Control of Hybrid HVDC Transmission System with LCC and FB-MMC

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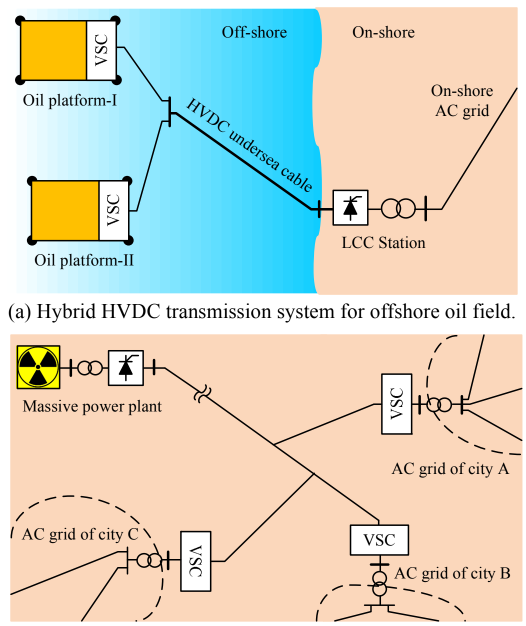
***Abstract*—Nowadays, a Line Commutated Converter (LCC)-HVDC is a mature technology with decades industry experience. Even though it's with several advantages such as higher reliability, lower cost, and higher efficiency, it presents some drawbacks such as large converter station size and lack of black starting capability. So the LCC-HVDC is not suitable for some applications in which black starting capability is necessary or high power density is highly emphasized. A LCC-Voltage Source Converter(VSC) hybrid HVDC transmission system combines the advantages of both technologies. In this paper, a comprehensive control strategy of a LCC and Full Bridge Modular Multi-level Converter(FB-MMC) hybrid HVDC transmission system, including converter control schemes, power flow control strategy, black starting strategy, and DC short circuit fault ride through strategy is proposed. Also, DC short circuit fault characteristics depending on AC grid types of the FB-MMC are analyzed and appropriate ride through strategies for each case are established. Validity of the proposed control strategies are verified by computer simulation and tested at reduced scale prototype set-up.**

I. INTRODUCTION

For last several decades, thyristor based Line Commutated Converter(LCC) topology has been used for High Voltage DC(HVDC) transmission. The LCC topology for HVDC transmission is a mature technology and well developed but it has some shortcomings such as no black starting capability, huge AC side filter and Static Var Generator to suppress harmonics and compensate reactive power, and incompatibility to the weak grid [1]. While, recently developed IGBT based Voltage Source Converter (VSC) topologies can cover the above drawbacks of the LCC topology at the cost of higher operating losses [2-3]. Among VSC topologies, Modular Multi-level Converter (MMC) has many advantages over two level VSC topology [4-5]. Series connection of power devices can be circumvented in the MMC topology, and the power rating of the MMC can be easily expanded by simply adding more modules because of its modularity. Two types of module can be used in the MMC, which are, namely, a half-bridge chopper module, and a full-bridge inverter module [6]. The half - bridge module has been used widely to reduce the



(a) Hybrid HVDC transmission system for offshore oil field.

(b) Hybrid HVDC transmission system for urban agglomeration.

Figure 1. Applications of the LCC-VSC hybrid HVDC system.

number of switching devices in a module and conduction loss. While, the output voltage of half-bridge module is confined to two levels, namely, null and DC link voltage of each module. While, that of Full-Bridge(FB) module includes negative of DC link voltage, and the FB module can synthesize AC output voltage even in the case that DC transmission voltage drops down to null due to DC short circuit faults and etc.

In some application, massive electricity may be transmitted from a strong AC grid, which consists of several large power plants to several distributed power loads [7-8]. In this case, the compactness and black starting capability in transmitting side may be not a crucial concern because of inherent power plants and site of HVDC converter. And, LCC type HVDC converter would be the best option to the transmitting side because of its technical maturity and higher operating efficiency. But in the receiving side,

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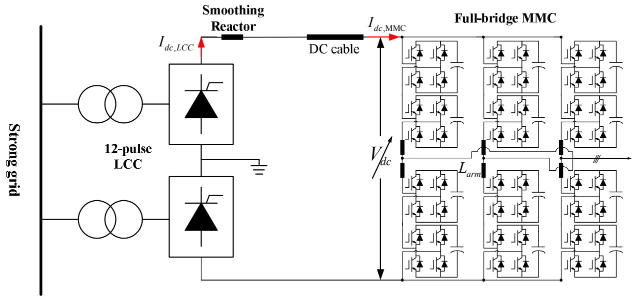


Figure 2. Conventional hybrid HVDC transmission system with LCC and FB-MMC.

compact structure and black starting capability cannot be traded if the distributed passive loads are in the city centers or off-shore platforms. In such an application, a hybrid HVDC structure which contains a high power LCC-HVDC converter in source side and several medium power VSC-HVDC converters in distributed load sides would be a promising solution as shown in Fig. 1.

For this reason, there have been several researches to accommodate LCC and VSC simultaneously in a HVDC transmission system [1, 8]. A conventional proposal consists of a LCC and a two-level VSC [9-10]. To support loads with AC grid, in this system, DC bus voltage of the VSC should be maintained at the rated value, and the power flow should be controlled by regulating transmission line current. This structure has some disadvantages such as series operation of power semiconductors, instability of commutation in the light load condition, and no short circuit fault ride through capability. In [11], a PWM Current Source Converter (CSC) was proposed to replace the VSC in the receiving side. The CSC converter is able to start without any source (black starting) and to supply power to receiving side AC grid, and to ride through a DC line short circuit fault for its current sourced nature. However, it still calls for series operation of IGBTs and diodes, and it leads to considerable switching and conduction losses.

In recent years, a hybrid HVDC transmission system with LCC and MMC has become the most compatible candidate. Since this configuration would combine the merits of the LCC as a single end in a large site and MMCs as distributed ends which have a compact structure, MMC could be installed in the distributed wind farms or offshore oil platforms, forming a multi-terminal system. Since the Half-Bridge MMC(HB-MMC) could not ride through the DC short circuit fault without introducing AC or DC breakers, several combinations with a DC short circuit fault ride through capability are proposed [7, 12]. In case of a LCC-diode-MMC which has high power diodes in the overhead lines to block the DC short circuit fault current paths, it's turned out that it performs excellent transient stability characteristics during DC short circuit faults [13]. However, it has to accept continuous diode conduction losses, and MMCs have no choice but to shut down at the fault of the LCC because MMCs could not operate as a

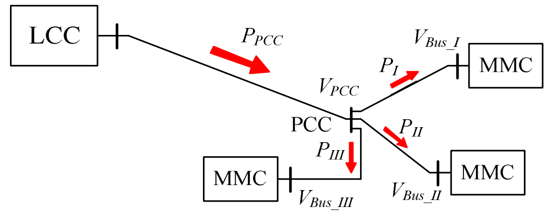


Figure 3. Conceptual diagram of a multi-terminal structure with LCC and MMCs.

rectifier mode. Meanwhile, in the configuration including Full-Bridge MMC (FB-MMC) proposed in [12] as shown in Fig. 2, however, discussions about DC short circuit fault ride through strategies or start-up schemes had been excluded though it was confirmed that the power reversal was possible.

Therefore, in this paper, a comprehensive control strategy of a LCC-FB-MMC hybrid HVDC transmission system, including converter control schemes, power flow control strategy, black starting strategy, and DC short circuit fault ride through strategy is proposed and discussed. Also, DC short circuit fault characteristics depending on AC grid types of the FB-MMC are analyzed and appropriate ride through strategies for each case are established. By using the proposed control strategy, AC side, DC side, and MMC capacitor voltage regulation can be fully decoupled. Then from AC side, the converter presents VSC characteristics, and from DC side, the converter presents CSC characteristics. Because of the CSC nature, this system is able to ride through a DC short circuit fault.

II. Control Strategy of Hybrid System

The most important assumption in the conventional hybrid HVDC transmission system was that there was a constant voltage DC-link. Thus, transferred power was determined by transmission line current which was induced by AC current regulation. In this paper, conventional assumption that there is the constant DC-link is avoided by applying the FB-MMC. Therefore, the AC grid voltage at the receiving side can be synthesized even when DC bus voltage is null. In this constitution, FB-MMC is operated in such a way that current source converter does in DC side, and regulation of DC bus voltage is carried out with very high bandwidth up to a few fraction of the sampling frequency of the FB-MMC controller. On the basis of the system with LCC and FB-MMC, initial capacitor charging and module capacitor boosting method for the black starting as well as power flow control schemes are proposed. Supplied power by the LCC can be controlled by regulating voltage of DC grid Point of Common Coupling (PCC) since the LCC operates in constant current mode. Therefore, the power flow distribution among different FB-MMC stations in Fig. 3 can be controlled by controlling differences among FB-MMC DC bus voltages. As the first approach, only a point-to-point transmission system is analyzed in this paper.

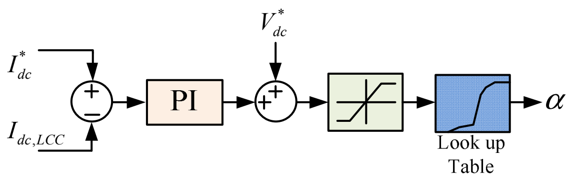


Figure 4. Block diagram of the LCC controller.

A. Control Scheme of LCC Rectifier

In a conventional hybrid HVDC transmission system, firing angle of the LCC was determined by the output of the rectified DC-link voltage regulator, whose reference was given by the rated voltage of the system. In the hybrid system including the FB-MMC, however, firing angle is determined by the output of the transmission line current regulator since the LCC operates in constant current mode. Namely, the transmission line current is regulated constant according to the power reference. In this case, transmitted power is determined by controlling the DC bus voltage of the FB-MMC not by the DC line current. Additionally, introduction of feed-forwarding term into the controller as shown in the Fig. 4 can improve the dynamic performance if the communication between stations is possible.

B. Control Scheme of FB-MMC

In this paper, by applying the MMC modeling proposed in [14] as shown in Fig. 5, leg current i_{xo} and AC current i_{xs} in the x-phase are defined such as (1) and (2), respectively.

$$i_{xo} = \frac{i_{xu} + i_{xl}}{2}. \quad (1)$$

$$i_{xs} = \frac{i_{xu} - i_{xl}}{2}. \quad (2)$$

In addition, if the output voltage and the leg internal voltage in the x-phase are defined as (3) and (4),

$$v_{xs} = -\frac{v_{xu} - v_{xl}}{2}, \quad (3)$$

$$v_{xo} = \frac{V_{dc} - (v_{xu} + v_{xl})}{2}, \quad (4)$$

upper and lower arm output voltage should be synthesized as (5), respectively, to generate desired v_{xs}* and v_{xo}* .

$$\begin{cases} v_{xu}^* = \dfrac{V_{dc}^*}{2} - v_{xs}^* - v_{xo}^* \\ v_{xl}^* = \dfrac{V_{dc}^*}{2} + v_{xs}^* - v_{xo}^* \end{cases}. \quad (5)$$

In this paper, a circulating current is defined as (6).

$$i_{xo,cir} = i_{xo} - \frac{i_{dc}}{3}. \quad (6)$$

Then, in accordance with Kirchhoff's law from Fig. 5, (7), (8), and (9) can be deduced.

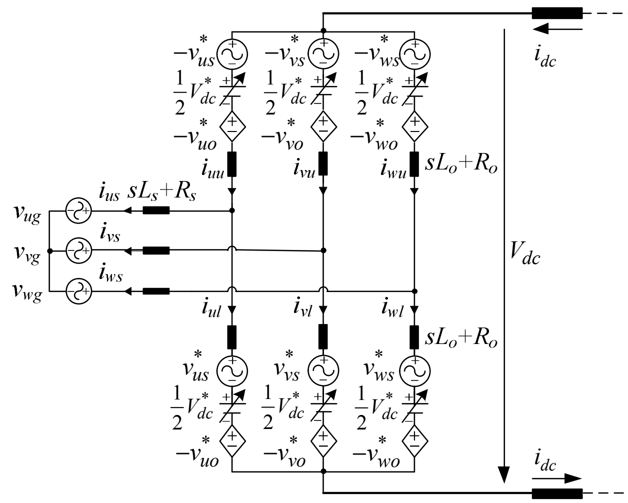


Figure 5. MMC modeling for HVDC application.

$$\begin{aligned} & v_{xs}^* - \frac{1}{2}\left(L_o\frac{d}{dt} + R_o\right)i_{xs} - \left(L_s\frac{d}{dt} + R_s\right)i_{xs} - v_{xg} \\ & -\left\{v_{ys}^* - \frac{1}{2}\left(L_o\frac{d}{dt} + R_o\right)i_{ys} - \left(L_s\frac{d}{dt} + R_s\right)i_{ys} - v_{yg}\right\} = 0 \end{aligned}. \quad (7)$$

$$V_{dc} = V_{dc}^* + 2(R_o + L_o\frac{d}{dt})(\frac{i_{dc}}{3}) - \frac{2}{3}(v_{uo}^* + v_{vo}^* + v_{wo}^*). \quad (8)$$

$$2(L_o\frac{d}{dt} + R_o)i_{xo,cir} = 2(v_{xo}^* - \frac{v_{uo}^* + v_{vo}^* + v_{wo}^*}{3}). \quad (9)$$

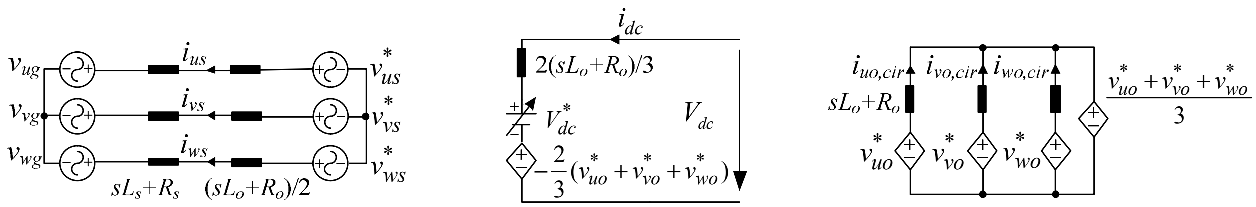
It means that the MMC model in the Fig. 5 can be represented as 3-separated models as shown in Fig. 6 for AC current, DC current, and circulating current. From this modeling, it's noticed that if the common mode voltage $v_{o,com}^*$, defined as (10) is regulated into 0, then control of AC current, DC current, and circulating current can be fully decoupled.

$$v_{o,com}^* = \frac{v_{uo}^* + v_{vo}^* + v_{wo}^*}{3}. \quad (10)$$

Module capacitor voltages of six arms can be balanced by only injecting circulating current inside the converter without affecting AC or DC side. Contrast to the conventional hybrid HVDC transmission system, V_{dc}* can be updated in every sampling period to regulate charged energy in whole capacitors of the FB-MMC and control the power flow. More details of the converter control strategy are described in [14]. Thus, the hybrid HVDC transmission system with LCC and FB-MMC can enhance dynamic performance conspicuously and simplifies the power flow control.

C. Control of Power Flow

When the constant current flows into the FB-MMC, V_{dc} should be adjusted properly to deliver the power to the loads and control the entire capacitor energy stored in the FB-MMC, E_{cap}^{Σ}. From the power relation between three terms: DC power flowing into the FB-MMC, consumed power in



(a) Simplified equivalent model of AC grid current. (b) Simplified equivalent model of DC bus current. (c) Simplified equivalent model of circulating current.

Figure 6. Extracted models from the conventional MMC model to analyze AC grid current, DC bus current, and circulating current.

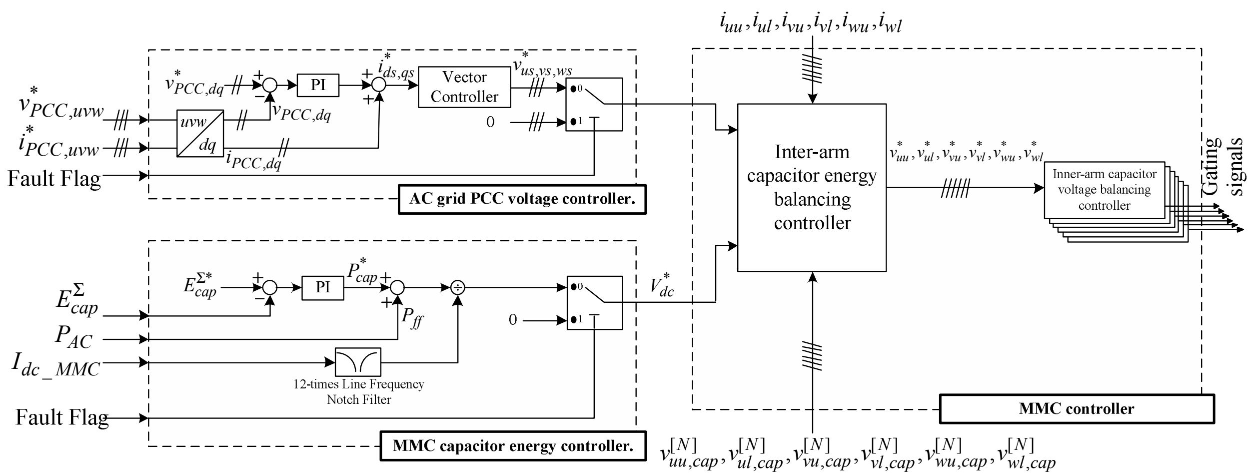


Figure 7. Conceptual block diagram of the receiving side MMC controller: Passive AC grid case.

the FB-MMC, and power delivered to the loads, V_{dc}^* can be described as (11).

$$V_{dc}^* = \frac{1}{I_{dc}}\left(P_{cap}^* + P_{load}\right). \quad (11)$$

If P_{cap}* is defined as the output of the total capacitor energy controller of the FB-MMC, reference of DC bus voltage is generated as shown in Fig. 7. When a DC short circuit fault occurs, since receiving active power from DC bus is impossible, particular actions to suppress inrush current and balance the converter energy should be taken. Details are in section III.

III. Black Starting and DC Short Circuit Fault Ride Through Strategy

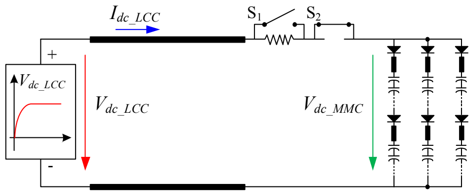
Power semiconductors in the FB-MMC could not operate unless the capacitor of each module is charged till a proper voltage level since the gate drivers is fed by module capacitors. Therefore, in case of feeding passive loads, black starting scheme must be applied to the systems. On the other hand, when the DC short circuit fault occurs, it should be noticed that entire capacitor energy of the MMC can be regulated through only AC side. In this section, black starting method and DC short circuit fault ride through strategy of hybrid HVDC system is proposed.

A. Black starting procedures

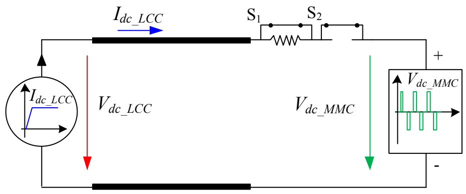
- During Period I of the proposed black starting strategy, module capacitors have to be charged by transmission line current. As shown in Fig. 8(a), after switch S2 is turned on, the LCC starts to boost DC transmission line voltage and the module capacitors would be charged till about half of its rated voltage. From the moment, modules in the FB-MMC are able to switch and the converter is controllable.
- During Period II as shown in Fig. 8(b), FB-MMC modules start to operate and synthesize its DC bus voltage as null. Switch S1 is turned on to bypass the pre-charging resistor, and transmission line current regulator of the LCC is activated and it regulates the DC current from zero to rated current smoothly.
- During Period III, FB-MMC capacitor energy controller is activated and the DC bus voltage varies to boost up module capacitor voltage to its rated voltage.
- In Period IV, as the module capacitor voltage is at rated voltage, mechanical switches between AC side of the FB-MMC and the supplied AC grid is turned on and the FB-MMC starts to synthesize AC voltage to support the passive AC grid.

B. DC transmission line short circuit fault ride through

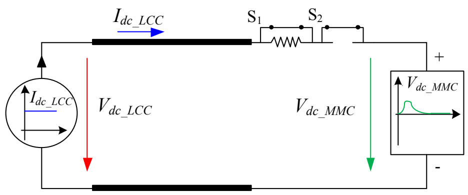
In this paper, a non-permanent DC short circuit fault is managed for each converter: LCC and FB-MMC. Ride through strategies depending on AC grid types of the FB-MMC are in the following.



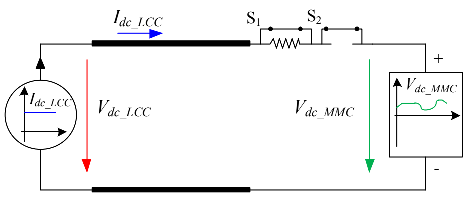
(a) Period I of the proposed black starting strategy.



(b) Period II of the proposed black starting strategy.



(c) Period III of the proposed black starting strategy.



(d) Period VI of the proposed black starting strategy.

Figure 8. Proposed black starting procedures.

1) LCC: As DC line current at the LCC side increases rapidly, LCC should synthesize the reverse DC-bus voltage to suppress the fault currents when the DC short circuit fault occurs. To prevent the overcurrent without any shut down of systems, reference current is changed into null immediately when the DC short circuit fault is detected. As a result, firing angle, alpha, which is larger than 90° is generated and DC line current decreases to null. Therefore, it is possible that DC line current is actively regulated to null without shut down of the LCC. After the fault is cleared, DC line current reference is increased to rated value and systems should restart from the Period III stage of black starting procedures.

2) FB-MMC(supplying power to the passive AC grid): If the FB-MMC drives passive loads when the DC short circuit fault, normal energy exchange through the DC or AC side is impossible. In this case, capacitor energy of the FB-MMC could not be regulated to its rated value, and control schemes of DC bus voltage and AC side are as follows.

a) DC bus voltage: The FB-MMC should synthesize DC bus voltage to null instantaneously. If DC voltage is varied to regulate the fault current as null, it can cause a unstability since the variation of capacitor energy could not be controlled.

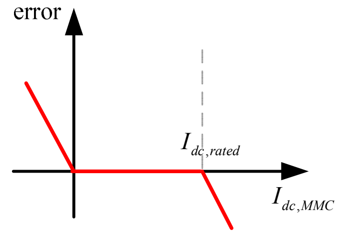


Figure 9. Control scheme for the DC bus voltage of the FB-MMC during the DC short circuit fault.

b) AC side output: If the passive AC grid is supplied when the DC short circuit fault occurs, the FB-MMC should synthesize AC side output voltage as null since the electricity could not be transmitted to the FB-MMC station during the fault period.

3) FB-MMC(connected with active AC grid): When the AC output of the FB-MMC is connected with active AC grid, capacitor energy could be regulated via drawing active power from AC grid. Thus, it's possible to cope more actively with the DC short circuit fault than the case of the passive AC grid.

a) DC bus voltage: DC bus voltage controller switches its mode to DC line current regulator when the DC short circuit fault occurs. Its regulation range is shown in Fig. 9. Namely, the controller has dead band, and receives its input, error, only when the DC line current is out of the normal operating ranges.

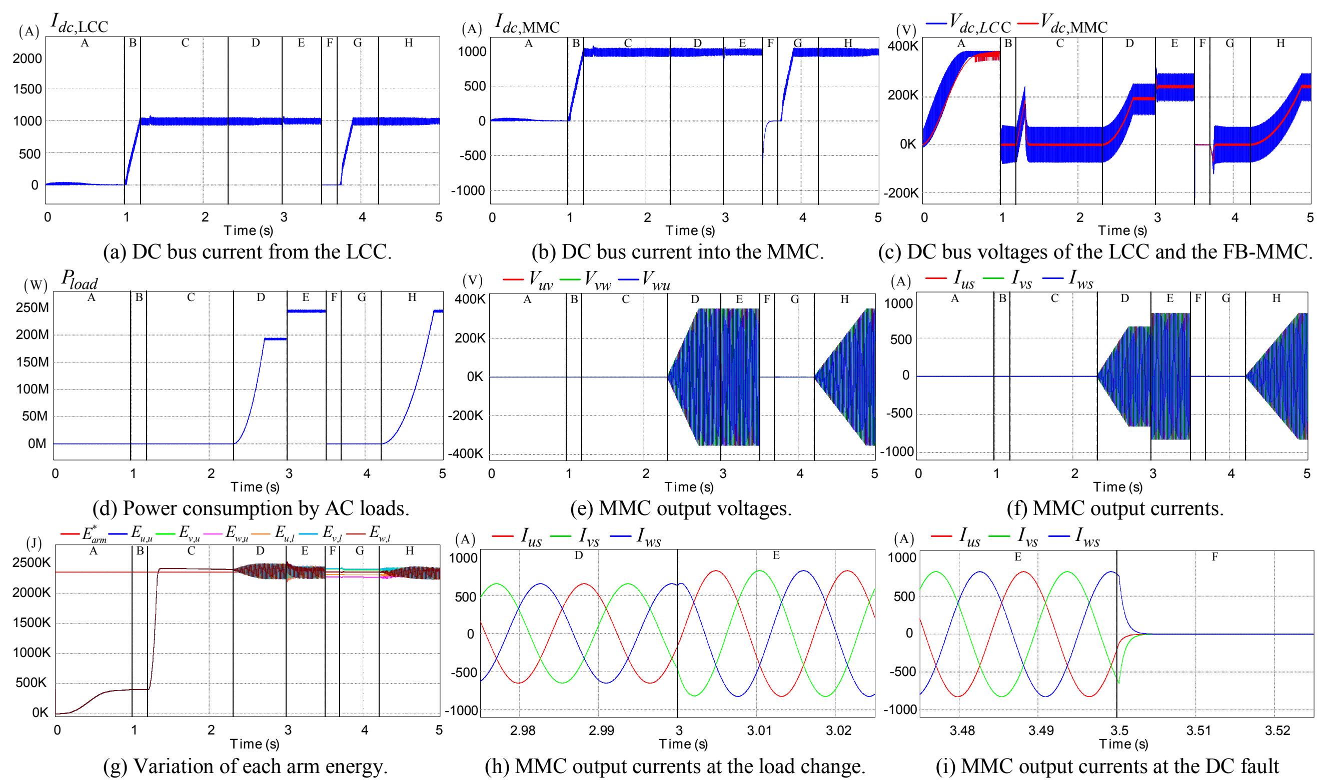
b) AC side output: In the case of the DC short circuit fault, q-axis current(namely the active current)reference would be determined by the internal capacitor energy controller such as (12).

$$i_{qs}^{e\,*} = \frac{-2}{3\cdot\left|v_{xs}\right|}\left(P_{cap}^{*} + V_{dc}^{*}\cdot I_{dc,MMC}\right). \tag{12}$$

Because of the energy through the q-axis current, smooth power flow caused by DC bus voltage variation and internal energy regulation could be achieved. Additionally, since the d-axis current could be varied independently even in the fault, the FB-MMC could supply AC grid with reactive power as a STACOM.

IV. VERIFICATION OF PROPOSED METHOD

A full-scale version of hybrid HVDC transmission system with LCC and FB-MMC with 217 levels is simulated by PSIM® to verify the proposed strategies. In addition, as a laboratory test setup, a seven level Full-Bridge MMC prototype has been constructed and it is tested under the proposed strategies.



(a) DC bus current from the LCC. (b) DC bus current into the MMC. (c) DC bus voltages of the LCC and the FB-MMC.
(d) Power consumption by AC loads. (e) MMC output voltages. (f) MMC output currents.
(g) Variation of each arm energy. (h) MMC output currents at the load change. (i) MMC output currents at the DC fault

Figure 10. Waveforms of the computer simulation.

A. Computer Simulation

The parameters for the computer simulation are given in Table I. The DC transmission line is modeled as an inductor.

Scenario of the simulation is as follows. During t=0~1.5s (sector A in Fig. 10), the LCC increases DC bus voltage from zero to the rated value and the FB-MMC is charged by the LCC through a pre-charging resistor. From t=1.5s to t=1.7s (sector B), the FB-MMC operates and its DC bus voltage is synthesized as null. The transmission line current regulator of the LCC is activated and the DC current is increased to its rated value. From t=1.7s to t=2.3s (sector C), the FB-MMC capacitor energy controller is activated and the module capacitor voltage is boosted up to its rated value. At t=2.3s, after the AC-breaker is closed (sector D), a passive load which is modeled as an R-L load is connected and AC side output voltage of the FB-MMC increases linearly to the rated voltage. When t=3s (sector E), an additional 60 MVA load is connected. A DC short circuit fault occurs on one point in transmission line at t=3.5s (sector F). As soon as the DC short circuit fault is detected, the proposed schemes are activated to nullify DC bus voltage and AC side output voltage and current. After the non-permanent short circuit fault is cleared, the transmission systems return to normal operating mode (sector G) and the transmitted power to the passive load is increased again at t=4.2s (sector H). Whole simulation results are shown in Fig. 10(a)-(i).

As shown in Fig. 10(a)-(c), initial charging and boosting

TABLE I. SIMULATION PARAMETERS

Quantity	Values
Grid line-to-line voltage (LCC side)	144 kV
Leakage Inductance of transformers (LCC)	13.8 mH (0.15p.u)
Inductance of Smoothing Reactor (LCC)	150 mH
Transmission line inductance	20mH
Number of full-bridge modules per Arm	216
Rated DC bus voltage	±200 kV
Rated DC bus current	1000 A
Rated module capacitor voltage	2.2 kV
Capacitance of module capacitor	4.5 mF
Inductance of arm inductor	15.0 mH
Resistance of arm inductor	367.0 mΩ
Sampling frequency (MMC)	10.0 kHz
Rated MMC output voltage	180.5 kV
Rated power of load impedance 1(MMC side)	200 MVA, 0.8 lagging p.f
Rated power of load impedance 2(MMC side)	60 MVA, 0.8 lagging p.f
MMC load impedance 1	303.2 + j75.9 Ω
MMC load impedance 2	1136.8+284.6 Ω

of the FB-MMC capacitor are completed without any overcurrent. In normal operation, Fig. 10(a) and Fig. 10(b) show that DC line current is regulated as constant, and Fig. 10(c) shows that the power flow between LCC and FB-MMC is controlled by adjusting V_{dc} as variation of P_{load} shown in Fig. 10(d) or MMC capacitor energy as shown in Fig. 10(g). Even the step load is connected at t=3s as shown in Fig. 10(d), enhanced power control dynamics doesn't cause any unstability. When a DC short circuit fault occurs at t=3.5s shown in Fig. 10(a)-(f), and (i), short circuit current is successfully suppressed to null in both sending and receiving sides without delivering the fault current to the loads. It's confirmed by Fig. 10(a), Fig. 10(b), and Fig. 10(i). From simulation all procedures including start-up and managing the DC short circuit fault as well as steady-state operation are verified.

B. *Experimental results*

The parameters for the test setup are given in Table II. In test setup which is shown in Fig. 11, LCC is emulated by a full-bridge chopper which is possible to control average DC bus voltage and DC line currents. Also, a DC short circuit fault is simulated by 5 Ohm resistor, and it is assumed that full-bridge chopper maintains the current as commanded value even in the DC short circuit fault.

1) *Case 1: Supplying Power to the Passive AC grid*

Fig. 12 shows start-up process under the proposed control method. First of all, DC bus voltage is increased to the rated value. At t_1, DC bus voltage of the emulated LCC is regulated to null. In Period II, the FB-MMC starts to synthesize the DC voltage as null, and DC line current is regulated to rated current. During Period III, DC bus voltage varies to boost up MMC capacitor energy to its rated value. In Fig. 13, AC output side of the FB-MMC begins to supply power to the passive loads. It's noticed that as the AC output voltage increases, phase current also does. In addition, along with the increase of the transmitted power to the loads, DC bus voltage of the FB-MMC increases. Fig. 14 shows the leg capacitor energy and the difference of upper and lower arm capacitor energy of u phase during the power variation. AC output voltage increases to 1.2 times of the rated value at t_2 and returns to the rated value at t_3. During the power variation it can be observed that u phase leg capacitor energy and the difference of upper and lower arm capacitor energy are kept as constant as commanded respectively. Fig. 15 shows the DC short circuit fault and fault ride through procedures of the FB-MMC. As mentioned in the previous section, DC bus voltage and AC side output voltage is nullified immediately as soon as the DC short circuit fault is detected. Also, it should be noticed that converter total capacitor energy could not be kept as its rated value because of the converter losses. Thus, continuous decline of capacitor energy is observed. At t_4, after the DC short circuit fault has been cleared, DC line current of the FB-MMC side is recovered to the rated current. Capacitor energy controller is re-activated at t_5, and DC bus voltage rises because the FB-MMC drives the passive loads since t_6.

2) *Case 2: Connected with Active AC grid*

Fig. 16 shows the case that AC output of the FB-MMC is connected to an active AC grid. Starting and boosting procedures are identical with the case of the passive load.

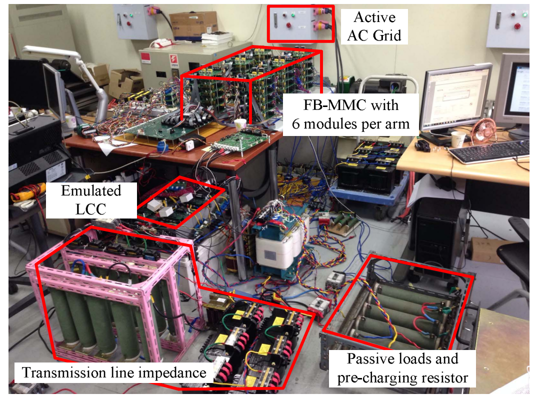


Figure 11. Experimental test set-up.

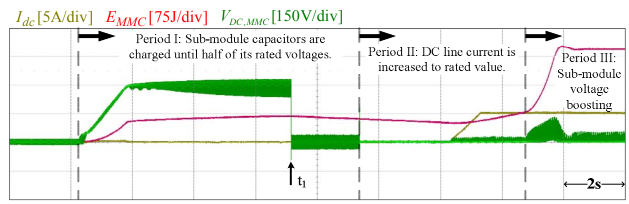


Figure 12. Start-up process applying the proposed schemes.

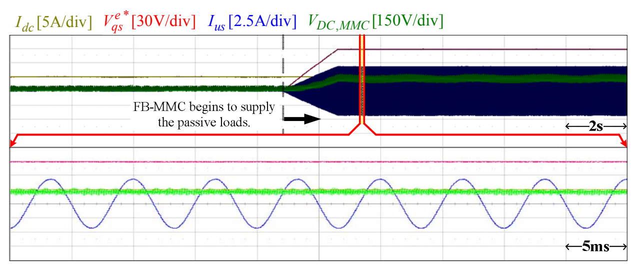


Figure 13. Variation of the DC bus voltage and current when the FB-MMC begins to supply the passive loads.

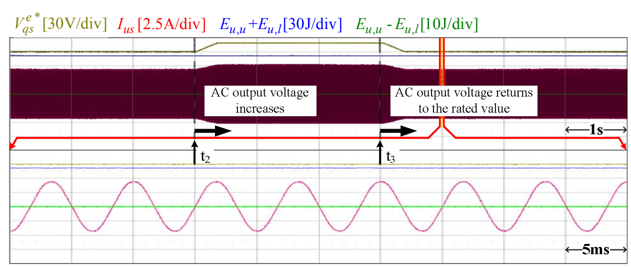


Figure 14. Leg capacitor energy and difference of upper and lower arm capacitor energy of u phase during the power variation.

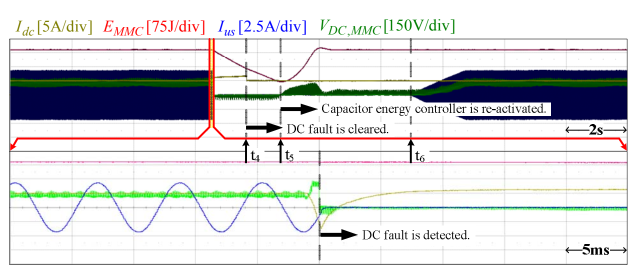


Figure 15. Fault ride through procedures of the FB-MMC during the DC short circuit fault in the passive AC grid case.

TABLE II. PROTOTYPE PRAMETERS

Quantity	Values
Transmission line inductance (LCC side)	15 mH
Transmission line inductance (MMC side)	12 mH
Transmission line resistance (LCC side)	0.5 Ω
Number of full-bridge modules per Arm	6
Rated DC bus voltage	300 V
Rated DC bus current	5 A
Rated module capacitor voltage	50 V
Capacitance of module capacitor	5.4 mF
Inductance of arm inductor	4 mH
Resistance of arm inductor	5 mΩ
Sampling frequency (MMC)	10.0 kHz
Rated MMC output voltage	110 V
Rated power of load impedance	1.8 kW
MMC load impedance	20 Ω

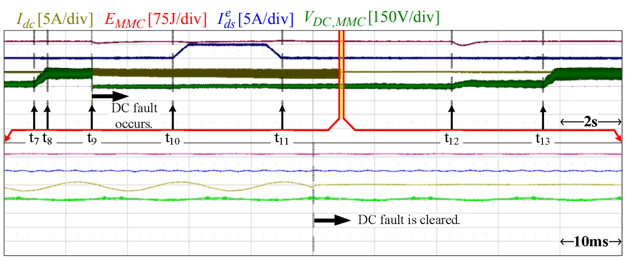


Figure 16. Fault ride through procedures of the FB-MMC during the DC short circuit fault in active AC grid case.

From t_7 to t_8, DC bus voltage is increased since q-axis current is regulated to 4A. At t_9, a DC short circuit fault occurs on the middle of the DC transmission line. As soon as the DC short circuit fault is detected, DC bus voltage of the MMC is controlled to keep the DC line current in the range of the rated value, and q-axis current is controlled to balance the capacitor energy and the power flow. Therefore, in contrast to the passive load case, entire capacitor energy could be kept as its rated value. Furthermore, it would be remarkable d-axis current could be controlled independently. From t_{10} to t_{11} d-axis current is changed from 10A to 15A, and returns to original value. Since the variation of d-axis current doesn't have any effect on converter capacitor energy regulation, the FB-MMC could be performed as a STACOM which could supply the reactive power even during the DC short circuit fault. After the DC short circuit fault has been cleared, the capacitor energy is controlled by regulating DC bus voltage again at t_{12}, and DC bus voltage rises to supply the AC grid since t_{13}.

V. CONCLUSION

This paper proposed a black starting scheme and a DC short circuit fault ride through strategy for a hybrid HVDC transmission system with LCC and FB-MMC and its associated control schemes. Especially, DC short circuit fault ride through strategies of the FB-MMC are classified depending on AC grid types. The control objectives of the FB-MMC are controlling the power flow and supplying the loads, while the LCC is providing constant current as a current source to DC transmission line. The system performance under possible operating situations was verified by computer simulation and experimental tests. By applying the proposed strategies, since the power flow is controlled by receiving side, not by the LCC, control dynamics is conspicuously enhanced. Moreover, stable start-up and ride through against the non-permanent DC short circuit fault have been demonstrated.

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