Modular Multilevel Converter Based on Full Bridge Cells for Multi-Terminal DC Transmission

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Keywords

«HVDC», «Multiterminal HVDC», «Multilevel converters»

Abstract

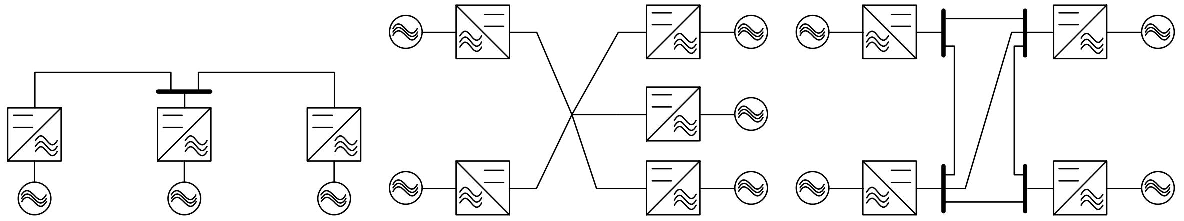
In the Multi-Terminal DC (MTDC) power transmission system, the power flows according to the DC voltages of the terminals and the line impedances. And, the power flowing through each DC line in the mesh MTDC system is not able to be controlled independently. In this paper, a Modular Multilevel Converter based on Full Bridge cells (MMC-FB) is proposed for auxiliary voltage control in the mesh type MTDC system. To control the MMC-FB in four-quadrant, the capacitor voltage balancing method is also proposed with three equivalent circuit models. All control algorithm associated with the proposed MTDC has been confirmed by computer simulation.

I. Introduction

Recently, the High Voltage Direct Current (HVDC) power transmission system has been considered as an adequate solution for effectively operating the established AC grid and easily integrating the renewable energy source. Moreover, the power demand centralization by the rapid urbanization makes the HVDC system more attractive to solve the complex AC power transmission and distribution problems. Until now, the most HVDC power transmission systems have been used for transferring the power from point to point. In these days the Multi-Terminal HVDC(MTDC) systems are planned for connecting various renewable sources and different AC grid system in one DC grid. In Europe, the Supergrid based on the MTDC system has been proposed to bring the renewable energy from North Africa to southern Europe. And, there have been many trials to connect multiple offshore wind power plants in the North Sea region with several countries by the MTDC system.

However, many challenges need to be solved before the MTDC systems are popularly installed in the real world: a practical DC circuit breaker to disconnect the DC lines at high DC voltage level, DC short fault protection strategies, the influence between the conventional AC grid fed by the AC/DC converter and DC grid, and so on. Not only that, the regulation of the power flowing on the MTDC grid is the critical issue to be solved. Droop control methods have been proposed as ways to control the DC link voltage of the DC grid and to coordinate many HVDC converter connected to the common DC grid [1]. All of droop control methods regulate the DC voltage of each HVDC converter and control the power from the converter into the DC grids. The power flows in the DC grids according to the line impedances, and the power flowing through each DC transmission line may not be controlled independently. That means that there are some limitations to control the load flows through the DC transmission lines [2]. To overcome these limitations, the auxiliary DC Transmission Controller (DCTC) has been proposed [2]-[3]. In [2], the thyristor converter had been introduced. This converter injects an arbitrary DC voltage into the DC line. Therefore the power flowing in the DC line can be regulated by the converter. Since it consists of two converters and each converter has six bunches of thyristors, it can run in four-quadrant of voltage/current plane. Most of all, it is economical and efficient. However, the DC voltage injected into the DC line by the thyristor converter has voltage ripple whose frequency is the six times fundamental frequency. And, this voltage ripple causes the current ripple in the DC lines. If the AC grid is not available due to any reason, the thyristor converter should be disconnected from the DC lines.

In this paper, the power flow in each DC line is analyzed according to the type of the MTDC configuration. In the mesh configuration, the power flowing from each converter can be controlled, not the power flowing through the DC lines. To regulate the power through each transmission line, in this paper the Modular Multilevel Converter based on Full Bridge cells (MMC-FB) is proposed as the DCTC. The MMC-FB can generate the DC voltage from the positive to the negative rated value, and the DC voltage of the MMC-FB is regulated without the voltage ripple. To control the MMC-FB in four-quadrant, the capacitor voltage balancing method is also proposed with three equivalent models.

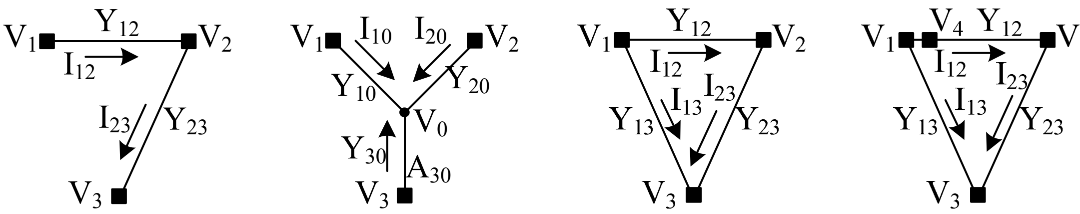


(a) Single line configuration (b) Radial configuration (c) Mesh configuration

Fig. 1: DC grid configurations with VSC-HVDC.

II. Power Flow in the DC Grid

The DC grids can be implemented in various types as shown in Fig. 1 [4]. If the DC grid consists of VSC-HVDC converters, the DC terminals of converters are connected in parallel. All converters operate within the same DC voltage range, and the power flows are determined by small difference in the DC terminal voltage of each converter and line impedances. These parallel connected DC grids are grouped into three configurations. The single line configuration, shown in Fig. 1(a), has only one DC line in the system. The single line configuration is suitable to transfer power from one point to other point. In the middle of the single DC line, another renewable energy source and/or load can be connected. The radial configuration is depicted in Fig. 1(b). In the radial configuration, every converter has only one DC line. Since all converters can share the voltage of the cross point, the entire power flow in the system can be easily controlled by droop control [5], and the power flowing through each line can be controlled independently. One converter in the radial configuration has only one DC line interfacing the whole DC grid. The mesh configuration in Fig. 1(c) is known to be more reliable than the radial configuration. One DC line in the mesh configuration can be disconnected from the DC grid without any converter action. When one DC line is disconnected by a fault, the power flow inherently redistributes on the remaining DC grid. In the mesh configuration, the power transferred from and/or into converter can be controlled. The flowing power in each DC line is inherently determined by the impedances of the DC lines and the terminal DC voltage of the converters.



(a) Single line Config. (b) Radial Config. (c) Mesh Config. (d) Mesh Config. with auxiliary controller

Fig. 2: Simple diagram of DC grid configurations.

The power flowing through each DC line can be calculated from the admittance of the DC grid. Simple three configurations are depicted in Fig. 2. The current of every DC line is determined by the

DC voltage of terminals and the impedances of the DC grid. The DC line current of the single line configuration in Fig. 2(a) can be calculated by the admittances of the DC lines and the terminal voltages as (1). In the single line configuration, two line currents can be obtained by three terminal voltages. Therefore, each line current can be controlled independently. The DC line currents of the radial configuration are also calculated by the admittances of the DC lines and the terminal voltages as (2). The voltage of the cross point, V0, is determined by other three terminal voltages. And three DC line currents are decided by the three terminal voltages and one cross point voltage, V0. Therefore, all DC line currents in the radial configuration can be also controlled by the terminal voltages independently.

$$\begin{bmatrix} I_{12} \\ I_{23} \end{bmatrix} = \begin{bmatrix} Y_{12} & -Y_{12} & 0 \\ 0 & Y_{23} & -Y_{23} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} I_{10} \\ I_{20} \\ I_{30} \end{bmatrix} = \begin{bmatrix} Y_{10} & 0 & 0 & -Y_{10} \\ 0 & Y_{20} & 0 & -Y_{20} \\ 0 & 0 & Y_{30} & -Y_{30} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_0 \end{bmatrix} \tag{2}$$

On the other hand, the DC line currents of the mesh configuration are determined by the terminal voltages and the admittances of the grid. As derived in (3), since the matrix of the admittance is singular, the power flowing through the DC lines cannot be controlled independently by the terminal DC voltages. In the mesh configuration, some DC lines can be overloaded even though the currents through other DC lines are under their rated values. In order to control the power flowing through all DC lines under their rated capability, additional voltage controller needs to be installed into the DC grid. This auxiliary DC Transmission Controller (DCTC) can be introduced in Fig. 2(d) [2]-[3]. Then, as described in (4), the three currents of the DC lines can be calculated by the admittances of the DC grid, three terminal voltages and the auxiliary voltage, V4. The currents flowing through the DC lines can be controlled through four voltages independently.

$$\begin{bmatrix} I_{12} \\ I_{13} \\ I_{23} \end{bmatrix} = \begin{bmatrix} Y_{12} & -Y_{12} & 0 \\ Y_{13} & 0 & -Y_{13} \\ 0 & Y_{23} & -Y_{23} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \tag{3}$$

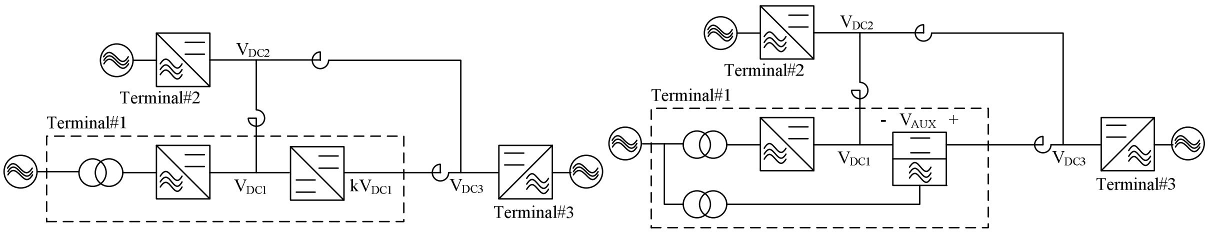
$$\begin{bmatrix} I_{12} \\ I_{13} \\ I_{23} \end{bmatrix} = \begin{bmatrix} 0 & -Y_{12} & 0 & Y_{12} \\ Y_{13} & 0 & -Y_{13} & 0 \\ 0 & Y_{23} & -Y_{23} & 0 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} \tag{4}$$

If the DC gird does not have any mesh configuration, therefore, the power flowing through each DC line can be controlled independently. If not, the loop in the mesh configuration can be partitioned by the DCTC and the all line power of the DC grid can be controlled independently.

III. Full-Bridge MMC for DC Transmission Control

A. DC transmission control

The DCTC can manage the DC power flowing through the specific DC line by being shunt connected and/or series connected as shown in Fig. 3 [2].



(a) Shunt connected DCTC. (b) Series connected DCTC.

Fig. 3: DC Transmission Controller in the MTDC system.

The shunt connected DCTC in Fig. 3(a) is a kind of DC/DC converter with the voltage transfer ratio, *k*.

$$V_{out} = kV_{DC1} \tag{5}$$

Since the DCTC controls the power flow between two DC terminals of which rated DC link voltage are identical, the voltage transfer ratio of the DCTC is generally between 0.9 and 1.1. Therefore, the voltage rating of the shunt DCTC is almost 1pu. And, the DC current flowing through the shunt connected DCTC can be up to 1pu. As a result, the power rating of the shunt DCTC would be approximately 1pu. The shunt connected DCTC can be implemented by a kind of high voltage DC/DC converter whose voltage conversion ratio is from 0.9 to 1.1.

In the other hand, the series connected DCTC is depicted in Fig. 3(b). Because the series DCTC is connected in the middle of the DC line, the output voltage of the series DCTC is added to the DC link voltage of the converter as (6).

$$V_{out} = V_{DC1} + V_{AUX} \tag{6}$$

Therefore, the voltage rating of the series DCTC is about 0.1pu. Even though the current rating is the same with that of the DC line, the power rating of the series DCTC is almost 0.1pu. However, the series DCTC requires a transformer to connect to the AC system.

Since the DC voltage of the series DCTC can vary from -0.1pu to 0.1pu, the series DCTC is generally known to be chosen as a current source converter. Especially, the thyristor converter which has been used for a long time and proven as the reliable system, is called to be a candidate as series DCTC. Because the thyristor converter switches according to the AC line frequency, however, the output DC voltage varies severely.

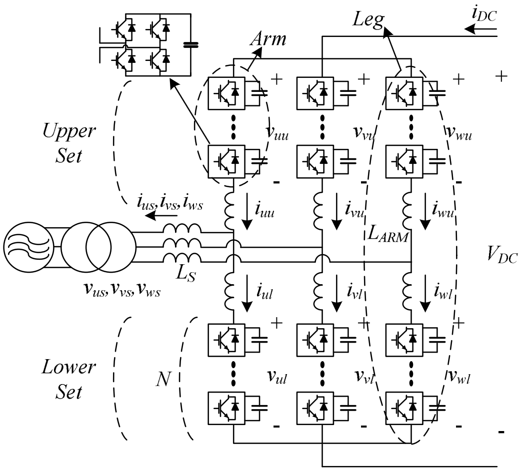


Fig. 4: Diagram of MMC-FB.

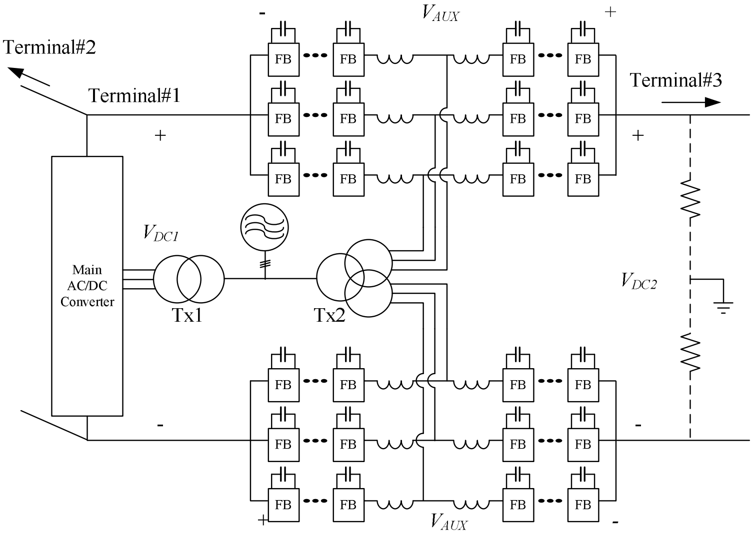
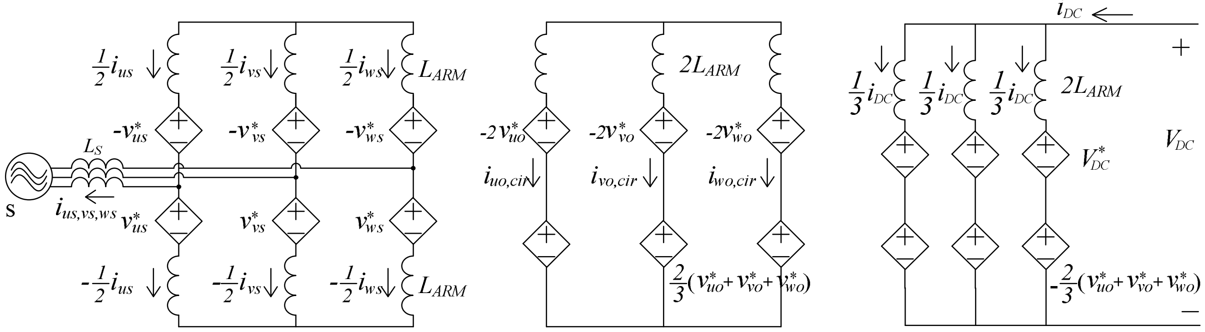


Fig. 5: MMC-FB for series connected DCTC in MTDC system.

The Modular Multilevel Converter based on Full Bridge converter (MMC-FB) shown in Fig. 4 can generate the output DC voltage from the positive to the negative rated DC voltage. Even though the MMC-FB is a kind of the VSC converter, therefore, the MMC-FB can be used as like the series DCTC. Fig. 5 illustrates the MMC-FB for the series DCTC in MTDC system. Since the midpoint of DC link of the HVDC system is generally grounded, the output voltage of the MMC-FB needs to be inserted equally into the positive side and the negative side of the DC terminal. Each MMC-FB has its own transformer to be connected to the AC system. If the turn ratio of the main transformer for the main converter, *Tx1* is 1:1, the turn ratio of the auxiliary transformer, *Tx2* for the MMC-FB may be about 1:20, because the rated DC voltage of the series DCTC is 0.1pu of the DC link voltage of the main converter.

B. Control of MMC-FB

In order to control the power flow, the MMC-FB should regulate the output DC voltage such as a rectifier whose DC link voltage is varying. According to the DC link voltage and the DC current, the capacitors of modules of MMC can be charged or discharged. In order to keep the energy charged in the entire capacitor of the MMC-FB be balanced, the AC power should be controlled instantaneously.



(a) Model of AC grid current (b) Model of circulating current (c) Model of DC grid current

Fig. 6: Equivalent model of MMC.

Fig. 6 shows the equivalent circuit model of the MMC. This model is divided into three equivalent sub-circuit models: the AC grid current model, the circulating current model, and the DC grid current model [6]. If the phase name is denoted as x ($x=u,v,w$), the upper and lower arm voltage references can be expressed as (5), where $V_{DC}*$ is the DC link voltage reference, $v_{xs}*$ is the phase voltage reference for AC grid current control, and $v_{xou}*$, $v_{xol}*$ are the leg voltage references for circulating current control of the upper and lower arm, respectively. The upper and lower arm current in (6) consists of the DC grid current, the AC grid current and the circulating current where i_{xu} and i_{xl} are the upper and lower arm current, i_{DC} is the DC current, i_{xs} is the AC phase current, and i_{xo} is the circulating current.

$$\begin{aligned} v_{xu}^* &= \frac{1}{2}V_{DC}^* - v_{xs}^* - v_{xou}^* \\ v_{xl}^* &= \frac{1}{2}V_{DC}^* + v_{xs}^* - v_{xol}^* \end{aligned} \qquad (5) \qquad \begin{aligned} i_{xu} &= \frac{1}{3}i_{DC} + \frac{1}{2}i_{xs} + i_{xo} \\ i_{xl} &= \frac{1}{3}i_{DC} - \frac{1}{2}i_{xs} + i_{xo} \end{aligned} \qquad (6)$$

The voltage reference for the AC current control is assumed as AC grid voltages as (7). And, the AC current are assumed to be controlled as (8).

$$v_{xs}^* = V_{AC}\sin(\omega t + \theta_x) \qquad (\theta_{u,v,w} = 0, -\frac{2\pi}{3}, \frac{2\pi}{3}) \qquad (7)$$

$$i_{xs} = I_{AC}\sin(\omega t + \theta_x + \varphi) \qquad (8)$$

The DC current and the AC current can be controlled based on the AC and DC model in Fig. 6(a) and (6c), respectively. By controlling the AC and DC current, the power flowing through the MMC-FB can be regulated. And, the energy stored in each arm can be balanced by regulating the circulating current and the zero sequence voltages of the upper arms and the lower arms based on the circulating current model in Fig. 6(b).

To balance the capacitor charged energy in six arms, three conditions should be satisfied: set energy balancing, leg energy balancing, and arm energy difference balancing. Set energy balancing means that three upper arms' capacitor energy should be equal with three lower arms' one.

$$E_{SetU} - E_{SetL} = (E_{uu} + E_{vu} + E_{wu}) - (E_{ul} + E_{vl} + E_{wl}) = 0 \qquad (9)$$

Leg energy balancing means that three legs' upper arm and lower arm capacitor energy should be balanced with each other.

$$E_{LegSumU} = E_{LegSumV} = E_{LegSumW} = (E_{uu} + E_{ul}) = (E_{vu} + E_{vl}) = (E_{wu} + E_{wl}) \qquad (10)$$

Last, arm energy difference balancing means that the energy difference between upper arm and lower arm of three legs should be equal.

$$E_{LegDiffU} = E_{LegDiffV} = E_{LegDiffW} = (E_{uu} - E_{ul}) = (E_{vu} - E_{vl}) = (E_{wu} - E_{wl}) \qquad (11)$$

To achieve these three balancing conditions, the circulating current can be used. When the circulating current consists of the DC, the positive sequence and the negative sequence components, the circulating current of each leg can be expressed as (12):

$$i_{xo} = i_{xoDC} + I_{oP}\sin(\omega t + \theta_x + \rho_P) + I_{oN}\sin(-\omega t + \theta_x + \rho_N) \qquad (12)$$

Then, the steady state power of the upper and low arms by the circulating current can be expressed as (13).

$$\begin{aligned} P_{xuCir} &= \frac{1}{2}V_{DC}^{*}i_{xoDC} - \frac{1}{2}V_{AC}I_{oP}\cos(\rho_P) + \frac{1}{2}V_{AC}I_{oN}\cos(2\theta_x + \rho_N) \\ P_{xlCir} &= \frac{1}{2}V_{DC}^{*}i_{xoDC} + \frac{1}{2}V_{AC}I_{oP}\cos(\rho_P) - \frac{1}{2}V_{AC}I_{oN}\cos(2\theta_x + \rho_N) \end{aligned} \tag{13}$$

From the steady state power, the positive sequence component of the circulating current can be used for set energy balancing control. The total power of upper set arms and that of lower set arms can be written as (14). By adjusting the magnitude of the positive sequence component of the circulating current, I_{oP}, the upper set energy and the lower set energy can be balanced.

$$\begin{aligned} P_{uCirP} &= -\frac{3}{2}V_{AC}I_{oP}\cos(\rho_P) \\ P_{lCirP} &= \frac{3}{2}V_{AC}I_{oP}\cos(\rho_P) \end{aligned} \tag{14}$$

And, the negative sequence component can control the energy difference between the upper arm and the low arm of each leg to achieve arm energy difference balancing condition. The power difference between upper arm and lower arm of each leg can be written as (15). By controlling the magnitude of the negative component of the circulating current, I_{oN}, and phase angle, ρ_N, the energy difference between upper arm and lower arm of three legs can be balanced.

$$P_{xuCirN} - P_{xlCirN} = V_{AC}I_{oN}\cos(2\theta_x + \rho_N) \tag{15}$$

The DC component of the circulating current can balance the energy of three legs to satisfy the leg energy balancing condition. The sum of DC component of the circulating current is zero. However, the difference between three legs' DC component of the circulating current can generate different power between three legs.

$$i_{uoDC} + i_{voDC} + i_{woDC} = 0 \tag{16}$$

$$P_{xCirDC} = V_{DC}^{*}i_{xoDC} \tag{17}$$

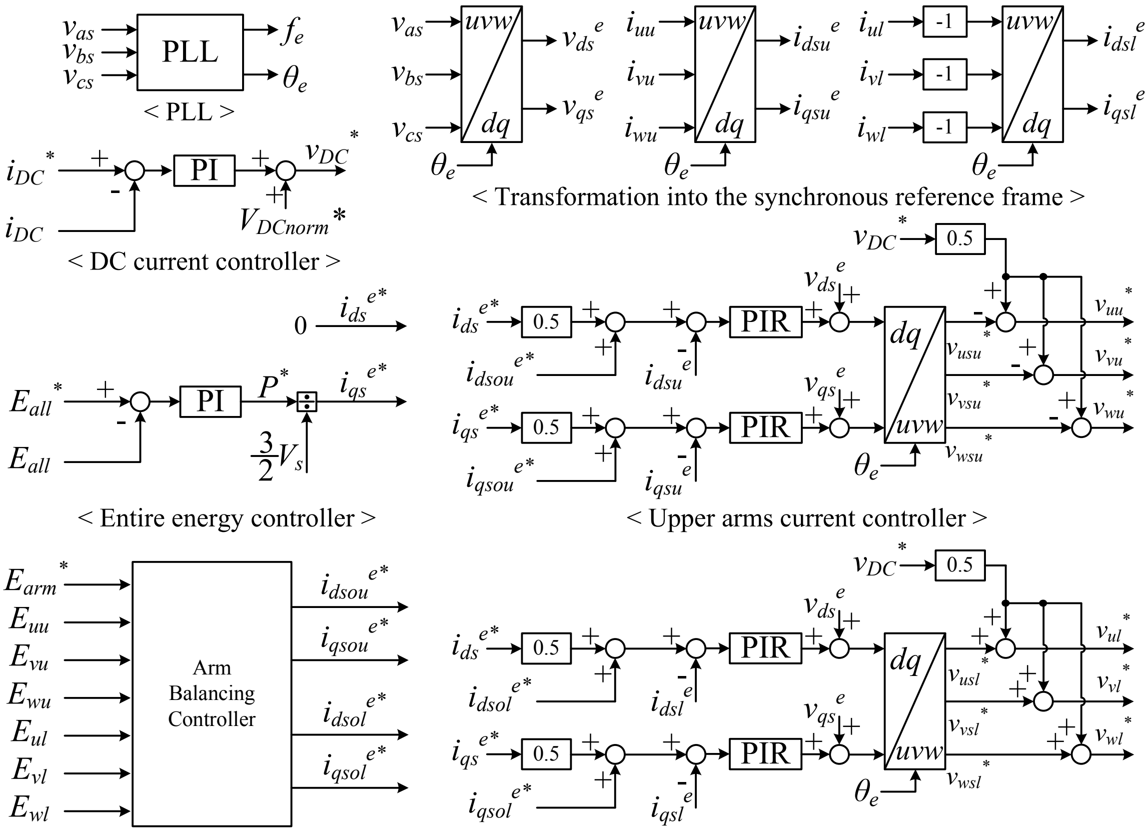
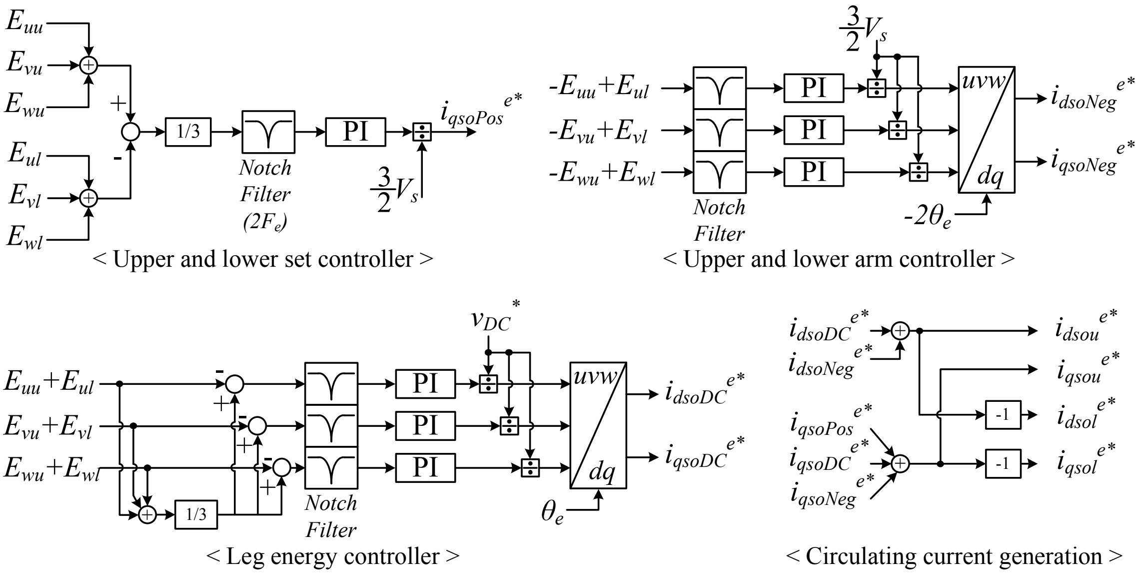


Fig. 7: Control structure of MMC-FB.

In Fig. 7, the entire control blocks are depicted. If the DC current of the MMC-FB is given, the DC current controller in Fig. 7 determines the DC voltage reference of the MMC-FB. Since the aim of the DCTC is the power flow control in DC line, the MMC-FB should regulate the DC current with the DC current controller. In order to maintain the entire capacitor energy of the MMC-FB, the AC active power needs to be controlled by the entire energy controller. The arm balance can be achieved by the arm balancing controller which is depicted in Fig. 8. The AC current reference and the circulating current references from the arm balancing controller are summed and used as upper and lower set current references. In order to control the three phase current of upper and lower sets, Proportional-Integral-Resonant (PIR) controllers are used because the DC and the negative sequence components of the circulating current are shown as AC quantities whose frequencies are the fundamental and twice fundamental frequency of AC grid in the synchronous reference frame, respectively.



< Upper and lower set controller >

< Upper and lower arm controller >

< Leg energy controller >

< Circulating current generation >

Fig. 8: Arm balancing controller.

In all operating condition, the magnitude and frequency of AC voltage would be constant. However, the DC voltage of MMC-FB is varying from negative rated voltage to positive rated voltage according to the requirement of transmission line power control. When the DC voltage is small or zero, the leg energy balancing condition could not be achieved by the DC component of the circulating current. Therefore, the zero sequence voltage can be used for the leg energy balancing condition. The zero sequence voltage for that purpose can be written as (18).

$$\begin{aligned} v_{ouZ}^* &= V_{oZAC}^* \sin(\omega t + \gamma) \\ v_{olZ}^* &= -V_{oZAC}^* \sin(\omega t + \gamma) \end{aligned} \tag{18}$$

Then, the steady state power of the upper and low arms by the zero sequence voltage can be expressed as (19).

$$\begin{aligned} P_{xCirVDC} &= -\frac{1}{2} V_{oZAC}^* I_{AC} \cos(\theta_x + \varphi - \gamma) \\ P_{xlCirVDC} &= -\frac{1}{4} V_{oZAC}^* I_{AC} \cos(\theta_x + \varphi - \gamma) \end{aligned} \tag{19}$$

This steady state power can be used for balancing energy of three legs instead of the power generated by the DC component of the circulating current in (17).

IV. Simulation Results

To verify the feasibility of the proposed DCTC and the control performance of the MMC-FB, four levels MMC-FB is simulated by Matlab/Simulink and PLECS and the system configuration is shown in Fig. 9. The specification of the system and MMC-FB is listed in Table I.

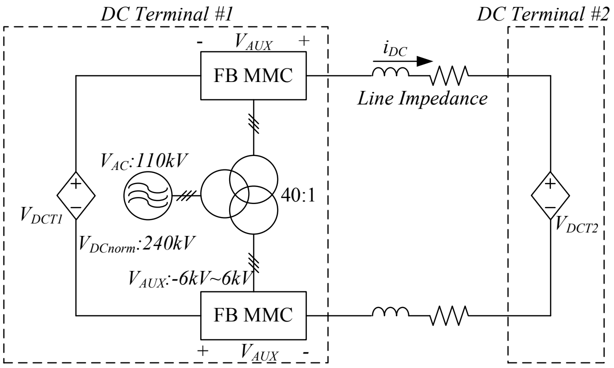


Fig. 9: Simulation configuration.

DC System	DC link voltage	240kV
	Rated DC current	1kA
	Line impedance	6Ω
MMC-FB	Module Number	3
	Module Cap. Voltage	2kV
	Rated DC current	1kA
	Auxiliary voltage, V_{AUX}	-6~6kV
	Transformer Turn Ratio	40:1
	Arm inductance	2mH

Table I: Specification of the simulation system.

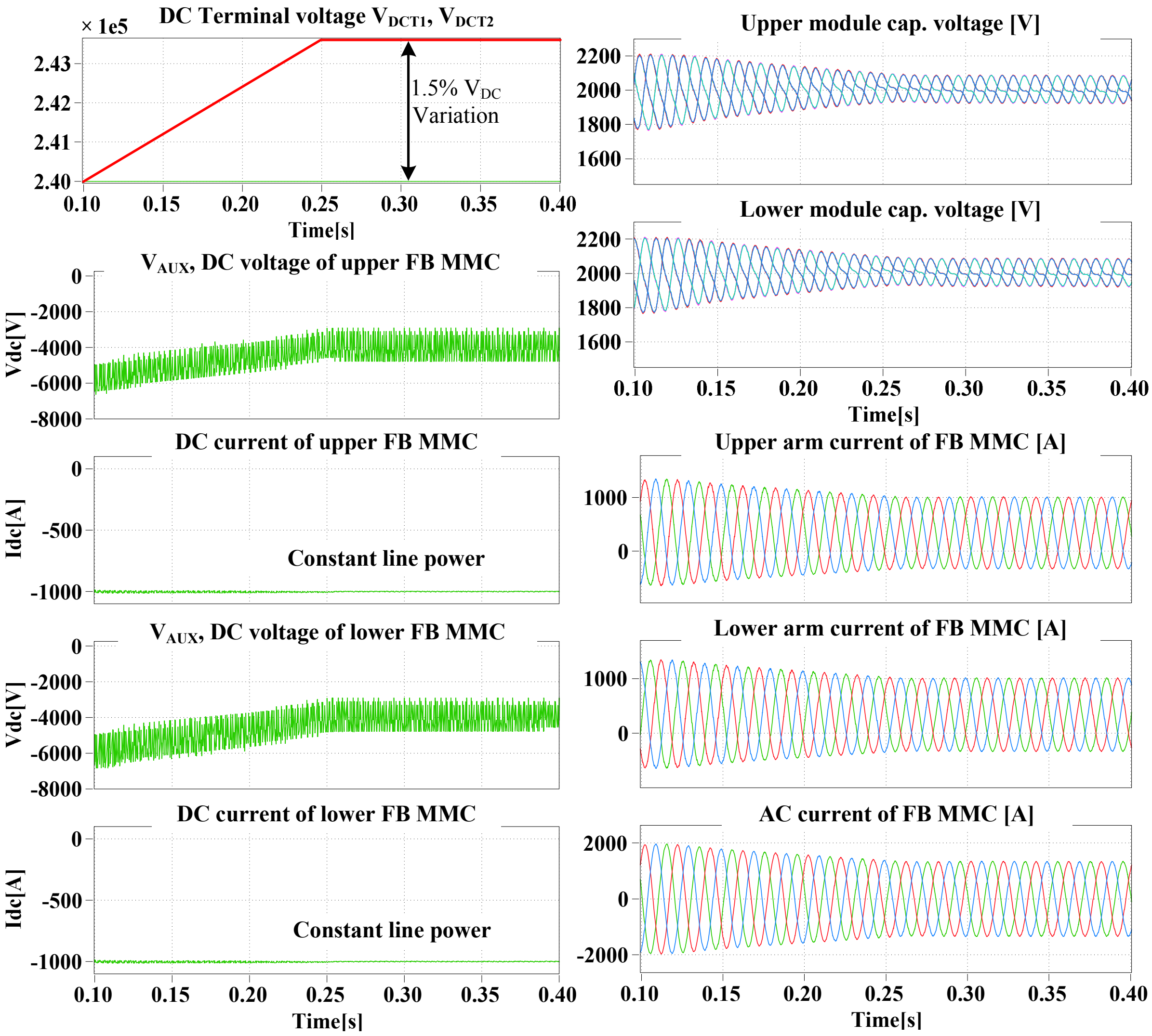


Fig. 10: Constant power control when terminal #2 DC voltage is varying.

The DCTC based on MMC-FB was installed in the DC terminal #1. The DC terminal #1 and #2 were connected through the MMC-FB and transmission line as shown in Fig. 9. The aim of the DCTC is to control the power flowing through the specific DC line even though the two terminal DC voltages of the DC line vary. When V_{DCT1} is constant as the rated value and V_{DCT2} is varying by 1.5%, the DCTC maintains the constant power by regulating V_{AUX} which is the DC voltage of MMC-FB. Therefore, the auxiliary voltage of the MMC-FB, V_{AUX} varies from -6kV to -4kV as shown in Fig. 10. The DC current between DC terminal #1 and #2 was controlled as 1kA. The capacitor voltage of each module of upper set and low set of MMC-FB are maintained as 2kV. Since the DC voltage of MMC-FB was reduced, the power flowing through the MMC-FB also decreased. Therefore the magnitude of AC current and the capacitor voltage variation of the MMC-FB were also reduced.

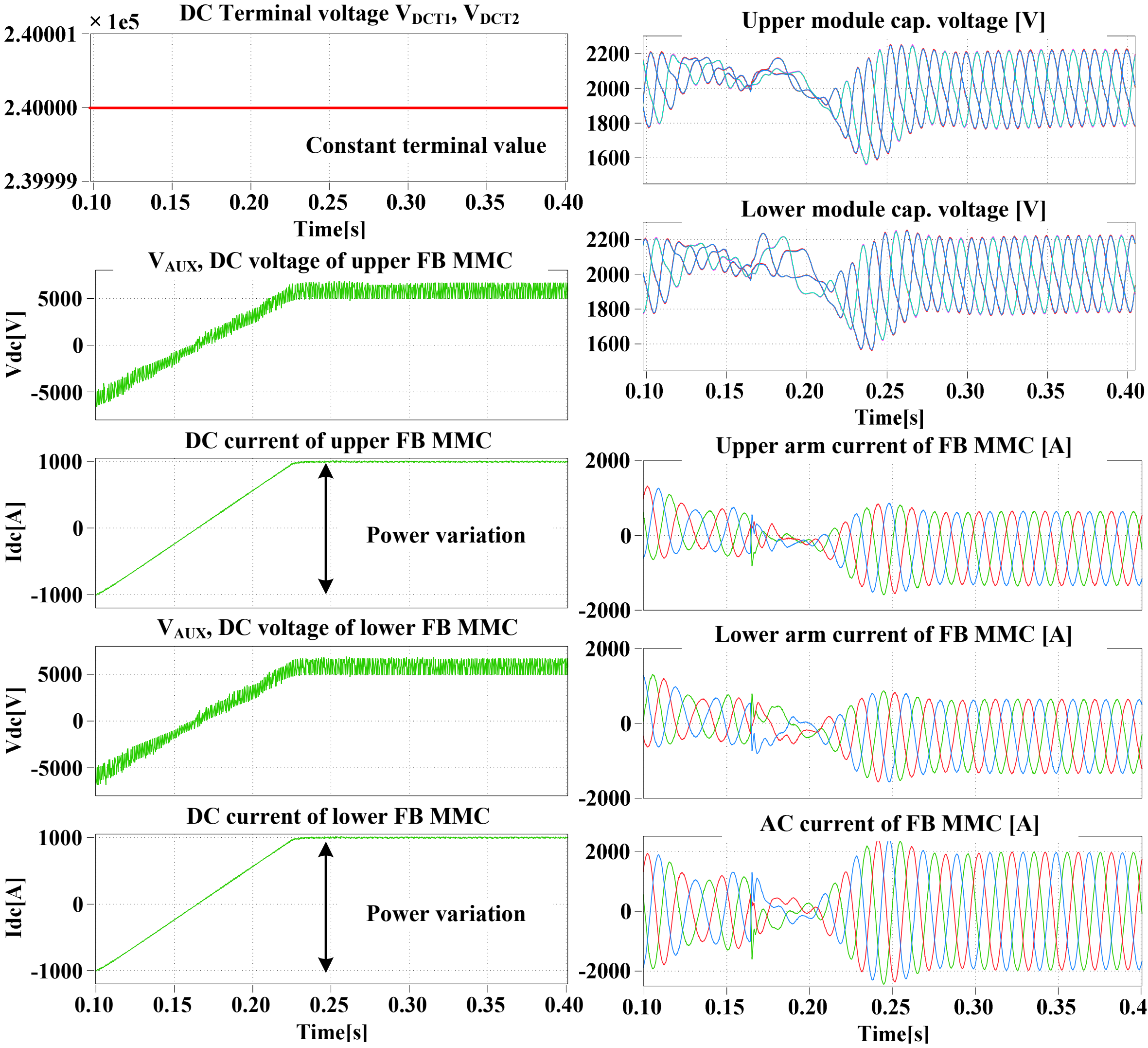
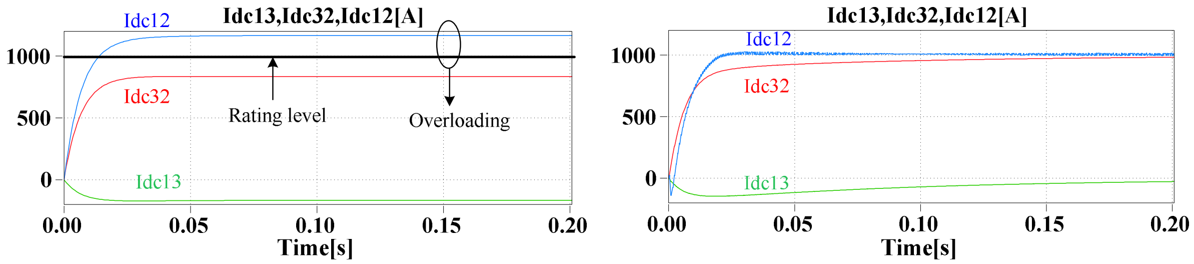


Fig. 11: Power control from negative to positive rated value.

The MMC-FB can not only maintain the constant power as the desire value with varying the terminal voltage, but also regulate the variable power with the constant terminal DC voltages. Fig. 11 shows the performance of variable power control with constant terminal DC voltages. When the voltage of DC terminal #1 and #2 is constant as 240kV, the DC current reference varied from -1kA to 1kA. Then, the DC voltage of the MMC-FB was controlled from -6kV to 6kV and the DC current was controlled as the current reference. The voltage variation of module capacitor of the MMC-FB varied according to the DC power flowing through the MMC-FB. Even though the power of the MMC-FB and the DC voltage of the MMC-FB were varying, the average voltage of module capacitor was controlled as their rated DC voltage, 2kV.

The DCTC can solve the overloading problem in the mesh configured MTDC HVDC transmission system. Fig. 12 shows the DC current in the lines of the mesh configured MTDC system in Fig. 2(c) and 2(d), respectively. Without DCTC, the current between the terminal 1 and 2, *Idc12* is overloaded even though the ampacity of DC line between terminal 2 and 3, *Idc23* are still available as shown in Fig. 12(a). While with MMC-FB, in Fig. 12(b) the current between the terminal 1 and 2 is controlled as the maximum value and the current between the terminal 2 and 3 increases.



(a) DC line current without DCTC (b) DC line current with DCTC

Fig. 12: DC line current control with DCTC

IV. Conclusion

This paper has proposed a MMC-FB as the DCTC. This converter makes all the DC line currents in mesh configured MTDC grid independently controllable. To operate the MMC-FB as the DCTC, a control algorithm has also been presented based on the proposed equivalent circuit. The control algorithm for MMC-FB has been derived and verified through computer simulation. Especially, the capacitor voltage balancing in all full bridge modules is successfully achieved in the variable DC terminal voltage operation. Also, thanks to MMC-FB working as DCTC, the ampacity of DC cables between DC terminals can be maximally exploited.

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