A New Topology of Multilevel VSC Converter for Hybrid HVDC Transmission System

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***Abstract*— In this paper, the existing Modular Multilevel Converter (MMC) topologies for Line Commutated Converter (LCC)-Voltage Source Converter(VSC) connected as a hybrid High Voltage DC (HVDC) transmission system are reviewed and a new topology of multilevel converter for a hybrid HVDC is introduced. Among the existing MMC topologies for the hybrid HVDC, an MMC structure consisted of Half-Bridge SubModule(HBSM)s and Full-Bridge SubModule(FBSM)s has characteristics such as reduced system cost, low operation loss, but still keeping capability to cope with DC short circuit fault. However, it is very difficult for the conventional hybrid MMC structure, where each arm of MMC is consisted of mixed HBSM and FBSM, to balance the submodule capacitor voltages under sliding of DC bus voltage. For solving the defect of the conventional structure of MMC, an asymmetric MMC, where in a leg an arm is consisted of HBSM and other arm of FBSM, is devised. The proposed asymmetric MMC can regulate the DC bus voltage freely without uncontrollable submodule capacitor voltages. The problems of the conventional structure of MMC and the validity of asymmetric MMC are verified by both computer simulation and experiment results.**

Keywords—asymmetric mixed MMC; hybrid hvdc; high voltage dc transmission system; hybrid mmc; modular multilevel converter; submodule balancing

I. INTRODUCTION

For decades, a Line Commutated Converter (LCC) based HVDC has been developed and applied to most of HVDC transmission system. And nowadays, most HVDC systems in commercial operation employ the LCCs. It has several advantages such as higher reliability, higher power capability, excellent overload capability, and higher efficiency. However, it presents some drawbacks such as strong AC grid requirements, larger system size for harmonic and reactive filters, and lack of black starting capability. On the other hand, IGBT based Voltage Sourced Converter (VSC) has been recently developed, and it can cover the above demerits of LCC schemes. Among the VSC technologies, Modular Multilevel Converter (MMC) is a promising and competitive technology over two- or three-level VSC topologies. MMC presents many advantages such as very low harmonics, low dv/dt, modularity and simple scaling, high reliability and low switching loss, no necessity of series connection of power semiconductors, and the DC bus capacitor elimination, etc. Two types of submodule could be used in the MMC, which are a half-bridge chopper module, and a full-bridge inverter module. The Half-Bridge SubModule (HBSM) has been used widely to reduce the number of switching devices in a module and conduction loss. While, the output voltage of HBSM is confined to two levels, namely, null and DC link voltage of each module. While, that of Full-Bridge SubModule (FBSM) includes negative of DC link voltage, and the FBSM 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. In this case, the compactness and black starting capability in sending side may be not a crucial concern because of inherent large power plants at the site of HVDC converter. And, LCC type HVDC converter would be the best option at the sending side because of its technical maturity and higher operating efficiency. But in the receiving side, compact structure and black starting capability cannot be traded if the distributed loads are at 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. For this reason, there have been several researches to accommodate LCC and VSC simultaneously in a HVDC transmission system, which is so called as a hybrid HVDC transmission system [1-3]. In recent years, a hybrid HVDC transmission system with LCC and MMC has become the most compatible candidate for future flexible DC transmission system. 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 [4-5].

In this paper, the existing MMC topologies proposed in several literatures [4-9] are reviewed and the validity of them for hybrid HVDC transmission system is addressed. And, based on the results of review, a new MMC topology is proposed. It has the advantages such as cost saving and low loss, and it can also regulate the DC bus voltage quite freely and quickly for adjusting the DC transmission power in hybrid HVDC system. Also, it can deal with the black starting and DC fault ride through. Finally, the full scaled computer simulation studies and experiment results with scaled version of the proposed MMC topology in laboratory are provided to support the validity of the proposed topology.

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II. HYBRID HVDC CONFIGURATION AND FUNDAMENTAL PRINCIPLES

The basic structure of hybrid HVDC is shown in Fig. 1. The sending end is the conventional LCC based HVDC system. The receiving end is a VSC based HVDC system. In this paper, it is assumed that the LCC-HVDC system controls the DC current as constant and the VSC-HVDC system controls the DC bus voltage for regulating DC transmission power. The VSC on the receiving end has the turn-off capability. The VSC can maintain voltage and frequency stability in independence on the AC grid. So, active and reactive power may be controlled independently by VSC. The VSC not only requires no reactive power from AC grid but also can operate as STATCOM to compensate reactive power dynamically. This is to say, if VSC has enough capacity the hybrid HVDC can supply active power and reactive power to improve voltage and power angle stability when a fault occurs. No need for enhanced short circuit capacity takes place in the AC grid since the AC current of VSC is controllable. This is said that the relay protection does not need to revise after VSC-HVDC lines are added. Many VSCs may connect with a fixed polarity DC bus. It is easy to comprise multi-terminal HVDC system that has the same topology with AC system and has flexible operating patterns. The sending converter adopts the conventional current source converter based HVDC rectifier system with perfect and mature technology and relatively at low cost. Therefore, the hybrid HVDC transmission system features both the well-developed technology and lower cost of LCC-HVDC and desirable regulating characteristics of VSC-HVDC. The candidates of the VSC-HVDC system can be two- or three-level converter, modular multilevel converter, and several modified modular structure based VSC high power converters.

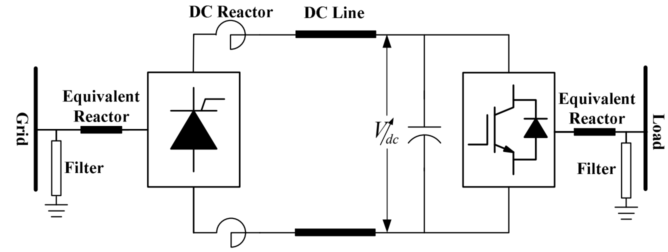
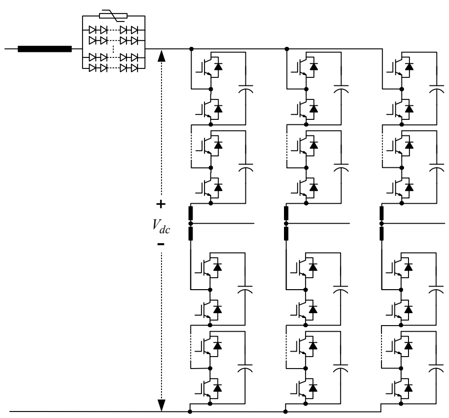
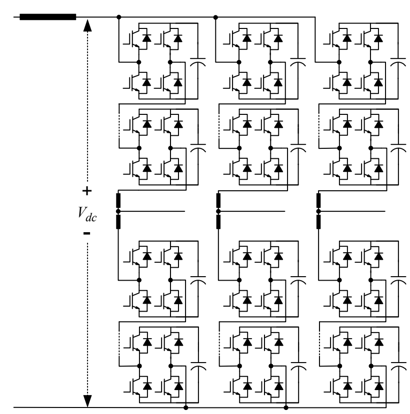


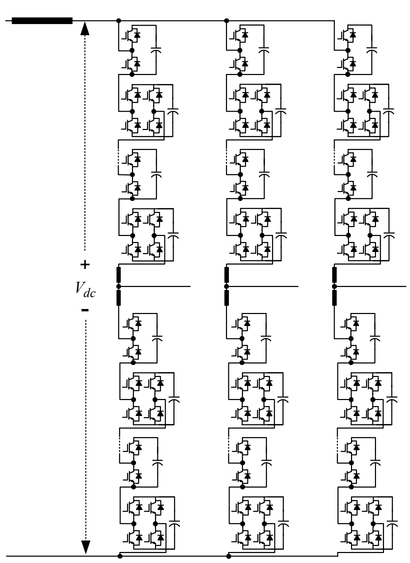
Fig. 1. The configuration diagram of Hybrid HVDC.



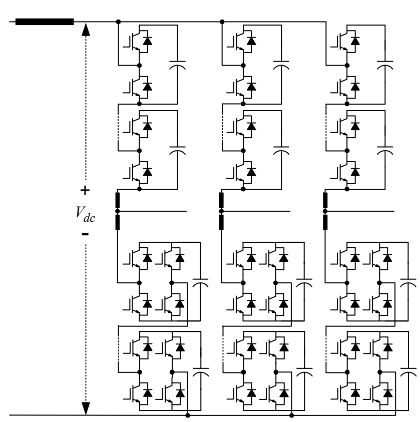
(a) HBSM-MMC with high power diodes



(b) FBSM-MMC



(c) Symmetric mixed MMC



(d) Proposed asymmetric mixed MMC

Fig. 2. The circuit diagrams of multilevel VSC converter topologies for hybrid HVDC transmission system.

III. Voltage Source Converter Topologies for Hybrid HVDC Transmission System

The HBSM-MMC could not ride through the DC short circuit fault without introducing AC or DC breakers. The circuit diagram of HBSM-MMC with high power diodes is shown like Fig. 2(a) [5]. A simple but effective method to block the DC fault current paths is to install the high power diodes in the overhead lines close to the MMC-based converters. The high power diodes consist of many rectifier diodes in series to withstand reverse blocking voltage during DC line faults. Given that the power flow of the proposed hybrid HVDC system is unidirectional, the high power diodes keep in conducting state in normal operation. However, the high power diode always causes not only the conduction loss in normal operation as well as fault operation, and but also additional installation and cost issue. Furthermore, the system has a disadvantage that DC bus voltage cannot be changed widely to vary the DC transmission power quantity because the HBSM-MMC has the narrow DC voltage variation abilities that is within output voltage margin range, near +Vdc (1p.u.).

The FBSM-MMC shown like Fig. 2(b) can make the DC side voltage from -1 p.u. to +1 p.u. by modulating output voltage of the FBSM without any restriction. So, it is very easy for FBSM-MMC to deal the black starting, power flow variation, and DC short circuit fault ride through. When DC short fault occurs, each submodule operates like a normal full-bridge and the DC bus voltage is synthesized as zero to clear the short circuit current of DC transmission line. Since a full-bridge inverter can output bipolar voltage, the converter can generate back-EMF to regulate AC side current during fault. Even though a full-bridge inverter can be modulated in bipolar or unipolar mode, to minimize switching loss, one of the lower switches should be normally ON and the other corresponding complementary switch should be normally OFF during normal operation. Then during normal operation, the full-bridge inverter based MMC operates like a conventional half-bridge chopper based MMC. As similar with aforementioned HBSM-MMC with high power diodes, the FBSM-MMC also causes extra loss while normal operation mode for most of its life.

Fig. 2(c) describes the circuit configuration of mixed HBSM and FBSM based MMC [6-8]. When the MMC operates at normal mode, the DC bus voltage is commonly synthesized as +Vdc, and when a DC short circuit fault occurs the DC bus voltage should be synthesized as 0. Then, in fact, a half of the DC bus voltage output capability is redundant. However, it should be noted that the FBSM based MMC can output back-EMF to regulate AC side current while the DC bus is synthesized from –Vdc (-1p.u.) to +Vdc (+1p.u.). Meanwhile, in case of hybrid HVDC transmission system, the FBSM-MMC has the ability of power flow reversal. In conventional and practical operation of hybrid HVDC transmission system, it is more general that the power flow is unidirectional from LCC-HVDC to VSC-HVDC system. Therefore, a structure of mixed HBSM and FBSM can take full advantage of converter output voltage capability in the hybrid HVDC transmission system. During normal operating condition, the symmetric mixed converter operates like a conventional HBSM-MMC, and during DC short circuit fault the half-bridge choppers are bypassed and the converter operates like a full-bridge based MMC to ride through the fault. Especially, in case of hybrid HVDC transmission system, the amount of DC transmission power can be regulated and varied by controlling the DC bus voltage from 0 to +Vdc (+1p.u.).

Contrary to existing structure, where equal number of HBSMs and FBSMs are used in an arm of each leg of MMC, a circuit shown in Fig. 2(d) can be considered as another option, where in a leg one arm is consisted of fully HBSMs and the other of fully FBSMs. Based on the configuration of a leg of MMC, the former one can be called as symmetric mixed MMC and the later one as asymmetric mixed MMC. In Fig. 2(d), upper arm is made up of series connection of HBSMs and lower arm consists of series connection of FBSMs in one case of two compositions of asymmetric mixed MMC. The number of HBSMs and FBSMs are the same in both mixed MMCs as described in Fig. 2(c) and (d). In the proposed asymmetric mixed MMC shown in Fig. 2(d), the upper arm which is composed of HBSMs operates like as normal mode of HBSM-MMC in both normal operation and fault operation. The lower arm which is composed of FBSMs operates like HBSM-MMC in normal mode and operates like FBSM-MMC in fault mode and also in the low power transmission mode which have lower amount of DC power than 1p.u. Like the symmetric mixed MMC in Fig. 2(c), the DC transmission power can be regulated and varied by controlling the DC bus voltage from 0 to +Vdc

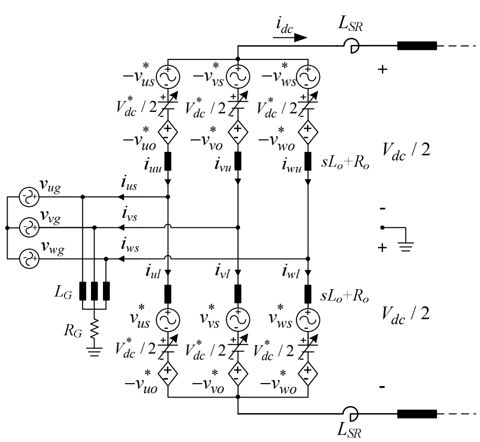


Fig. 3. Modeling of the symmetric mixed MMC

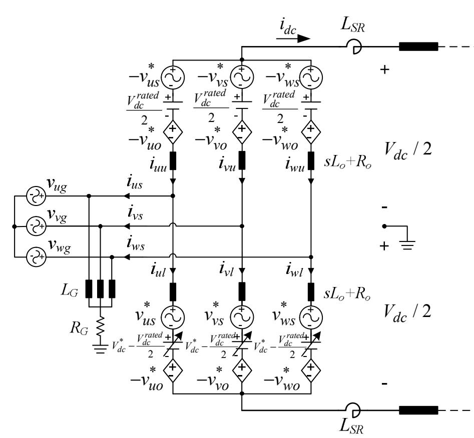


Fig. 4. Modeling of the asymmetric mixed MMC.

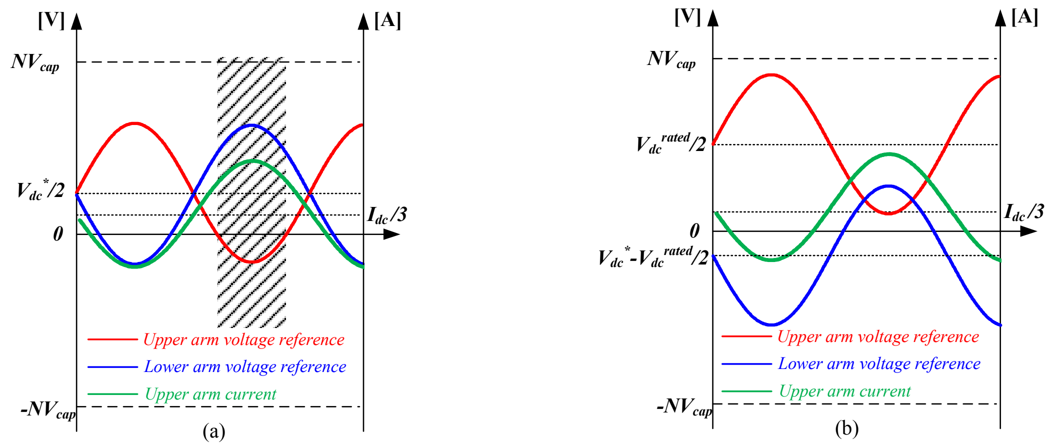


Fig. 5. The arm voltage references and arm current of (a) symmetric mixed MMC and (b) asymmetric mixed MMC when the DC bus voltage is lower than V_{dc}^{rated} (+1p.u.) for example in this figure, $V_{dc}^{*}=V_{dc}^{rated}/2$.

(+1p.u.). The advantages and characteristics of asymmetric mixed MMC will be described in the subsequent sections compared to symmetric mixed MMC.

IV. Comparisons of Symmetric and Asymmetric mixed MMC in Hybrid HVDC Transmission System

A. Operation Principles of the Symmetric mixed MMC

Modeling of the symmetric mixed MMC with the closed-loop indirect modulation [10] is shown in Fig. 3(a). The reference voltages (v_{xu}^{*} , v_{xl}^{*}) of upper and lower arm are derived by (1), where V_{dc}^{*} is DC bus voltage reference, v_{xs}^{*} is the phase voltage reference and x denotes a phase among u, v, and w. The leg internal voltage (v_{xo}^{*}) associated with circulating current for system balancing [11]. The leg internal voltage is omitted for simplification, by reason of its negligible magnitude as compared with that of DC bus voltage and phase voltage reference.

$$v_{xu}^{*}=\frac{V_{dc}^{*}}{2}-v_{xs}^{*},\qquad v_{xl}^{*}=\frac{V_{dc}^{*}}{2}+v_{xs}^{*}. \tag{1}$$

Under the assumption that the number of submodules in one arm is N, each arm is composed of $N/2$ HBSMs and $N/2$ FBSMs. So, the capable range of an arm output voltage is from $-NV_{cap}/2$ to NV_{cap}, assuming the capacitor voltages of all submodule are the same as V_{cap} .

B. Operating Principles of the Asymmetric mixed MMC

In modeling of the asymmetric mixed MMC of Fig. 4, the arm voltage references are given by (2) where V_{dc}^{rated} means the rated DC bus voltage in condition of the rated power transmission. And, the leg internal voltage is also excluded in (2).

$$v_{xP}^{*}=\frac{V_{dc}^{rated}}{2}-v_{xs}^{*},\qquad v_{xN}^{*}=(V_{dc}^{*}-\frac{V_{dc}^{rated}}{2})+v_{xs}^{*}. \tag{2}$$

In Fig. 2(d) and Fig. 4, the upper arm consists of N HBSMs and the lower arm is composed of N FBSMs. The capable range of an upper arm output voltage is from 0 to NV_{cap}, and that of an lower arm output voltage is from $-NV_{cap}$ to NV_{cap}. And, the upper arm voltage is always positive, and the lower arm voltage can be negative as well as positive.

C. Characteristics of the Symmetric and Asymmetric mixed MMC in DC Transmission Power Variation Mode in Hybrid HVDC System

In the case of the conventional hybrid HVDC system, LCC based HVDC system is sending end which operates as rectifier mode and VSC based HVDC system is receiving end which operates inverter mode [1-2]. The VSC based HVDC system regulates the DC bus voltage in case of point-to-point hybrid HVDC transmission system. The system operated as the DC bus voltage regulation mode can be named as voltage regulator. In conventional point-to-point hybrid HVDC system, LCC-HVDC controls the DC bus current to be constant and VSC-HVDC determines the quantity of the DC transmission power by regulating the DC bus voltage. Therefore, for controlling the DC bus voltage, the MMC-HVDC system should have the ability to regulate the DC bus voltage.

The arm voltage references and arm current of the symmetric mixed MMC while the DC voltage is lower than the rated DC bus voltage are depicted in Fig. 5(a). In this figure, as an example, $V_{dc}^{*}=V_{dc}^{rated}/2$. Because the DC bus voltage is lower than the rated voltage, the arm voltage references have the negative value within the region which is marked in Fig. 5(a). If the upper arm voltage is positive, all submodules operate like the half-bridge chopper cells by unipolar mode of FBSMs. While the upper arm voltage is negative like the marked section of Fig. 5(a), all HBSMs of the upper arm are bypassed, and FBSMs in upper arm operate

TABLE I. COMPARISONS BETWEEN FOUR DIFFERENT MMC TOPOLOGIES FOR HYBRID HVDC TRANSMISSION SYSTEM.

	HBSM-MMC with high power diodes	FBSM-MMC	Symmetric mixed MMC	Asymmetric mixed MMC
Cells per arm	N	N	N	N
IGBTs per arm	2N	4N	3N	3N
DC short circuit fault blocking	Yes	Yes	Yes	Yes
DC fault ride through as a STATCOM	Yes	Yes	Yes	Yes
Conducting IGBTs per leg	2N	4N	3N	3N
Conduction loss	Low (when using low loss model of high power diodes)	High	Medium	Medium
DC power flow variation capability	No (Limited range around 1p.u.)	Yes (-1p.u.~1p.u.)	Yes (when 0 and 1p.u.) Difficult or imperfect (when $0<P_{dc}<1$p.u.)	Yes (0~1p.u.)
Submodule balancing in power variation mode	Not available	Good	Not good	Good

in bipolar mode and make the negative arm voltage. Assuming that the power factor is unity and the arm voltage is negative and the arm current is positive as shown like Fig. 5(a), the capacitor voltages of FBSMs of upper arm decrease, whereas those of HBSMs of upper arm are unchanged, in accordance with the aforementioned modulation principle. Therefore, the voltage difference between FBSMs and HBSMs in the upper arm is getting larger in the interval during the arm voltage is negative. And the same difference may also happen in the lower arm when the arm voltage is negative and the arm current is positive. In this case, the capacitor voltages of FBSMs of lower arm decrease, whereas those of HBSMs of lower arm are unchanged. On the other hand, the voltage difference between FBSMs and HBSMs is getting smaller in the region during the arm voltage is positive, because FBSMs operate like half-bridge chopper module and thus the cell balancing algorithm applies equally to all submodules. However, as the interval of negative arm voltage is getting larger and the arm current is getting larger, the unbalance of the symmetric mixed MMC in each arm becomes worse and the system would be stalled finally.

The arm voltage references and arm current in case of the asymmetric mixed MMC system while the DC voltage is lower than the rated DC bus voltage can be depicted as Fig. 5(b). Again, in this figure, as an example, $V_{dc}^{*}=V_{dc}^{rated}/2$. As shown like (2), the DC component of the upper arm voltage reference is fixed as a half of the rated DC bus voltage. While, the lower arm voltage reference determines the DC bus voltage and thus the DC component of the lower arm voltage reference can vary between $-V_{dc}^{rated}/2$ and $V_{dc}^{rated}/2$. The cell balancing algorithm applies equally to HBSMs in upper arm and FBSMs in lower arm respectively. Hence, the voltage unbalance between submodules cannot occur obviously.

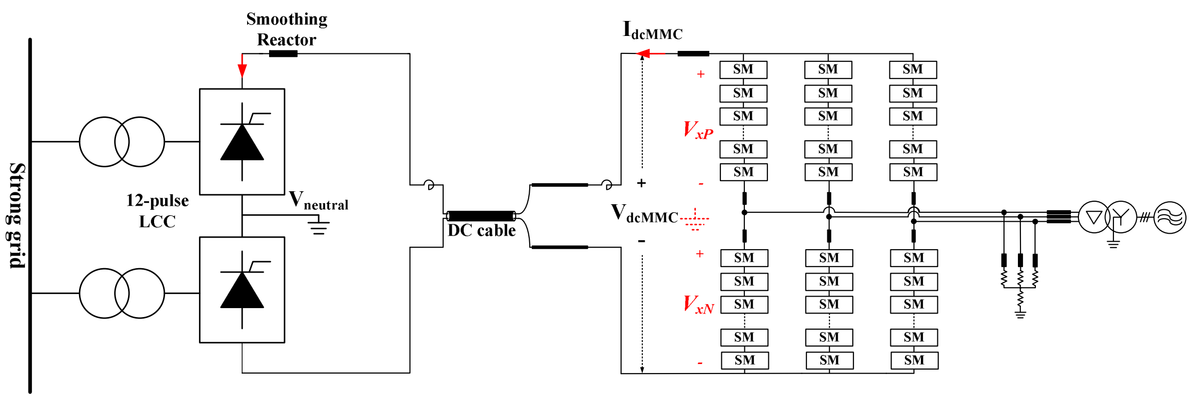


Fig. 6. Schematic diagram of the simulated hybrid HVDC transmission system with symmetric and asymmetric mixed MMCs.

Taking consideration of other MMC topologies, the characteristics of those can be summarized as described in Table I. And the intensive comparison and verification by simulation and experimental results between the symmetric and asymmetric mixed MMC are described in the next Section V and Section VI.

V. FULL SCALE SIMULATION RESULTS

A 400MVA MMC model has been established by using full scale computer simulations based on PSIM software. The schematic of the simulated system is illustrated in Fig. 6. The number of submodules per arm is 216, the rated DC bus voltage is 400kV, and the rated submodule capacitor voltage is 2200V. The detailed parameters for the simulation can be referred to Table II.

TABLE II. PARAMETERS OF THE SIMULATED SYSTEM.

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	20 mH
Number of submodules per Arm	216
Rated DC bus voltage	400kV
Rated DC bus current	1500 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

Fig. 7 shows the simulation results of the symmetric mixed MMC when the DC bus voltage is changed from 400kV (1 p.u.) to 140kV (0.35 p.u.) at 1.5s. And, the current is regulated to be -1500A as constant. As shown like the 3rd trace of Fig. 7, the DC components of the upper and lower arm voltage references are changed from 200kV to 70kV as aforementioned the arm voltage references like (1). The 5th and 6th traces of Fig. 7 show the averages of upper and lower arm HBSMs and FBSMs capacitor voltages of u-phase, respectively. When the DC bus voltage is the rated 400kV, all cell voltages are well balanced. However, when the DC bus voltage is reduced down to 140kV, the cell voltages between HBSMs and FBSMs are unbalanced each other. Fig. 8 shows the magnified waveforms of the section between 1.6s and 1.7s. From the moment that arm voltage reference becomes negative, the difference between HBSM and FBSM capacitor voltages starts to increase. Because the arm current is positive when the arm voltage is negative, capacitor voltages in FBSMs are discharged. When the arm voltage is positive, the cell balancing algorithm applies equally to all submodules. So, the difference between HBSM and FBSM voltages decreases, and the unbalance is resolved finally within one period.

Fig. 9 shows the simulation results when the DC transmission power decreases from 1 p.u. to 0.25 p.u. Because the DC bus voltage is stepped down to 100kV, the region where the arm voltage is negative is enlarged. The unbalance becomes more severe and the unbalance is not resolved even during the region of positive arm voltage. In other words, the discharged energy in FBSMs is larger than charged energy during one fundamental period. Hence, energy in FBSMs is depleted and thus the system is diverged finally. As shown like results of Fig. 9, it may have a severe effect on the stability and result in control and capacitor sizing issues of converter systems.

On the other hand, the simulation result of asymmetric MMC system is shown as Fig. 10. Because the upper and lower arm voltage references follow (2), the upper arm voltage reference is always positive and the lower one regulates the DC component for producing exact DC bus voltage reference as shown by 3rd trace of the figure. From 5th trace of Fig. 10, the submodule capacitor voltages in both upper and lower arm are well regulated below the allowable bound. Therefore, for regulating variable DC transmission power, the proposed

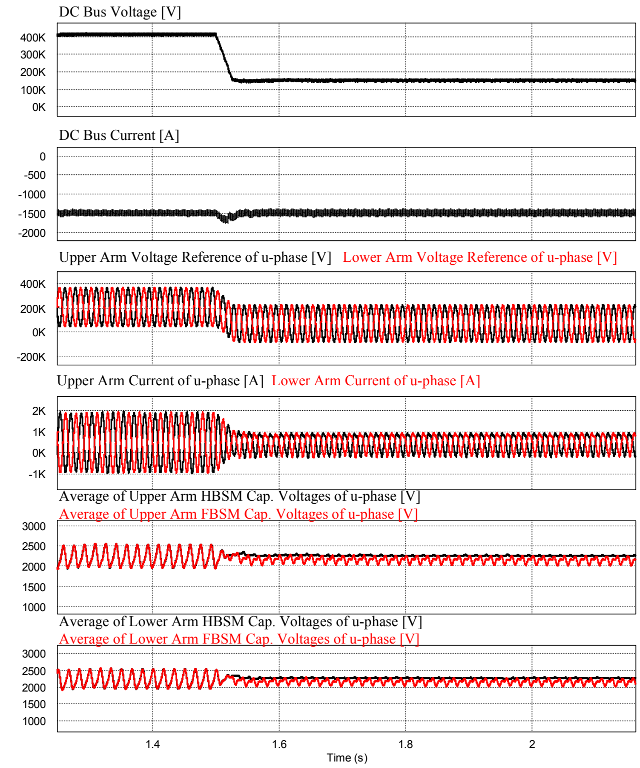


Fig. 7. Simulation results of the symmetric mixed MMC when the DC transmission power decreases from 1 p.u. to 0.35 p.u. by regulating the DC bus voltage.

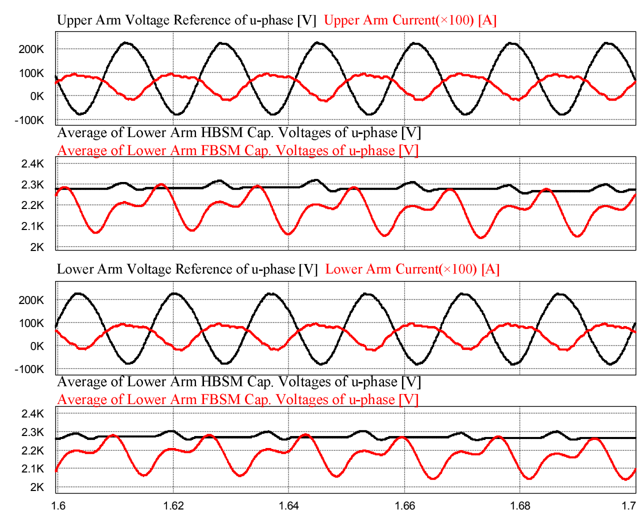


Fig. 8. Magnified waveforms of the section between 1.6s and 1.7s in Fig. 6.

asymmetric mixed MMC topology would be a promising option for LCC-VSC hybrid HVDC system.

VI. EXPERIMENT RESULTS

The comparison of the symmetric and asymmetric mixed MMC and the validity of the asymmetric mixed MMC are verified by the 10kVA reduced scale prototype hybrid HVDC system shown in Fig. 11(a). The number of cells in each arm, N, is 6, so there are a total of 36 cells used for the three-phase system. The parameters for the test setup are given in Table III. LCC is emulated by the full-bridge chopper in DC link of 2-level converter as shown like Fig. 11(b).

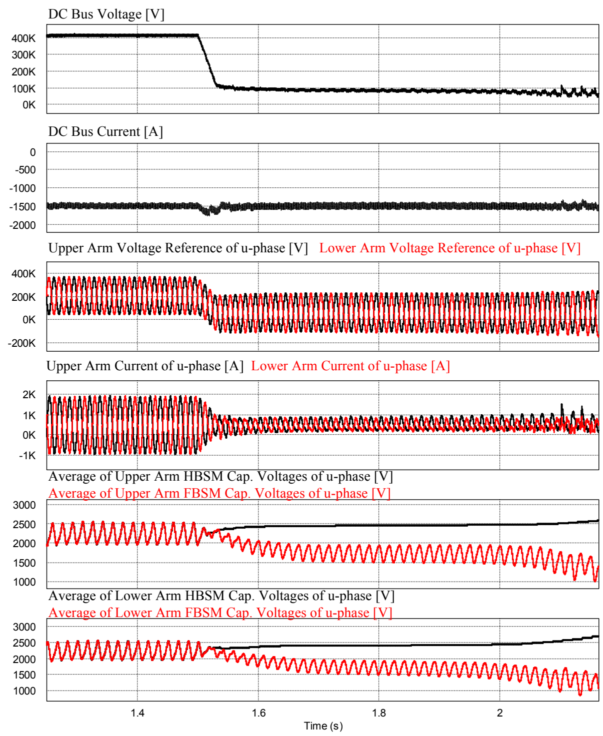


Fig. 9. Simulation results of the symmetric mixed MMC when the DC transmission power decreases from 1 p.u. to 0.25 p.u. by regulating the DC bus voltage.

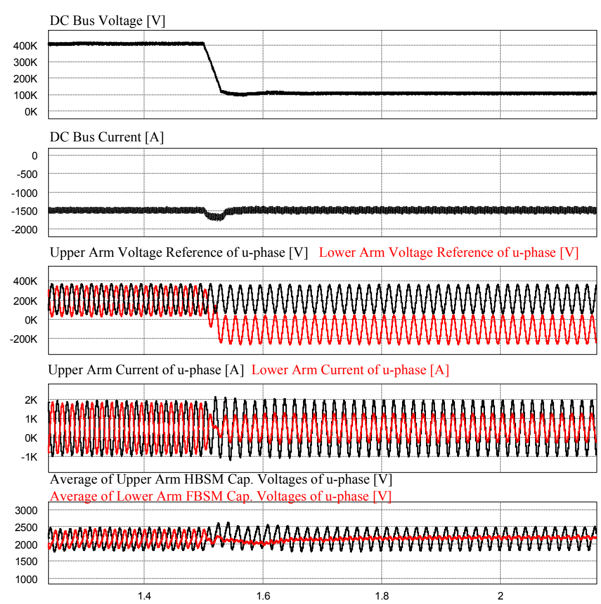
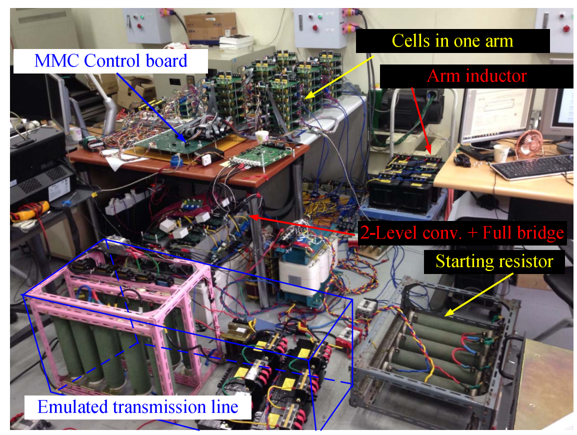


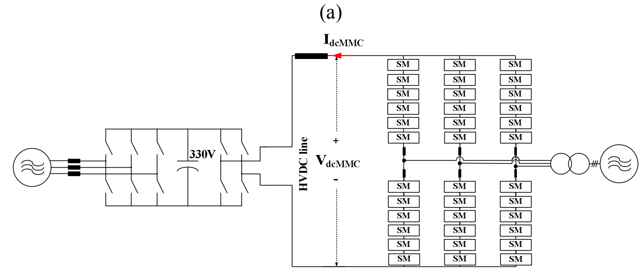
Fig. 10. Simulation results of the asymmetric mixed MMC when the DC transmission power decreases from 1 p.u. to 0.25 p.u. by regulating the DC bus voltage.

Fig. 12 shows the experiment results of the symmetric mixed MMC when the DC bus voltage decreases from 300V (1 p.u.) to 150V (0.5 p.u.) and 75V (0.25 p.u.) and the DC bus current is regulated as -5A constantly. As shown like the upper and lower arm voltage reference in Fig. 12, the DC components of the arm voltage references are changed from 150V to 75V and 37.5V as the aforementioned arm voltage references like (1). When the DC bus voltage is the rated 300V, all cell voltages are well balanced. However, when the DC bus voltage is 150V and 75V, the cell voltages between HBSMs and FBSMs are unbalanced each other.

From the moment when arm voltage reference is negative, the difference of HBSM and FBSM capacitor voltages begins to increase. When the DC voltage is 75V, the unbalance is more conspicuous.



(a)



(b)

Fig. 11. Experimental setup: (a) a down scaled prototype hybrid HVDC system and (b) schematic diagram of experimental setup.

TABLE III. PARAMETERS OF PROTOTYPE HYBRID HVDC SYSTEM.

Quantity	Values
Transmission line inductance	8 mH
Transmission line resistance	0.5 Ω
Number of full-bridge modules per Arm	6
Rated DC bus voltage	300 V
Rated DC bus current	30 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 (line-to-line rms)	140 V

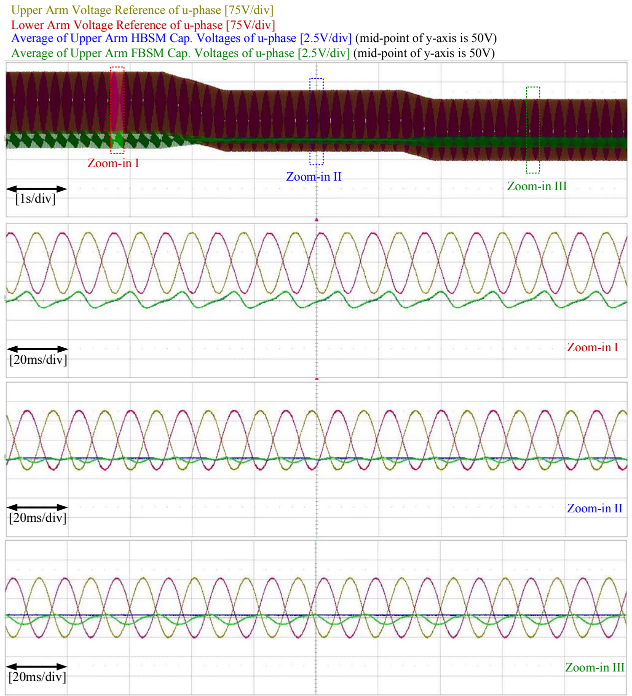


Fig. 12. Experiment results of the symmetric mixed MMC when the DC bus voltage decreases from 300V (1 p.u.) to 150V (0.5 p.u.) and to 75V (0.25 p.u.) and DC bus current is -5A as constant.

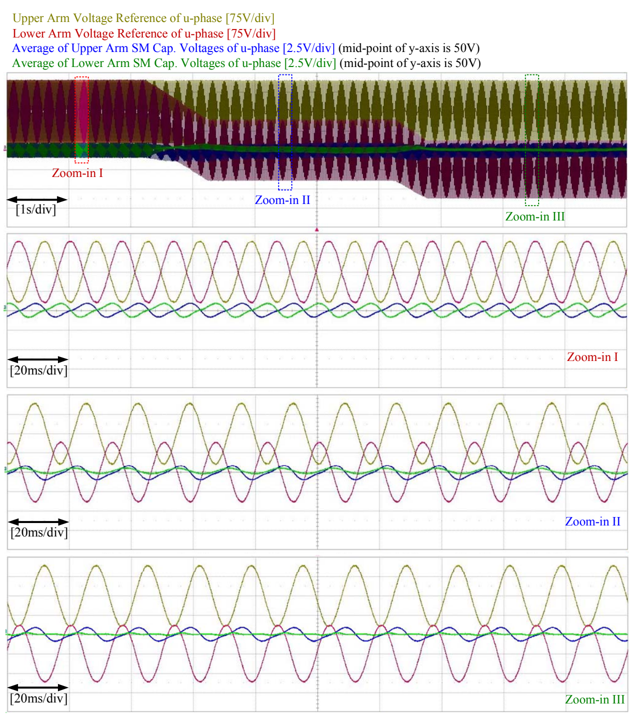


Fig. 13. Experiment results of thea symmetric mixed MMC when the DC bus voltage transfers from 300V (1 p.u.) to 150V (0.5 p.u.) and 75V (0.25 p.u.) and DC bus current is -5A as constant.

On the other hand, Fig. 13 shows the experiment results of the asymmetric mixed MMC when the DC bus voltage decreases from 300V to 150V and 75V and the DC bus current is controlled as -5A constantly. As the upper and lower arm voltage references follow (2), the upper arm voltage is modulated as positive and the lower arm voltage is modulated for producing exact DC bus voltage. As shown in Fig. 13, the submodule capacitor voltages in both upper and lower arm are well controlled within allowable bound.

Fig. 14 and Fig. 15 show the experimental results in condition that the DC current reference of emulated LCC system is changed from -10A to -15A rapidly. In Fig. 14, after the moment of DC current change, the symmetric mixed MMC system becomes unstable and the system is stalled eventually. The capacitor voltages in FBSMs could not follow the reference value, 50V and energy in FBSMs was exhausted. However, the asymmetric mixed MMC system is stable even after DC current change from -10A to -15A as shown in Fig. 15. The reduced scale experimental results also support the validity of asymmetric mixed MMC topology in LCC-VSC hybrid HVDC transmission system.

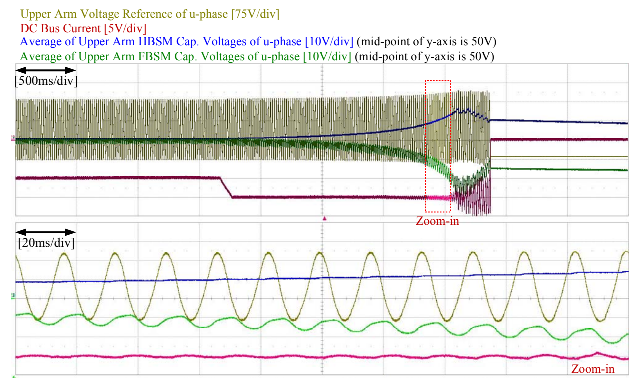


Fig. 14. Experiment results of the symmetric mixed MMC when the DC current is changed from -10A to -15A and the DC bus voltage is 75V (0.25 p.u.) as constant.

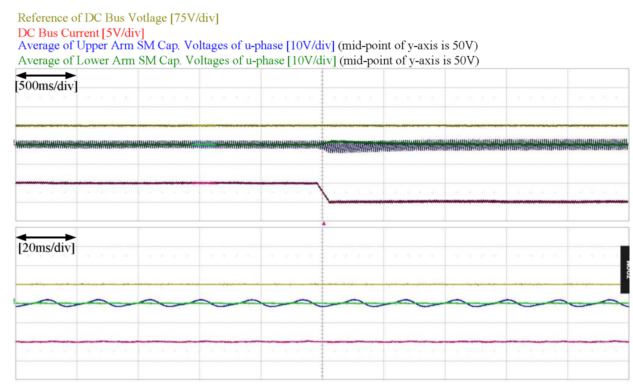


Fig. 15. Experiment results of the asymmetric mixed MMC when the DC current is changed from -10A to -15A and the DC bus voltage is 75V (0.25 p.u.) as constant.

VII. Conclusions

In this paper, the existing multilevel MMC topologies for LCC-VSC connected hybrid HVDC transmission system are reviewed and an asymmetric mixed MMC topology has been introduced. It has characteristics such as reduced system cost, less operational loss, and ability to cope with DC short circuit fault, as same with conventional symmetric mixed MMC. As contrast with the conventional mixed MMC, the asymmetric mixed MMC for hybrid HVDC transmission system can regulate the DC bus voltage freely without uncontrollable submodule capacitor voltages. The drawbacks of the conventional symmetric mixed MMC for hybrid HVDC have been identified and the validity of the asymmetric MMC system has been supported by the simulation studies and scaled version experimental results.

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