoid affecting voltage and current of both sides systems connected with M3C, branch energy balancing is achieved by circulating currents which remain circulating inside the M3C. Eight capacitor voltage components corresponding to branch energy balancing are obtained based on double $\alpha\beta 0$ transformation and diagonal transformation in [15]. In order to analyze and control these eight components they are further divided into horizontal, vertical and diagonal directions. Branch energy balancing control is also divided into inner-subconverter and inter-subconverter balancing control in [17]. As a function of circulating current and common-mode voltage, branch power is derived in [18]. According to that, branch capacitor voltages are controlled by circulating current and common-mode voltage, which includes both input and output frequency components. However, common-mode voltage affects the insulation level of M3C and it is not suitable for high voltage transmission systems. Only circulating current is used for balancing capacitor voltages in [19]

and this method is proven effective in an MW wind energy transmission system. For higher precision and robustness, circulating current is transformed to dq -axis dc components in [20]. On this basis, reference [21] analyzes unbalanced branch energy caused by negative-sequence component of grid and proposes a compensation strategy using circulating current control. A new form of circulating current is presented to balance energy of inter-subconverter in [22] and energy balancing of inner-subconverter is not considered. Control methods in [15]–[22] are based on double $\alpha\beta 0$ transformation. There are also null space vector projection control [23] and direct arm energy control [24]. These three types of control methods are implemented, and performances are compared in [25]. Control methods based on double $\alpha\beta 0$ transformation have good performance in terms of dynamic response, degrees of freedom and low voltage ride through.

Branch energy balancing control methods mentioned above only consider power generated by interaction of circulating current and branch voltage. Circulating voltage between branches generated at the same time is usually neglected. However, for large-capacity M3C in low-frequency AC transmission system, performance of branch energy balancing control is also influenced by interaction of circulating voltage and branch current. Furthermore, the above control methods cannot theoretically provide fully decoupled control to branch energy balancing, either for three directions of horizontal, vertical and diagonal or inter-subconverter and inner-subconverter. Branch energy balancing control of different directions affects each other and control precision decreases.

To effectively control branch capacitor voltage, this paper proposes a branch energy balancing control method based on sequence circulating components. Different types of sequence circulating components are defined. Considering circulating current and circulating voltage, the influence mechanism of different sequence circulating components on branch capacitor voltage is theoretically analyzed. Control method is designed accordingly and verified from simulation. The rest of the paper is organized as follows. Section II presents an overview of M3C, including basic mathematical model, arm power analysis and basic control structure. Section III defines sequence circulating components and derives instantaneous power of each branch considering circulating currents and voltages. Section IV designs branch energy balancing control method based on sequence circulating components. Simulation results are presented to validate effectiveness and precision of this control method in Section V. Finally, Section VI concludes this paper.

II. BASIC MODEL AND CONTROL OF M3C

A. Basic Mathematical Model

The circuit configuration of M3C is shown in Fig. 1. Two three-phase systems of grid side and low frequency side are connected by nine branches of M3C. Each branch consists of multiple cascaded H-bridge submodules and a branch inductor in series. From two different perspectives, M3C can be divided into three star-figure subconverters a, b, c on the grid side. and subconverter u, v, w on the low frequency side.

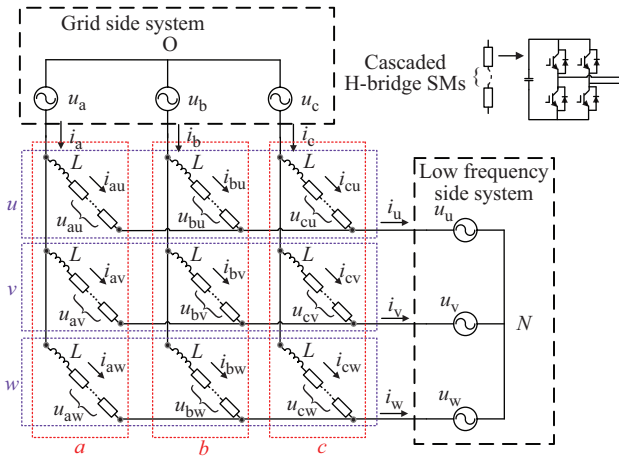


Fig. 1. Circuit configuration of the M3C.

Based on Kirchhoff's voltage and current law in Fig. 1, the mathematical model of M3C can be described as (1):

$$\begin{bmatrix} u_a & u_a & u_a \\ u_b & u_b & u_b \\ u_c & u_c & u_c \end{bmatrix} - \begin{bmatrix} u_u & u_v & u_w \\ u_u & u_v & u_w \\ u_u & u_v & u_w \end{bmatrix} = \begin{bmatrix} u_{au} & u_{av} & u_{aw} \\ u_{bu} & u_{bv} & u_{bw} \\ u_{cu} & u_{cv} & u_{cw} \end{bmatrix} + L \frac{d}{dt} \begin{bmatrix} i_{au} & i_{av} & i_{aw} \\ i_{bu} & i_{bv} & i_{bw} \\ i_{cu} & i_{cv} & i_{cw} \end{bmatrix} + u_{on} \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \quad (1)$$

The double $\alpha\beta 0$ transformation $T_{2\alpha\beta 0}$ are defined as (2).

$$T_{2\alpha\beta 0}(A_{3 \times 3}) = C_{\alpha\beta 0} A_{3 \times 3} C_{\alpha\beta 0}^T, \quad C_{\alpha\beta 0} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \quad (2)$$

Applying $T_{2\alpha\beta 0}$ to (1), the following equation is derived:

$$\begin{bmatrix} 0 & 0 & u_{m\alpha} \\ 0 & 0 & u_{m\beta} \\ 0 & 0 & 0 \end{bmatrix} - \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ u_{s\alpha} & u_{s\beta} & 0 \end{bmatrix} = \begin{bmatrix} u_{\alpha\alpha} & u_{\alpha\beta} & u_{\alpha 0} \\ u_{\beta\alpha} & u_{\beta\beta} & u_{\beta 0} \\ u_{0\alpha} & u_{0\beta} & u_{00} \end{bmatrix} + L \frac{d}{dt} \begin{bmatrix} i_{\alpha\alpha} & i_{\alpha\beta} & i_{\alpha 0}/3 \\ i_{\beta\alpha} & i_{\beta\beta} & i_{\beta 0}/3 \\ i_{0\alpha}/3 & i_{0\beta}/3 & 0 \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & u_{on} \end{bmatrix} \quad (3)$$

Double $\alpha\beta 0$ transformation decouples the grid side and low frequency side systems. Both sides control strategies are designed to achieve different control objectives. Internal and external equations of M3C are also decoupled and circulating components can be used as control degrees of freedom.

B. Arm Power and Capacitor Voltage

Neglecting power losses of branches and assuming capacitor voltage is maintained around average value of all capacitance voltage, module capacitor voltage and power of each branch are as follow:

$$\begin{bmatrix} u_{Cau} & u_{Cav} & u_{Caw} \\ u_{Cbu} & u_{Cbv} & u_{Cbw} \\ u_{Ccu} & u_{Ccv} & u_{Ccw} \end{bmatrix} = \frac{1}{CU_C} \int \begin{bmatrix} p_{au} & p_{av} & p_{aw} \\ p_{bu} & p_{bv} & p_{bw} \\ p_{cu} & p_{cv} & p_{cw} \end{bmatrix} dt + nU_C \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \quad (4)$$

Applying $T_{2\alpha\beta}$ to (4), the following equation is obtained:

$$\begin{bmatrix} u_{C\alpha\alpha} & u_{C\alpha\beta} & u_{C\alpha 0} \\ u_{C\beta\alpha} & u_{C\beta\beta} & u_{C\beta 0} \\ u_{C0\alpha} & u_{C0\beta} & u_{C00} \end{bmatrix} = \frac{1}{CU_C} \int \begin{bmatrix} p_{\alpha\alpha} & p_{\alpha\beta} & p_{\alpha 0} \\ p_{\beta\alpha} & p_{\beta\beta} & p_{\beta 0} \\ p_{0\alpha} & p_{0\beta} & p_{00} \end{bmatrix} dt + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & nU_C \end{bmatrix} \quad (5)$$

U_C is controlled by p_{00} , where p_{00} represents active power flowing into or out of the M3C. When p_{00} is equal to zero, U_C remains at its reference value. $p_{0\alpha}$ and $p_{0\beta}$ represent power flowing between three subconverters a, b, c. $p_{\alpha 0}$ and $p_{\beta 0}$ represent power flowing between three subconverters u, v, w. $p_{\alpha\alpha}$, $p_{\alpha\beta}$, $p_{\beta\alpha}$ and $p_{\beta\beta}$ represent power flow inside the subconverter. To ensure proper operation of M3C, all average capacitor voltages must be kept constant around reference value. Therefore, eight $u_{C\alpha\beta 0/\alpha\beta 0}$ components except u_{C00} are controlled to be zero through control of eight $p_{\alpha\beta 0/\alpha\beta 0}$ elements except p_{00} .

C. Basic Control Structure

Based on (2) and (3), overall control structure of the M3C in low-frequency AC transmission system is shown in Fig. 2. Grid side and low frequency side control are classical inner and outer loop control in $\alpha\beta$ or dq frame. Grid side outer loop controls are module capacitor DC voltage control and reactive power control for total energy balancing and reactive power to grid side system. When the connected low frequency side system is a passive system, the low frequency side outer loop control employs voltage control to provide voltage and phase support. When the connected low frequency side system is an active system, the low frequency side outer loop controls are power controls. Grid side and low frequency side inner loop control are current controls. As the focus of this paper, branch energy balancing control superimposes on both sides control to obtain modulation waveforms for nine branches. Combined with compensation of submodule energy balancing control, modulation waveforms for each submodule are obtained.

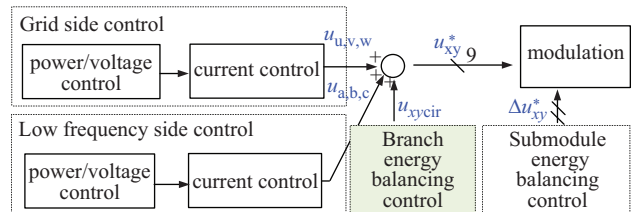


Fig. 2. Overall control structure of the M3C.

III. SEQUENCE CIRCULATING COMPONENTS AND BRANCH POWER

A. Constraints of Circulating Components

Circulating components including circulating current and circulating voltage appear only inside the M3C and have no influence on both sides system. M3C contains nine circuits of circulating components in Fig. 3. Based on (3), the nine circuits of circulating components are decoupled into four independent circuits based on double $\alpha\beta 0$ transformation. It is shown in Fig. 4.

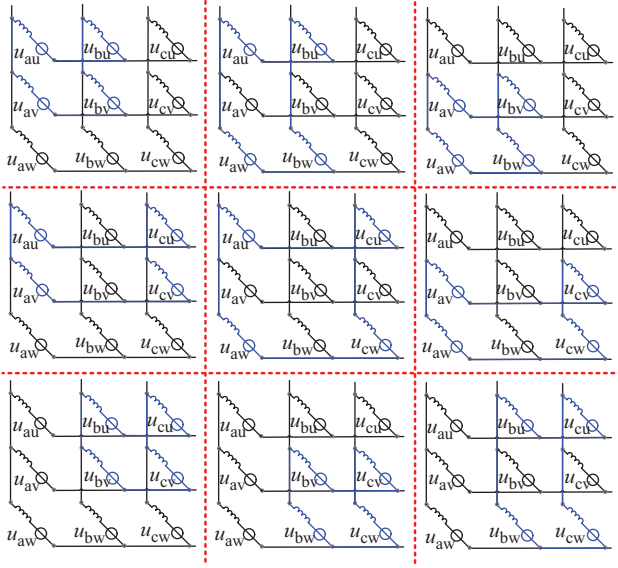
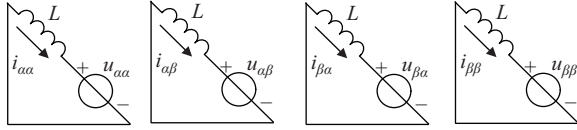


Fig. 3. Circuit of circulating components in M3C.

Fig. 4. Equivalent circuits of circulating components based on double α/β transformation.

The circulating components satisfy the corresponding constraints:

1) The sum of circulating currents of three branches which are connected to any phase of both sides system is zero.

$$i_{a\text{ucir}} + i_{a\text{vcir}} + i_{a\text{wcir}} = 0, \quad i_{a\text{ucir}} + i_{b\text{ucir}} + i_{c\text{ucir}} = 0 \quad (6)$$

$$i_{b\text{ucir}} + i_{b\text{vcir}} + i_{b\text{wcir}} = 0, \quad i_{a\text{vcir}} + i_{b\text{vcir}} + i_{c\text{vcir}} = 0 \quad (7)$$

$$i_{c\text{ucir}} + i_{c\text{vcir}} + i_{c\text{wcir}} = 0, \quad i_{a\text{wcir}} + i_{b\text{wcir}} + i_{c\text{wcir}} = 0 \quad (8)$$

2) The circulating voltages of branches acts on branch inductors to form circulating currents. Therefore, circulating voltage and current of branch xy follows:

$$u_{xy\text{cir}} = -L \frac{d}{dt} i_{xy\text{cir}} \quad (9)$$

B. Definition of Sequence Circulating Components

A kind of circulating component usually has four degrees of freedom. By constraining the form of circulating component, degrees of freedom can decrease to two. Therefore, four kinds of circulating components can be used to achieve branch energy balancing, as well as decoupling control of components in horizontal, vertical and diagonal directions. Frequency of circulating components must be the frequency of both sides of the system. According to constraints of circulating components, form of circulating components is designed.

The positive-sequence circulating voltage of low frequency u_{scirp} is defined as (10), and negative-sequence circulating voltage of low frequency u_{scirn} is defined as (11).

$$\mathbf{u}_{\text{scirp}} = \begin{bmatrix} u_{\text{scirp}1} & u_{\text{scirp}2} & u_{\text{scirp}3} \\ u_{\text{scirp}2} & u_{\text{scirp}3} & u_{\text{scirp}1} \\ u_{\text{scirp}3} & u_{\text{scirp}1} & u_{\text{scirp}2} \end{bmatrix} \quad \text{or}$$

$$\mathbf{u}_{\text{scirn}} = \begin{bmatrix} u_{\text{scirn}1} & u_{\text{scirn}3} & u_{\text{scirn}2} \\ u_{\text{scirn}3} & u_{\text{scirn}2} & u_{\text{scirn}1} \\ u_{\text{scirn}2} & u_{\text{scirn}1} & u_{\text{scirn}3} \end{bmatrix} \quad \text{or} \quad (10)$$

$$\begin{bmatrix} u_{\text{scirn}1} & u_{\text{scirn}3} & u_{\text{scirn}2} \\ u_{\text{scirn}2} & u_{\text{scirn}1} & u_{\text{scirn}3} \\ u_{\text{scirn}3} & u_{\text{scirn}2} & u_{\text{scirn}1} \end{bmatrix} \quad (11)$$

$u_{\text{scirp}1}, u_{\text{scirp}2}, u_{\text{scirp}3}, u_{\text{scirn}1}, u_{\text{scirn}2}, u_{\text{scirn}3}$ are as follows:

$$\begin{aligned} u_{\text{scirp}1} &= U_{\text{scirp}} \cos(\omega_s t + \varphi_{\text{scirp}}) \\ u_{\text{scirp}2} &= U_{\text{scirp}} \cos(\omega_s t + \varphi_{\text{scirp}} - 2\pi/3) \\ u_{\text{scirp}3} &= U_{\text{scirp}} \cos(\omega_s t + \varphi_{\text{scirp}} + 2\pi/3) \\ u_{\text{scirn}1} &= U_{\text{scirn}} \cos(\omega_s t + \varphi_{\text{scirn}}) \\ u_{\text{scirn}2} &= U_{\text{scirn}} \cos(\omega_s t + \varphi_{\text{scirn}} - 2\pi/3) \\ u_{\text{scirn}3} &= U_{\text{scirn}} \cos(\omega_s t + \varphi_{\text{scirn}} + 2\pi/3) \end{aligned} \quad (12)$$

In (10), the three circulating components of each horizontal direction are in positive-sequence phase, and the three circulating components of each vertical direction are in positive or negative-sequence phase. In (11), the three circulating components of each horizontal direction are in negative-sequence phase, and the three circulating components of each vertical direction are in positive or negative-sequence phase.

The positive-sequence circulating voltage of grid side frequency u_{mcirp} is defined as (13), and negative-sequence circulating voltage of grid side frequency u_{mcirn} is defined as (14).

$$\mathbf{u}_{\text{mcirp}} = \begin{bmatrix} u_{\text{mcirp}1} & u_{\text{mcirp}2} & u_{\text{mcirp}3} \\ u_{\text{mcirp}2} & u_{\text{mcirp}3} & u_{\text{mcirp}1} \\ u_{\text{mcirp}3} & u_{\text{mcirp}1} & u_{\text{mcirp}2} \end{bmatrix} \quad \text{or} \quad (13)$$

$$\mathbf{u}_{\text{mcirn}} = \begin{bmatrix} u_{\text{mcirn}1} & u_{\text{mcirn}3} & u_{\text{mcirn}2} \\ u_{\text{mcirn}3} & u_{\text{mcirn}2} & u_{\text{mcirn}1} \\ u_{\text{mcirn}2} & u_{\text{mcirn}1} & u_{\text{mcirn}3} \end{bmatrix} \quad \text{or} \quad (14)$$

$u_{\text{mcirp}1}, u_{\text{mcirp}2}, u_{\text{mcirp}3}, u_{\text{mcirn}1}, u_{\text{mcirn}2}, u_{\text{mcirn}3}$ are as follows:

$$\begin{aligned} u_{\text{mcirp}1} &= U_{\text{mcirp}} \cos(\omega_m t + \varphi_{\text{mcirp}}) \\ u_{\text{mcirp}2} &= U_{\text{mcirp}} \cos(\omega_m t + \varphi_{\text{mcirp}} - 2\pi/3) \\ u_{\text{mcirp}3} &= U_{\text{mcirp}} \cos(\omega_m t + \varphi_{\text{mcirp}} + 2\pi/3) \\ u_{\text{mcirn}1} &= U_{\text{mcirn}} \cos(\omega_m t + \varphi_{\text{mcirn}}) \\ u_{\text{mcirn}2} &= U_{\text{mcirn}} \cos(\omega_m t + \varphi_{\text{mcirn}} - 2\pi/3) \\ u_{\text{mcirn}3} &= U_{\text{mcirn}} \cos(\omega_m t + \varphi_{\text{mcirn}} + 2\pi/3) \end{aligned} \quad (15)$$

In (13) and (14), the three circulating components of each vertical direction are in positive and negative-sequence phase, and the three circulating components of each horizontal direction both have two forms in positive or negative-sequence phase.

Each kind of sequence circulating component has two degrees of freedom: amplitude and phase angle, which can be further expressed in terms of dq components.

C. Analysis of Branch Power and Sequence Circulating Components

Sequence circulating voltage and current in branch interact with current and voltage of the same frequency to produce power. Voltages and currents of low frequency side and grid side are expressed as (16) and (17).

$$\begin{bmatrix} u_u \\ u_v \\ u_w \end{bmatrix} = U_s \begin{bmatrix} \cos \omega_s t \\ \cos(\omega_s t - 2\pi/3) \\ \cos(\omega_s t + 2\pi/3) \end{bmatrix}$$

$$\begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix} = I_s \begin{bmatrix} \cos(\omega_s t + \varphi_s) \\ \cos(\omega_s t + \varphi_s - 2\pi/3) \\ \cos(\omega_s t + \varphi_s + 2\pi/3) \end{bmatrix} \quad (16)$$

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = U_m \begin{bmatrix} \cos \omega_m t \\ \cos(\omega_m t - 2\pi/3) \\ \cos(\omega_m t + 2\pi/3) \end{bmatrix}$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = I_m \begin{bmatrix} \cos(\omega_m t + \varphi_m) \\ \cos(\omega_m t + \varphi_m - 2\pi/3) \\ \cos(\omega_m t + \varphi_m + 2\pi/3) \end{bmatrix} \quad (17)$$

Containing circulating components of grid side frequency and low frequency, voltages and currents of branches are expressed as (18).

$$\begin{cases} u_{xy} = u_x - u_y + u_{xymcir} + u_{xyscir} \\ i_{xy} = \frac{1}{3}i_x + \frac{1}{3}i_y + i_{xymcir} + i_{xyscir} \end{cases} \quad (18)$$

Assuming the total energy of M3C keeps balancing, dc components of instantaneous power of the nine branches are generated by circulating components which lead to constant energy transfer. Taking branch au for example, dc component of instantaneous power includes two parts:

$$\Delta \bar{p}_{sau} = U_s I_{scir} \sin \varphi_{scir} + \frac{1}{3} U_{scir} I_s \cos(\varphi_{scir} - \varphi_s)$$

$$\Delta \bar{p}_{mau} = -U_m I_{mcir} \sin \varphi_{mcir} + \frac{1}{3} U_{mcir} I_m \cos(\varphi_{mcir} - \varphi_m) \quad (19)$$

In (19), dc components of instantaneous power generated by circulating components can be subdivided into two parts. First part is power generated by interaction of circulating current and branch voltage. Second part is power generated by interaction of circulating voltage and branch current. This second part should not be neglected, especially under conditions of large capacity.

When containing positive-sequence circulating components of low frequency, the following dc components of instantaneous power $\Delta \bar{p}_{scirp}$ are derived as (20) after double $\alpha\beta 0$ transformation.

$$\Delta \bar{p}_{scirp} = U_s I_{scirp} \begin{bmatrix} 0 & 0 & \sin \varphi_{scirp} \\ 0 & 0 & -\cos \varphi_{scirp} \\ 0 & 0 & 0 \end{bmatrix}$$

$$+ \frac{1}{3} I_s U_{scirp} \begin{bmatrix} 0 & 0 & \cos \Delta \varphi_{scirp} \\ 0 & 0 & \sin \Delta \varphi_{scirp} \\ 0 & 0 & 0 \end{bmatrix} \text{ or}$$

$$U_s I_{scirp} \begin{bmatrix} 0 & 0 & \sin \varphi_{scirp} \\ 0 & 0 & \cos \varphi_{scirp} \\ 0 & 0 & 0 \end{bmatrix}$$

$$+ \frac{1}{3} I_s U_{scirp} \begin{bmatrix} 0 & 0 & \cos \Delta \varphi_{scirp} \\ 0 & 0 & -\sin \Delta \varphi_{scirp} \\ 0 & 0 & 0 \end{bmatrix} \quad (20)$$

where $\Delta \varphi_{scirp} = \varphi_{scirp} - \varphi_s$.

Positive-sequence circulating components of low frequency only affects $p_{\alpha 0}$, $p_{\beta 0}$ of $p_{\alpha\beta 0}/\alpha\beta 0$, that is, it only controls power flowing between three subconverters u, v, w.

When containing positive-sequence circulating components of grid side frequency, the following dc components of instantaneous power $\Delta \bar{p}_{mcirp}$ are derived as (21) after double $\alpha\beta 0$ transformation.

$$\Delta \bar{p}_{mcirp} =$$

$$U_m I_{mcirp} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ -\sin \varphi_{mcirp} & \cos \varphi_{mcirp} & 0 \end{bmatrix}$$

$$+ \frac{1}{3} I_m U_{mcirp} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \cos \Delta \varphi_{mcirp} & \sin \Delta \varphi_{mcirp} & 0 \end{bmatrix} \text{ or}$$

$$U_m I_{mcirp} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ -\sin \varphi_{mcirp} & -\cos \varphi_{mcirp} & 0 \end{bmatrix}$$

$$+ \frac{1}{3} I_m U_{mcirp} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \cos \Delta \varphi_{mcirp} & -\sin \Delta \varphi_{mcirp} & 0 \end{bmatrix} \quad (21)$$

where $\Delta \varphi_{mcirp} = \varphi_{mcirp} - \varphi_m$.

Positive-sequence circulating components of grid side frequency only affects $p_{0\alpha}$, $p_{0\beta}$ of $p_{\alpha\beta 0}/\alpha\beta 0$, that is, it only controls power flowing between three subconverters a, b, c.

When containing negative-sequence circulating components of low frequency, the following dc components of instantaneous power $\Delta \bar{p}_{scirn}$ are derived as (22) after double $\alpha\beta 0$ transformation.

$$\Delta \bar{p}_{scirn} =$$

$$U_s I_{scirn} \begin{bmatrix} \sin \varphi_{scirn} & -\cos \varphi_{scirn} & 0 \\ \cos \varphi_{scirn} & \sin \varphi_{scirn} & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$+ \frac{1}{3} I_s U_{scirn} \begin{bmatrix} \cos \Delta \varphi_{scirn} & \sin \Delta \varphi_{scirn} & 0 \\ -\sin \Delta \varphi_{scirn} & \cos \Delta \varphi_{scirn} & 0 \\ 0 & 0 & 0 \end{bmatrix} \text{ or}$$

$$U_s I_{scirn} \begin{bmatrix} \sin \varphi_{scirn} & -\cos \varphi_{scirn} & 0 \\ -\cos \varphi_{scirn} & -\sin \varphi_{scirn} & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$+ \frac{1}{3} I_s U_{scirn} \begin{bmatrix} \cos \Delta \varphi_{scirn} & \sin \Delta \varphi_{scirn} & 0 \\ \sin \Delta \varphi_{scirn} & -\cos \Delta \varphi_{scirn} & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (22)$$

where $\Delta \varphi_{scirn} = \varphi_{scirn} - \varphi_s$.

Negative-sequence circulating components of low frequency only affects $p_{\alpha\alpha}$, $p_{\alpha\beta}$, $p_{\beta\alpha}$ and $p_{\beta\beta}$ of $p_{\alpha\beta 0}/\alpha\beta 0$, that is, it only controls power flowing inside the subconverter. Moreover, first form has the same value on $p_{\alpha\alpha}$, $p_{\beta\beta}$ and opposite value on

$$U_{\text{mcirp-q}} = -k_4 u_{C0\alpha} + k_3 u_{C0\beta} \quad (28)$$

In (28), k_1 and k_2 can be simplified from (27) as:

$$k_1 = \frac{1}{3} I_{\text{sd}} \\ k_2 = \frac{\sqrt{U_{\text{sd}}^2 + U_{\text{sq}}^2}}{\omega_s L} + \frac{1}{3} I_{\text{sq}} \quad (29)$$

Control of branch capacitor voltage components $u_{C0\alpha}$, $u_{C0\beta}$ control based on positive-sequence circulating components of grid side frequency is shown in Fig. 6.

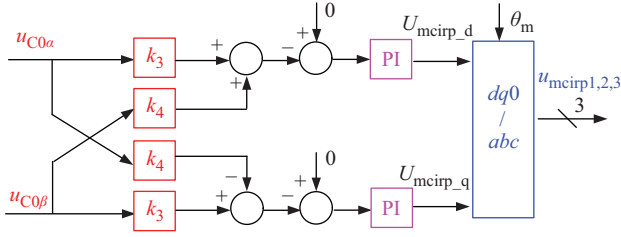


Fig. 6. Control block diagram of branch voltage components $u_{C0\alpha}$, $u_{C0\beta}$ based on positive-sequence circulating components of grid side frequency.

$u_{C\alpha 0}$, $u_{C\beta 0}$ and $u_{C0\alpha}$, $u_{C0\beta}$ are controlled by two kinds of circulating components, including a group of positive-sequence circulating components of low frequency and a group of positive-sequence circulating components of grid side frequency.

$u_{C\alpha\alpha}$, $u_{C\alpha\beta}$, $u_{C\beta\alpha}$ and $u_{C\beta\beta}$ are controlled by two groups of negative-sequence circulating components. Both the first form of negative-sequence component of grid side frequency and low frequency have the same control effect on $p_{\alpha\alpha}$ and $p_{\beta\beta}$. Similarly, both the second form of negative-sequence component of grid side frequency and low frequency have the same control effect on $p_{\alpha\beta}$, and $p_{\beta\alpha}$. Therefore, there are four feasible options to satisfy the requirement for control degrees of freedom:

- 1) the first form of negative-sequence component of low frequency and the second form of negative-sequence component of grid side frequency.
- 2) the second form of negative-sequence component of low frequency and the first form of negative-sequence component of grid side frequency.
- 3) two forms of negative-sequence component of low frequency.
- 4) two forms of negative-sequence component of grid side frequency.

Option 1 is taken as an example to design control method. For the first form of negative-sequence component of low frequency, instantaneous power components and circulating components in the dq frame are expressed as (30). The linearized relationship between sequence circulating components in the dq frame and branch capacitor voltage components $u_{C\alpha\alpha}$, $u_{C\alpha\beta}$, $u_{C\beta\alpha}$, $u_{C\beta\beta}$ are expressed as (31).

$$p_{\alpha\alpha} + p_{\beta\beta} = 2 \times \left[\frac{1}{3} I_s \cos \varphi_s U_{\text{scirn-d}} + \left(\frac{U_s}{\omega_s L} + \frac{1}{3} I_s \sin \varphi_s \right) U_{\text{scirn-q}} \right]$$

$$p_{\alpha\beta} - p_{\beta\alpha} = 2 \times \left[\frac{1}{3} I_s \cos \varphi_s U_{\text{scirn-q}} - \left(\frac{U_s}{\omega_s L} + \frac{1}{3} I_s \sin \varphi_s \right) U_{\text{scirn-d}} \right] \quad (30)$$

where $U_{\text{scirn-d}} = U_{\text{scirn}} \cos \varphi_{\text{scirn}}$, $U_{\text{scirn-q}} = U_{\text{scirn}} \sin \varphi_{\text{scirn}}$

$$U_{\text{scirn-d}} = k_5 (u_{C\alpha\alpha} + u_{C\beta\beta}) - k_6 (u_{C\alpha\beta} - u_{C\beta\alpha}) \\ U_{\text{scirn-q}} = k_6 (u_{C\alpha\alpha} + u_{C\beta\beta}) + k_5 (u_{C\alpha\beta} - u_{C\beta\alpha}) \quad (31)$$

In (31), k_1 and k_2 can be simplified from (30) as:

$$k_5 = \frac{1}{2} k_1, \quad k_6 = \frac{1}{2} k_2 \quad (32)$$

Branch voltage components $u_{C\alpha\alpha}$, $u_{C\alpha\beta}$, $u_{C\beta\alpha}$, $u_{C\beta\beta}$ control based on negative-sequence circulating components of low frequency are shown in Fig. 7.

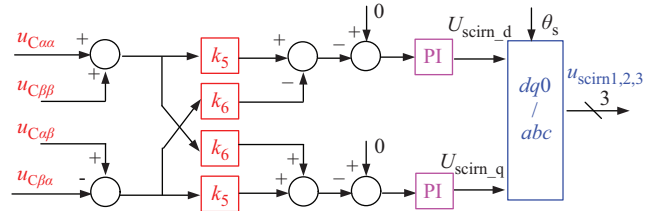


Fig. 7. Control block diagram of branch voltage components $u_{C\alpha\alpha}$, $u_{C\alpha\beta}$, $u_{C\beta\alpha}$, $u_{C\beta\beta}$ based on negative-sequence circulating components of low frequency.

For the second form of negative-sequence component of grid side frequency, instantaneous power components and circulating components in the dq frame are expressed as (33), and the linearized relationship between sequence circulating components in the dq frame and branch capacitor voltage components $u_{C\alpha\alpha}$, $u_{C\alpha\beta}$, $u_{C\beta\alpha}$, $u_{C\beta\beta}$ are expressed as (34).

$$p_{\alpha\alpha} - p_{\beta\beta} = 2 \times \left[\frac{1}{3} I_m \cos \varphi_m U_{\text{mcirn-d}} - \left(\frac{U_m}{\omega_m L} - \frac{1}{3} I_m \sin \varphi_m \right) U_{\text{mcirn-q}} \right] \\ p_{\alpha\beta} + p_{\beta\alpha} = 2 \times \left[-\frac{1}{3} I_m \cos \varphi_m U_{\text{mcirn-q}} + \left(\frac{U_m}{\omega_m L} - \frac{1}{3} I_m \sin \varphi_m \right) U_{\text{mcirn-d}} \right] \quad (33)$$

where $U_{\text{mcirn-d}} = U_{\text{mcirn}} \cos \varphi_{\text{mcirn}}$, $U_{\text{mcirn-q}} = U_{\text{mcirn}} \sin \varphi_{\text{mcirn}}$

$$U_{\text{mcirn-d}} = k_7 (u_{C\alpha\alpha} - u_{C\beta\beta}) + k_8 (u_{C\alpha\beta} + u_{C\beta\alpha}) \\ U_{\text{mcirn-q}} = -k_8 (u_{C\alpha\alpha} - u_{C\beta\beta}) + k_7 (u_{C\alpha\beta} + u_{C\beta\alpha}) \quad (34)$$

In (33), k_1 and k_2 can be simplified from (34) as:

$$k_7 = \frac{1}{2} k_3, \quad k_8 = \frac{1}{2} k_4 \quad (35)$$

Branch voltage components $u_{C\alpha\alpha}$, $u_{C\alpha\beta}$, $u_{C\beta\alpha}$, $u_{C\beta\beta}$ control based on negative-sequence circulating components of grid side frequency are shown in Fig. 8.

Fully decoupled control of branch energy balancing in horizontal, vertical and diagonal directions is achieved by

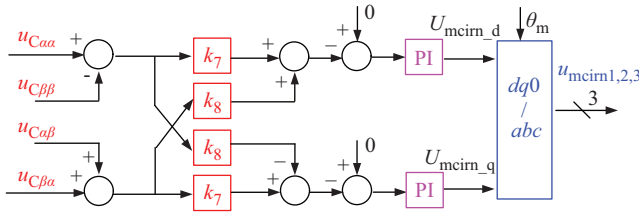


Fig. 8. Control block diagram of branch voltage components $u_{C\alpha\alpha}$, $u_{C\alpha\beta}$, $u_{C\beta\alpha}$, $u_{C\beta\beta}$ based on negative-sequence circulating components of grid side frequency.

four groups of sequence circulating components. Positive-sequence circulating components of grid side frequency and low frequency are used for horizontal and vertical control. Two different forms of negative-sequence components of low frequency and grid side frequency are used for diagonal control. Total control block diagram of branch energy balancing control is shown in Fig. 9.

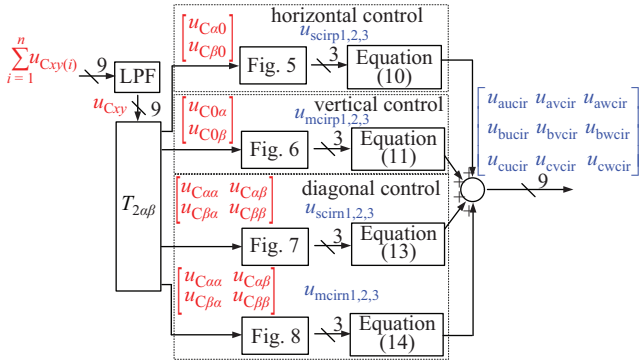


Fig. 9. Control block diagram of the proposed control method for branch energy balancing.

Capacitor voltages of all submodules are summed by branch and filtered with a low pass filter (LPF) to obtain average capacitor voltages. The eight $u_{C\alpha\beta 0/\alpha\beta 0}$ elements are obtained through double $\alpha\beta 0$ transformation of average capacitor voltages of nine branches. Based on the control of sequence circulating components Figs. 5–8 and (10), (11), (13), (14), the four groups of sequence circulating components of nine branches are obtained separately. Modulation waveforms of the nine branches' circulating components are obtained by adding the four groups.

V. SIMULATION VERIFICATION

A. Overview of the Simulation Platform

To verify effectiveness of the proposed control method, a simulation system of low-frequency AC transmission for offshore wind power is implemented in PSCAD/EMTDC. The configuration is shown in the Fig. 10.

Grid-side converter of constant power control is equivalent to offshore wind farm, in which active power is 300 MW and reactive power is zero. The offshore wind farm is linked to onshore converter station through a 100 km, 220 kV submarine cable. In onshore converter station, two star-delta transformers are installed on both sides of M3C, which can reduce voltage

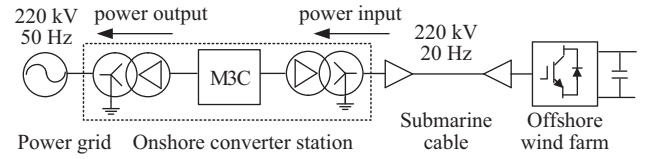


Fig. 10. Configuration of the low-frequency AC transmission system for offshore wind power.

of M3C to fully use the current capability of power electronic devices, and block the zero-sequence component generated by faults. For M3C, control of grid side is capacitor voltage control and reactive power control, and control of low frequency side is voltage control. The main simulation parameters are given in Table I.

TABLE I
MAIN PARAMETERS OF THE SYSTEM

	Parameters	Value
low frequency side system	frequency	20 Hz
	system voltage	220 kV
grid side system	frequency	50 Hz
	system voltage	220 kV
transformer	transformer ratio	220 kV/64 kV
	short-circuit impedance	15%
	connection	YNd
M3C	number of SMs per branch	58
	branch inductance	14 mH
	SM capacitance	1400 μ F
	rated voltage of SM capacitor	2.15 kV
submarine cable	length	100 km
	resistance	0.0151 Ω /km
	inductance	0.372 mH/km
	capacitance	0.179 μ F/km

B. Verification of Branch Energy Balancing Control Method

1) Case I: Energy Balancing for Nonuniform Parameters

In this case, 200 Ω resistors are connected in parallel with six branches (au , bu , cu , av , aw , bw) to unbalance branch power. To verify decoupled control performance of the proposed control method, the diagonal, vertical, and horizontal balancing control are respectively set to start at $t_1 = 4.5$ s, $t_2 = 5.5$ s and $t_3 = 6.5$ s. Simulation results are shown in Fig. 11. Fig. 11(a)–(d) present voltage and current of low frequency and grid sides, respectively. The proposed control method achieves energy balancing only inside the M3C, therefore voltage and current of both sides are stable after energy balancing control starts. Fig. 11(e)–(g) present average capacitor voltage of the nine branches. The system is in a stable state and eight $u_{C\alpha\beta 0/\alpha\beta 0}$ elements except u_{00} are not zero before $t_1 = 4.5$ s. As controls are started in sequence, the control effect gradually appears. $u_{C\alpha\alpha}$, $u_{C\alpha\beta}$, $u_{C\beta\alpha}$ and $u_{C\beta\beta}$ are controlled at t_1 and gradually to zero. At the same time, $u_{C\alpha 0}$, $u_{C\beta 0}$, $u_{C0\alpha}$ and $u_{C0\beta}$ are not affected. $u_{C\alpha 0}$, $u_{C\beta 0}$ are controlled at t_2 and $u_{C0\alpha}$, $u_{C0\beta}$ are controlled at t_3 . The horizontal, vertical, and diagonal balancing control are all separate from others. The eight $u_{C\alpha\beta 0/\alpha\beta 0}$ elements except u_{00} are controlled to zero after $t = 7.5$ s in Fig. 11(e)–(f) and average capacitor voltage of the nine branches are controlled to reference value of 124.7 kV in Fig. 11(g). The difference between input and output power is consumed by

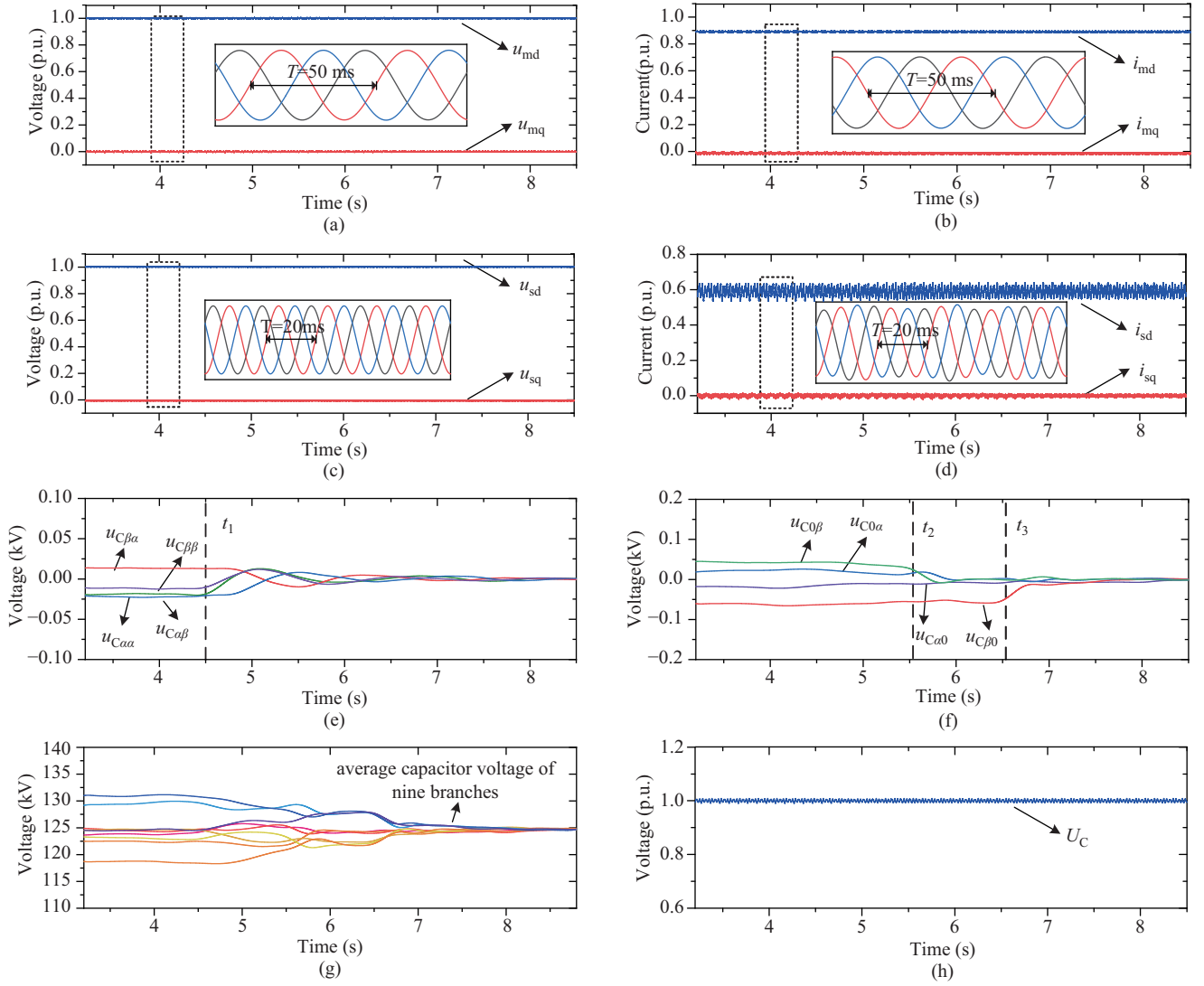


Fig. 11. Simulation results of the branch energy balancing in the case of nonuniform parameters. (a) The voltage of low frequency side. (b) The current of low frequency side. (c) The voltage of grid side. (d) The current of grid side. (e) The voltage of $u_{C\alpha\alpha}$, $u_{C\alpha\beta}$, $u_{C\beta\alpha}$ and $u_{C\beta\beta}$. (f) The voltage of $u_{C\alpha0}$, $u_{C\beta0}$, $u_{C0\alpha}$ and $u_{C0\beta}$. (g) The average capacitor voltage of nine branches. (h) The sum of average capacitor voltage of all the submodules.

parallel resistors and there is no change for total energy of submodules in M3C. Therefore, average capacitor voltage of all submodules keeps stable in Fig. 11(h). Simulation results demonstrate effectiveness of the proposed branch energy balancing control method in the case of nonuniform parameters.

2) Case II: Energy Balancing for Unbalanced Power System

In this case, single-phase faults with $10\ \Omega$ grounding resistance are assumed to have occurred on grid side frequency and low frequency side system at $t_4 = 4\text{ s}$ and duration is 3 s. Branch energy balancing control is set to start at $t_5 = 5.5\text{ s}$. Fig. 12 shows simulation results. Fig. 12(a)–(d) present voltage and current of low frequency and grid sides respectively, including positive-sequence and negative-sequence components in the dq frame. Since transformers block the zero-sequence component of unbalanced power system, M3C contains only positive-sequence and negative-sequence components of the input and output systems. Negative-sequence components of grid side frequency and low frequency side system cause power to flow only between subconverters. After the faults,

the $u_{C\alpha0}$, $u_{C\beta0}$, $u_{C0\alpha}$ and $u_{C0\beta}$ change and $u_{C\alpha\alpha}$, $u_{C\alpha\beta}$, $u_{C\beta\alpha}$ and $u_{C\beta\beta}$ are almost unaffected in Fig. 12(e)–(f). After $t_5 = 5.5\text{ s}$, balancing controls make $u_{C\alpha0}$, $u_{C\beta0}$, $u_{C0\alpha}$ and $u_{C0\beta}$ gradually to zero and average capacitor voltage of the nine branches are controlled to reference value of 124.7 kV in Fig. 12(g). During this time, voltage and current of input and output systems are unaffected by control. At $t_6 = 7\text{ s}$, fault is cleared and voltage and current of both side systems are restored to the state before the faults. The average capacitor voltage of the nine arms are controlled to reference value in a short dynamic control process. Fig. 12(h) shows the energy of M3C changes transiently and fluctuates during the occurrence, clearance, and persistence of faults, but also kept close to reference value. Simulation results demonstrate effectiveness of the proposed method in the case of unbalanced power system.

C. Performance Comparison

In terms of control performance of branch energy balancing

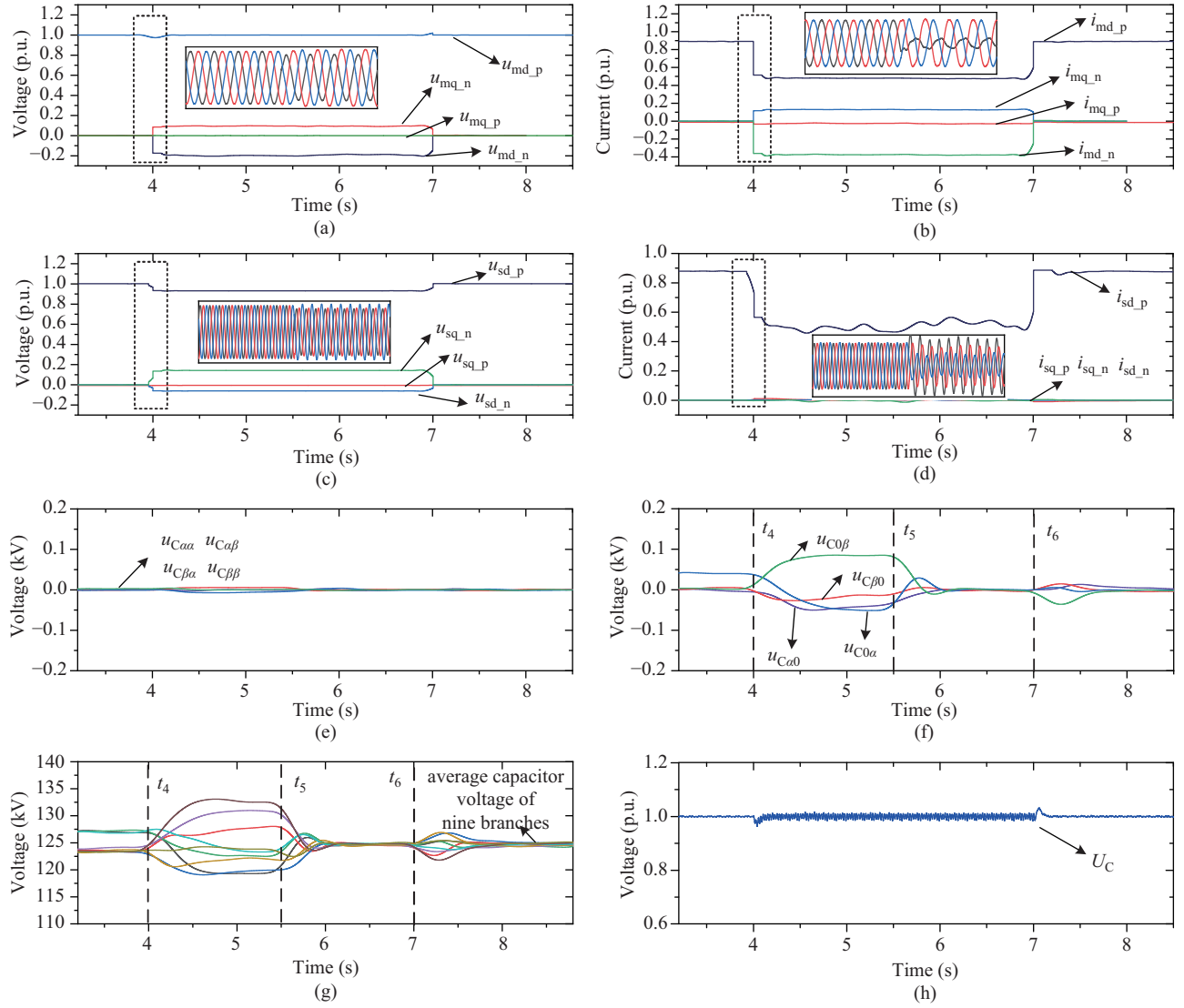


Fig. 12. Simulation results of the branch energy balancing in the case of unbalanced power system. (a) The voltage of low frequency side. (b) The current of low frequency side. (c) The voltage of grid side. (d) The current of grid side. (e) The voltage of $u_{C\alpha\alpha}$, $u_{C\alpha\beta}$, $u_{C\beta\alpha}$ and $u_{C\beta\beta}$. (f) The voltage of $u_{C\alpha0}$, $u_{C\beta0}$, $u_{C0\alpha}$ and $u_{C0\beta}$. (g) The average capacitor voltage of nine branches. (h) The sum of average capacitor voltage of all the submodules.

control, the conventional control method based on double $\alpha\beta0$ transformation [25] (control method I) and the proposed control method (control method II) are compared. In order to verify impact of circulating voltage, the proposed control method without considering circulating voltage (control method III) is added to the comparison. Control performance of three control methods are given in Table II and simulation results of average capacitor voltage of nine branches are shown in Figs. 13–15.

TABLE II
CONTROL PERFORMANCE OF THREE CONTROL METHOD

Verification case	Control method	Voltage range (kV)	Average voltage (kV)	Standard deviation
Nonuniform parameters	I	122.39–129.62	124.70	0.73
	II	124.02–125.35	124.70	0.29
	III	123.91–125.43	124.70	0.37
Unbalanced power system	I	122.39–129.62	124.70	2.23
	II	124.02–125.35	124.70	0.41
	III	123.91–125.43	124.70	0.57

Both conventional control method based on double $\alpha\beta0$ transformation and the proposed control method do not affect the both side system connected with M3C. For the case of nonuniform parameters, the conventional control method controls average capacitor voltage of nine branches in the range of 123.59–126.21 kV and standard deviation is 0.73. The proposed control method controls voltage in the range of 124.14–125.10 kV and standard deviation is 0.29. Control performance is improved by 60.3% from the perspective of standard deviation. For the case of unbalanced power system, the conventional control method controls voltage in the range of 122.39–129.62 kV and standard deviation is 2.23. The proposed control method controls voltage in the range of 124.01–125.35 kV and standard deviation is 0.41. Control performance is improved by 81.6% from the perspective of standard deviation. Control performance of the proposed control method without considering circulating voltage is improved by 49.3% and 74.4%. Higher control precision can

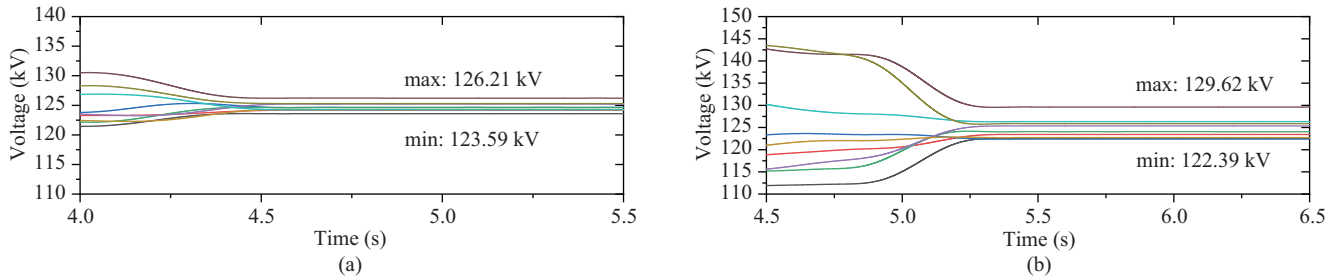


Fig. 13. The average capacitor voltage of nine branches based on the proposed control method. (a) In the case of nonuniform parameters. (b) In the case of unbalanced power system.

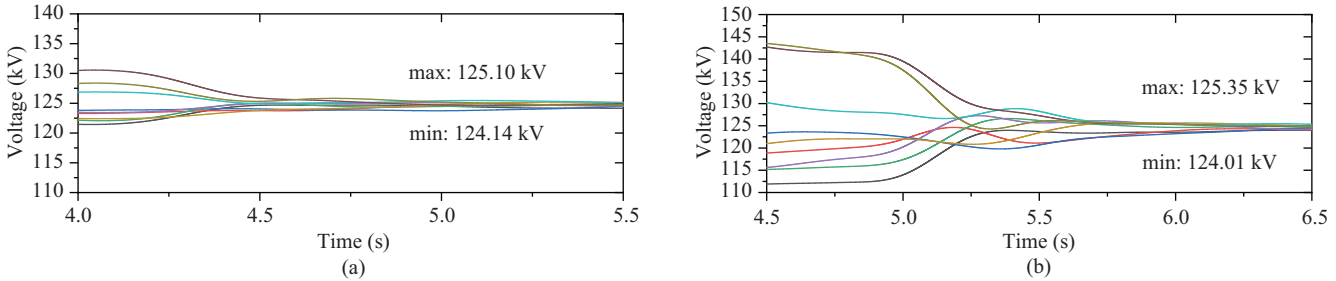


Fig. 14. The average capacitor voltage of nine branches based on the conventional control method based on double α/β transformation. (a) In the case of nonuniform parameters. (b) In the case of unbalanced power system.

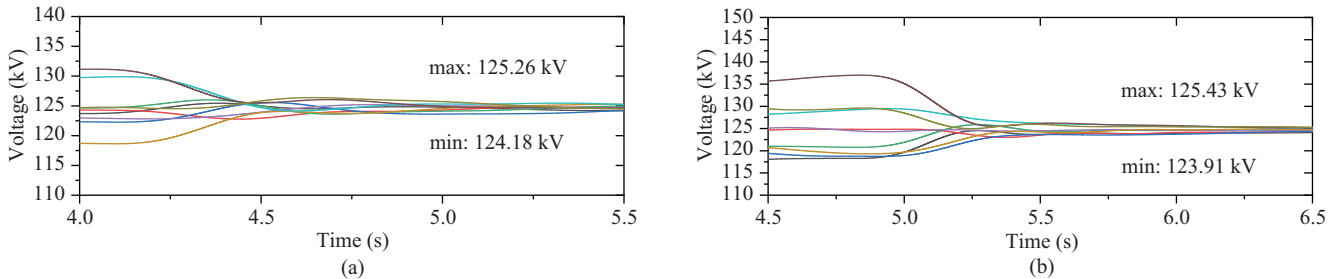


Fig. 15. The average capacitor voltage of nine branches based on the proposed control method without considering circulating voltage. (a) In the case of nonuniform parameters. (b) In the case of unbalanced power system.

be obtained by using the proposed control method compared with the conventional control method and the proposed control method without considering circulating voltage. It should be noted the advantages of the proposed control method will be more obvious when transmission power of M3C is increased.

VI. CONCLUSION

This paper proposes a fully decoupled branch energy balancing control method for M3C based on sequence circulating components. The influence mechanism of different sequence circulating components on branch capacitor voltage has been analyzed in detail. Positive-sequence circulating components of grid side frequency and low frequency are used for horizontal and vertical balancing control. Negative-sequence circulating components of grid side frequency and low frequency are used for diagonal balancing control. Considering the influence of sequence circulating voltage and current on branch energy, a cross decoupled control is added to the proposed control method. Through simulation, it is verified the proposed control method achieves fully decoupled control of branch capacitor voltage and has higher control precision. The

proposed control method can provide a technical scheme for capacitor voltage balance of high-voltage and large-capacity M3C in low-frequency AC transmission.

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