A Novel Control Strategy of a Modular Multilevel Converter (MMC) based VSC-HVDC Transmission System

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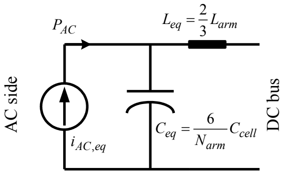
***Abstract*— In the conventional control strategy of the VSC-HVDC system based on the MMC, direct modulation was employed and the terminal behavior of the MMC was similar to that of the two-level converter. The DC bus voltage of the power dispatcher side was regulated indirectly by controlling voltage regulator side DC bus voltage, and the transmission line current was determined passively by the power flow. Fluctuation of the transmission line voltage would occur during rapid power flow variation due to the inherent capacitor-inductor coupling in the DC transmission line. In this paper, a new concept of the control strategy is proposed. At first, by the proposed control strategy AC grid current control, DC bus current control, and arm capacitor voltage balancing control of the MMC are fully decoupled. Secondly, the DC bus of the MMC operates as a controlled voltage source and the power flow is controlled by regulating the transmission current directly and actively, and the transmission line voltage fluctuation is fully suppressed during power flow variation. Validity of the proposed control strategy is verified by both full scale simulation and down scale experiment.**

Keywords—modular multilevel converter(MMC); VSC-HVDC; power flow; decoupling

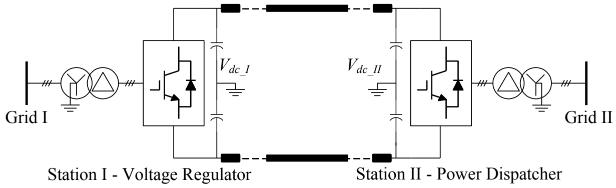
I. INTRODUCTION

Voltage Source Converter (VSC) based High Voltage Direct Current (HVDC) transmission is a promising solution for future smart grid which would integrate a great amount of renewable energy sources into the existing AC grid. For VSC-HVDC, compared to the conventional two level or three level converters, a Modular Multilevel Converter (MMC) is a competitive candidate and is attracting worldwide attention [1-3]. 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 [4-6], etc.

Control of a VSC-HVDC transmission system based on the MMC is investigated in several articles [7-9]. In the conventional control strategy, direct modulation was employed for the MMCs. It had been revealed that the terminal behavior of the MMC was similar to that of the two-level VSC converter [10]. The DC voltage of the MMC was coupled with the energy stored in the sub-module capacitors of the converter and the DC bus of the MMC can be modeled as an equivalent capacitor behind an equivalent inductor and being fed by the AC grid side as shown in Fig. 1(a).



(a) Equivalent model of the DC bus of the MMC



(b) Conceptual equivalent structure of the MMC-HVDC system by the conventional control method

Figure.1 Modeling of a single station and the MMC-HVDC transmission system controlled by the conventional control method.

Typically, in the conventional control strategy one of the stations in the transmission system operates in the Voltage Regulator (VR) mode and the other one operates in the Power Dispatcher (PD) mode as shown in Fig. 1(b). The DC bus voltage of the VR converter was controlled by regulating the energy stored in the sub-module capacitors by the AC grid side active power regulation. And the DC bus voltage of the PD converter was determined indirectly and passively by the DC bus voltage of the VR converter. The PD converter controlled the active power that imported into the Grid II and then the transmission line power flow and current were indirectly and passively determined in accordance with the power balance. Because of an inherent capacitor-inductor-capacitor coupling in the transmission line as shown in Fig. 1(b), if the conventional control strategy was employed transmission line voltage fluctuation would occur inevitably during the power flow variation [11]. In [12] it has been investigated that damping of the DC transmission system is related to the transmission line resistance and the power flow. Since the transmission line resistance is very small, a rapid power flow variation would lead to overvoltage or even make the system unstable [12].

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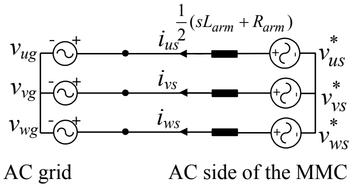
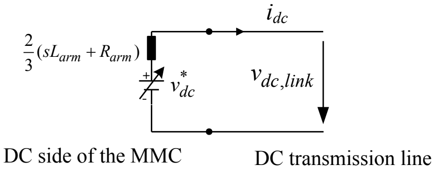
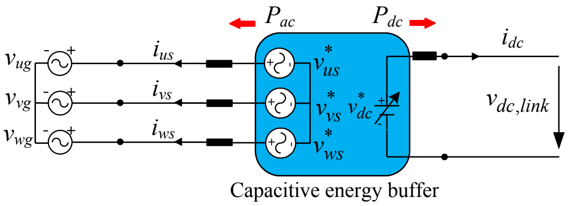


(a) AC grid current model



(b) DC bus current model



(c) Model of the single MMC by the proposed control strategy

Figure 2. Modeling of the single MMC controlled by the proposed control strategy.

In this paper, a novel control strategy based on the so called indirect modulation is proposed. By the proposed control strategy, the DC bus voltage of the MMC is fully decoupled with the energy stored in the sub-module capacitors and the DC bus of the MMC operates as a high bandwidth voltage source. The controlled voltage source regulates the transmission line current directly and actively to control the power flow, and the transmission line voltage fluctuation can be fully suppressed even during very rapid power flow variation (50p.u./s).

II. PROPOSED CONTROL STRATEGY OF THE SINGLE MMC CONVERTER

A. *Arm Capacitor Voltage Balancing*

A basis of this work, a control strategy of the single MMC converter based on the indirect modulation was proposed in [13] by authors. In the proposed single converter control strategy, the MMC circuit is divided into three equivalent models extracted from MMC circuit, namely the AC grid current model, the DC bus current model, and the circulating current model. Balancing of energy stored in sub-module capacitors of each arm is one of the main concerns of the control of the MMC.

In the proposed control strategy, the six arm capacitor energies are balanced only by the circulating current that flows inside the converter without affecting neither the AC grid side nor the DC bus side. One of the features of the proposed control strategy is that the AC grid current regulation, the DC bus current regulation, and the arm capacitor energy balancing are fully decoupled. It means that the arm capacitor energy balancing would not affect the dynamics of the AC grid side current and the DC bus side current and it's just an internal event of the MMC.

B. *Terminal Behavior of the MMC by the Proposed Control Strategy*

Fig 2.(a) shows the AC grid current model of the single MMC controlled by the proposed indirect modulation based control strategy. From the AC grid side, the MMC converter looks like a three phase controlled AC voltage source behind three phase inductors. The reactance of each inductor is a half of that of the arm inductor.

Fig 2.(b) shows the DC bus current model of the single MMC controlled by the proposed indirect modulation based control strategy. From the DC transmission line side, the MMC converter looks like a controlled DC voltage source behind an equivalent inductor. The inductance of the inductor is 2/3 of that of the arm inductor. It should be taken in mind that different from the MMC controlled by the conventional direct modulation based control strategy shown in Fig. 1(a), the voltage of the controlled DC voltage source is fully decoupled from the energy stored in the sub-module capacitors of the converter and it can be updated at each sampling period.

Then the terminal behavior of the MMC by the proposed control strategy can be modeled as Fig. 2(c). The role of the sub-module choppers is simply generating three-phase AC voltage to the AC grid side and generating DC voltage to the DC bus side. In addition, the capacitors of the sub-modules play a role of energy buffer between three-phase AC voltage source and the DC voltage source. Then dynamics of the energy stored in the whole sub-module capacitors of the MMC can be described as (1).

$$\frac{d}{dt}E_{total} = -\left(v_{us}^{*} i_{us} + v_{vs}^{*} i_{vs} + v_{ws}^{*} i_{ws} + v_{dc}^{*} i_{dc}\right). \tag{1}$$

From (1), in the steady state the DC components of the power flows into AC and DC sides of the MMC should be balanced. The total capacitor energy of the MMC, namely E_{total}, can be regulated either by controlling AC grid side active power or by controlling DC bus side power.

In the proposed converter control strategy, since the arm capacitor energy of the six arms are balanced only by the injection of the circulating current that flows inside the converter in a closed-loop manner, it would not contribute to the dynamics of the AC grid current or the DC bus current. Then in the transmission system control level, the issue of arm capacitor energy balancing does not have to be taken into consideration.

III. PROPOSED CONTROL STRATEGY OF THE MMC-BASED HVDC TRANSMISSION SYSTEM

Before introducing the proposed transmission system control strategy, it's necessary to review the operation principle of the conventional system control strategy. The case of the inverter operation of the PD converter is discussed as an example. As shown in Fig. 1(b), the DC bus voltage of the converter is coupled with the energy stored in the sub-module capacitors. While the power that flows from the PD converter to the AC grid increases, the DC bus voltage of the PD converter decreases. Then the transmission line current from the VR side to the PD side increases because of the voltage difference between DC buses of two converters. Consequently

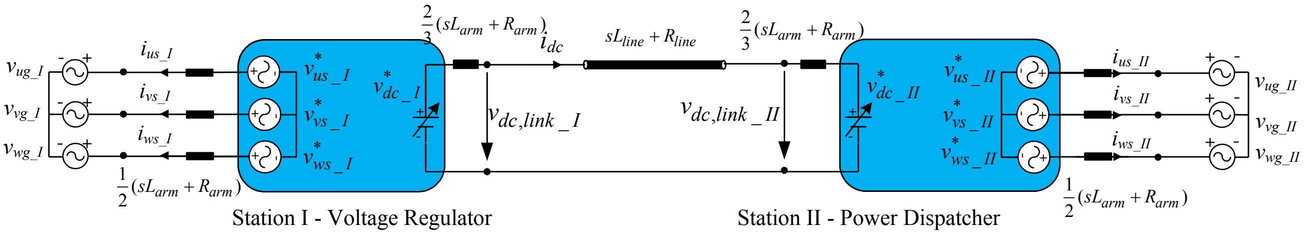


Figure 3. Modeling of the MMC based VSC-HVDC transmission system controlled by the proposed converter control strategy.

the increase of the transmission line power leads to the decrease of the DC bus voltage of the VR converter. After this, the capacitor energy controller of the VR converter would operate to restore the DC bus voltage of the VR converter and the DC bus voltage of the PD converter would be restored passively. According to the principle of the conventional control strategy, transmission line voltage fluctuation is inevitable during power flow variation. Moreover, a rapid power flow variation would lead to overvoltage or system instability problem [11].

With the proposed indirect modulation based control strategy, a new concept of the VSC-HVDC transmission system control can be implemented. Fig.3 shows the modeling of the MMC-based HVDC transmission system controlled by the proposed single MMC control strategy. Without loss of generality, it's assumed that the Station I operates in VR mode and the Station II in PD mode.

The DC bus side of the MMC is decoupled from both the AC grid side and the converter total capacitor energy. Different from the two-level converter or the MMC that controlled by the conventional direct modulation based control method, the sub-module capacitors of the MMC just act as an energy buffer between the three-phase AC voltage source and the DC voltage source. In a HVDC transmission system, since the voltage drop across the transmission line is negligible compared to the transmission line rated voltage, it's reasonable to assume that $v_{dc,link\_I} = v_{dc,link\_II}$ and power flow control is equivalent to the transmission line current regulation. Dynamics of the transmission line current can be described as (2).

$$\left(\frac{4}{3}\left(L_{arm}\frac{d}{dt}+R_{arm}\right)+\left(L_{line}\frac{d}{dt}+R_{line}\right)\right)i_{dc}=v^*_{dc\_I}-v^*_{dc\_II}. \quad (2)$$

Equation (2) means that the voltage difference of two controlled DC voltage sources can be adjusted to actively regulate the transmission line current as it's usually done in the DC motor current regulation.

A. Control of the Voltage Regulator

The main objective of the VR converter is to support the HVDC transmission line voltage. Then the voltage of the controlled DC voltage source in the DC bus side can be controlled constantly as transmission line rated voltage regardless of the capacitor energy to stabilize the transmission line voltage as (3).

$$v^*_{dc\_I}=V_{dc,rated}. \quad (3)$$

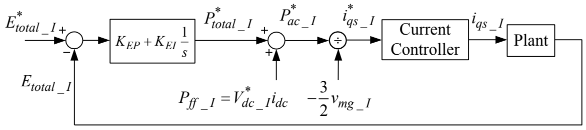
From the transmission line side, the DC bus of the VR converter is a constant DC voltage source behind an inductor. Then the energy stored in the whole sub-module capacitors of the VR converter should be controlled by regulating the AC grid side active power. Fig 4.(a) shows a block diagram of the capacitor energy controller of VR. The total capacitor energy is regulated by a PI controller in a closed-loop manner and the power flow from the sub-module capacitors into the DC side is utilized as a feed-forward term to improve dynamic performance. It should be mentioned that in this paper the AC grid voltage vector is oriented to the q-axis of the synchronous rotating reference frame. Fig 4.(b) shows the plant of the VR converter. Since the dynamics of the AC grid current regulation are much faster than that of the capacitor energy regulation, the transfer function of the VR converter in the view point of the total capacitor energy regulation can be deduced as (4) from Fig.4.

$$\frac{E_{total\_I}}{E^*_{total\_I}}=\frac{sK_{EP}+K_{EI}}{s^2+sK_{EP}+K_{EI}}. \quad (4)$$

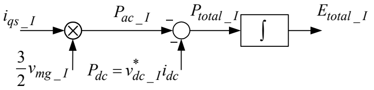
B. Control of the Power Dispatcher

The main objective of the PD converter is controlling the power that flows through the HVDC transmission line. Fig. 5 shows the power flow controller of PD. The power that flows from the PD converter to the AC grid is controlled by regulating AC grid side active current. A closed loop PI controller is employed to guarantee zero steady state error.

Then the energy stored in the whole sub-module capacitors should be controlled by regulating the DC transmission line side power. Fig 6.(a) shows a block diagram of the total capacitor energy controller of PD. The total capacitor energy is regulated by a PI controller in a closed-loop manner and the power flow from the sub-module capacitors into the AC grid



(a) Block diagram of the capacitor energy controller of the VR converter



(b) Plant of the controller of the VR converter

Figure 4. Capacitor energy controller block diagram and plant of the voltage regulator.

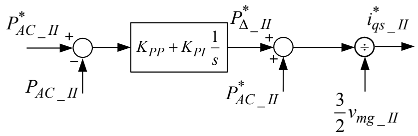
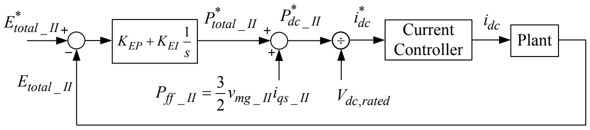
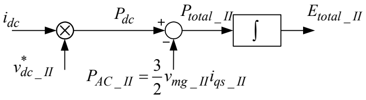


Figure 5. Block diagram of the power flow controller of the power dispatcher.



(a) Block diagram of the capacitor energy controller of the PD converter



(b) Plant of the controller of the PD converter

Figure 6. Capacitor energy controller block diagram and plant of the PD converter.

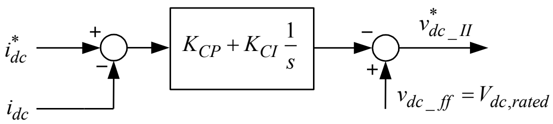


Figure 7. Block diagram of the proposed transmission line current controller.

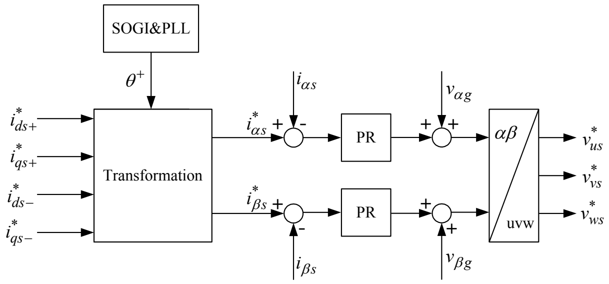


Figure 8. Block diagram of the proposed AC grid current controller.

side is utilized as a feed-forward term to improve dynamic performance. Fig 6.(b) shows the plant of the PD converter. If the dynamics of the HVDC transmission line current regulation are much faster than those of the capacitor energy regulation and the voltage drop across the transmission line is neglected, the transfer function of the PD converter total capacitor energy can be deduced as (5) from Fig.6.

$$\frac{E_{total\_II}}{E^*_{total\_II}}=\frac{sK_{EP}+K_{EI}}{s^2+sK_{EP}+K_{EI}}. \tag{5}$$

C. Control of the Transmission Line Current

The DC voltage source in the DC bus of the PD converter should operate to draw transmission current actively to regulate the total capacitor energy of the PD converter.

Fig.7 shows the block diagram of the proposed transmission line current controller. Transmission line current is regulated by a PI regulator and the transmission line rated voltage, namely the voltage of the controlled DC voltage source in the DC bus side of the VR converter, is utilized as a feed-forward term to improve dynamic performance. If the gains of the transmission line current PI regulator are set as (6) and (7), then the dynamics of the transmission line current is derived as (8).

$$K_{CP}=\omega_{cc}\left(\frac{4}{3}L_{arm}+L_{line}\right). \tag{6}$$

$$K_{CI}=\omega_{cc}\left(\frac{4}{3}R_{arm}+R_{line}\right). \tag{7}$$

$$\frac{i_{dc}}{i^*_{dc}}=\frac{\omega_{cc}}{s+\omega_{cc}}. \tag{8}$$

In practical application, the inductances of the inductor and the transmission line are almost time-invariant. However, the resistance of the transmission line would vary in a wide range in accordance with the ambient temperature and the current of the transmission line. Then to improve the dynamic performance, active damping method can be employed if necessary.

D. Control of the AC Grid Current

In the AC grid current control of the grid connected VSC converters, it's a conventional way to employ the so-called Double Synchronous Reference Frame (DSRF) controller [7,9] to manage the positive sequence and negative sequence components of the AC grid current. In the DSRF controller, a clockwise rotating reference frame and an anti-clockwise rotating reference frame are employed to separate the positive sequence and the negative sequence components and to manage them independently.

However, in the DSRF controller notch filters (whose central frequency is twice the line frequency) have to be employed to filter out the negative sequence components in the anti-clockwise rotating reference frame of the positive sequence components and vice versa [14,15]. One of the drawbacks of this architecture is that the introduction of the time delay caused by the notch filters and it would lead to current overshoot during fast transient such as a Single Line to Ground (SLG) fault.

In this paper, a new AC grid current controller constructed in the stationary $\alpha\beta$-reference frame is proposed as shown in Fig. 8. The AC grid current references (including both positive sequence and negative sequence components) generated by the power related controllers are transformed into the stationary reference frame. To guarantee the zero steady state error, the Proportional-Resonance (PR) regulators are employed. In the proposed control structure, since the grid current and the grid voltage used in the controller are directly measured variables without time delay caused by the filters, the AC grid current would be controlled with better dynamic performance compared to the conventional DSRF controller.

IV. FULL SCALE SIMULATION STUDIES

To verify the proposed control strategy, full scale computer simulations are performed by a point-to-point HVDC transmission system platform. Schematic of the system

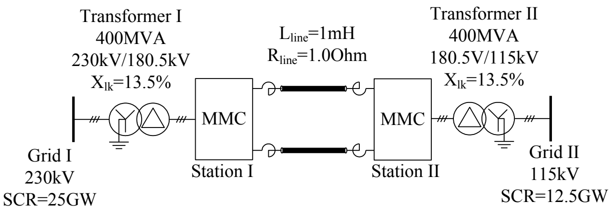


Figure 9. Schematic diagram of the HVDC system in simulation.

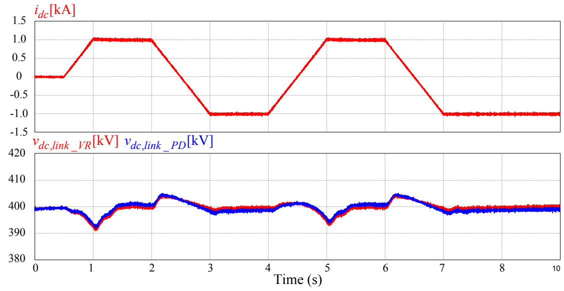
TABLE I. PARAMETERS OF THE SIMULATED SYSTEM

MMC converter	
Number of sub-modules per arm	216
Rated sub-module capacitor voltage	2.2kV
Sub-module capacitor	4.5mF
Inductance of arm inductor	15mH
Resistance of arm inductor	10mΩ
Controller sampling frequency	10kHz
Smoothing reactor	
Resistance	36mΩ
Inductance	10mH
HVDC transmission line	
Rated voltage	400kV
Rated current	1kA

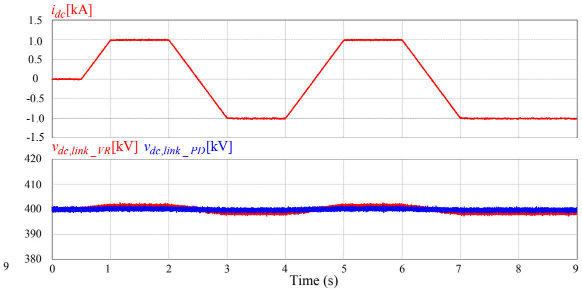
under the simulation is shown in Fig. 9. Detailed parameters of the transmission system are shown in Table I.

A. Comparison of the Conventional and the Proposed Control Strategies

Fig. 10 shows the simulation results of the conventional and the proposed control strategies during power flow variation with 2p.u./s. In Fig. 10(a), if the conventional direct modulation based control strategy is employed, it can be observed that voltage fluctuation appears in the transmission line during power flow variation as stated in Section III. However, if the proposed indirect modulation based control strategy is employed, the voltage fluctuation is actively suppressed as shown in Fig. 10(b). The DC link voltage of the VR converter is kept constant as its rated value during power flow variation, and the DC link voltage of the PD converter varies slightly to compensate the voltage drop across the transmission line resistance.



(a) Simulation results of the conventional control strategy



(b) Simulation results of the proposed control strategy

Figure 10. Simulation results during power flow variation with 2p.u./s.

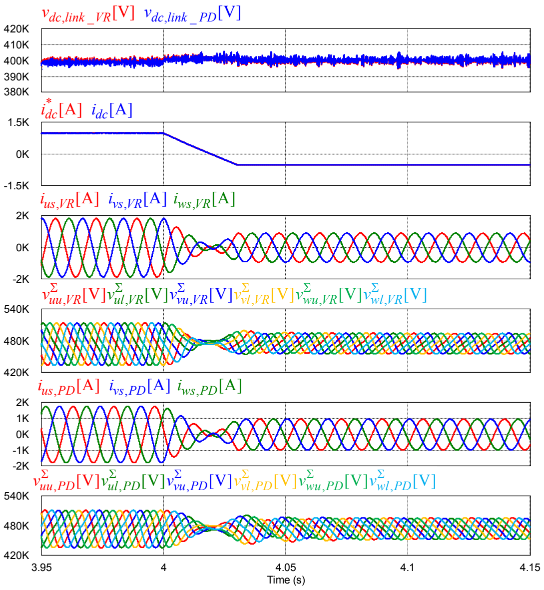


Figure 11. Simulation results of the proposed control strategy during fast power flow variation with 50p.u./s.

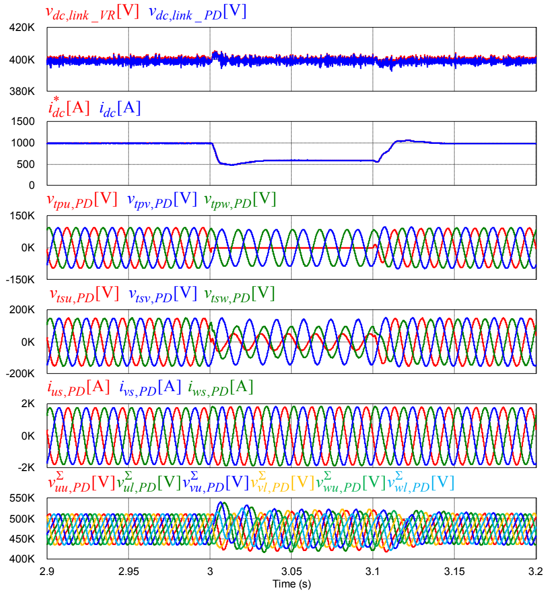


Figure 12. Simulation results of the proposed control strategy during SLG fault at full power.

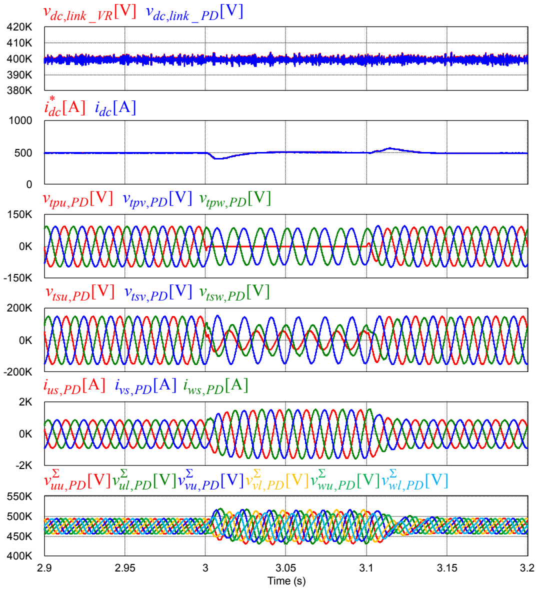
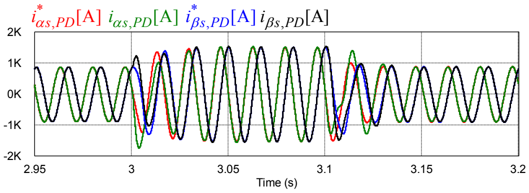
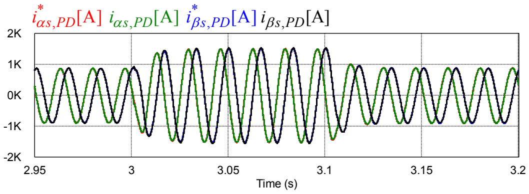


Figure 13. Simulation results of the proposed control strategy during SLG fault at light load condition.



(a) AC grid current regulation performance by the conventional DSRF controller.



(b) AC grid current regulation performance by the proposed SRF-PR controller.

Figure 14. Comparison of AC grid current regulation performance during SLG fault.

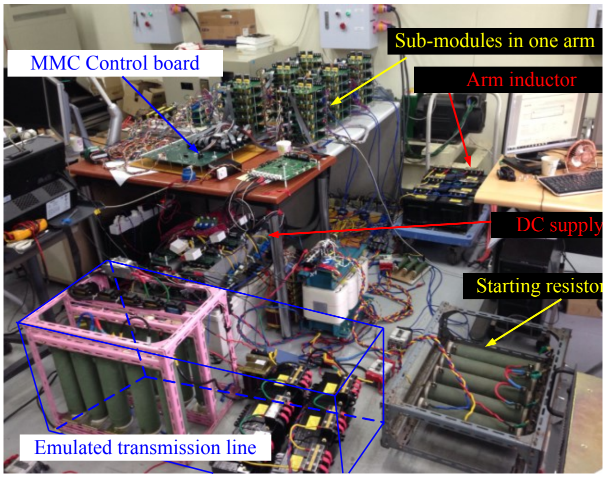


Figure 15. Constructed 300V/3kW down scale experimental setup of a point-to-point HVDC transmission system.

TABLE II. PARAMETERS OF THE EXPERIMENTAL SETUP

MMC converter	
Number of sub-modules per arm	6
Rated sub-module capacitor voltage	50V
Sub-module capacitor	5.4mF
Inductance of arm inductor	4mH
Resistance of arm inductor	5mΩ
Grid voltage	110V
Controller sampling frequency	10kHz
HVDC transmission line	
Rated voltage	300V
Rated current	10A
Transmission line inductance	27.0mH
Transmission line resistance	0.5Ω

B. *Performance during Fast Power Flow Variation*

Performance of the proposed controller during very fast power flow variation (50p.u./s) is verified as shown in Fig. 11. The power flow starts to change from 400MW to -200 MW in 0.03s. It can be observed that even during such a fast power flow variation, the transmission line voltage fluctuation is fully suppressed. The transmission line current tracks its reference value with very fast dynamics and the sums of the sub-module capacitor voltages of six arms are kept at its rated value 475.2kV well. With the conventional control strategies the same rate of power variation would result in severe DC link voltage fluctuation and whole system would be tripped.

C. *Performance during SLG Fault at Full Power*

Performance of the proposed controller during a SLG fault is verified while the transmission system is delivering 400MW full power as shown in Fig. 12. At 3.0s a SLG fault occurs at the Gird II and the fault is cleared at 3.1s. Since the magnitude of the positive sequence component of the grid voltage decreases to around 2/3 of the rated value during the fault, transmission capability decreases temporarily due to limitation of converter AC side current capability. It can be observed that no transmission line voltage fluctuation occurs during fault ride through and the transmission line current tracks its reference with fast dynamics. By the proposed control strategy, the sums of the sub-module capacitor voltages are recovered to its rated value in about 0.03s. It should be mentioned that a double line frequency fluctuation would appear in the transmission line voltage during SLG fault due to the active power fluctuation in the AC grid side if the conventional control strategy was employed [8]. However, since the DC bus of the MMC is fully decoupled from the AC grid side and the energy stored in the sub-module capacitors, the twice line frequency fluctuation in the transmission line is inherently prevented.

D. *Performance during SLG Fault at Light Power*

Performance of the proposed controller during a SLG fault is verified while the transmission system is delivering 200MW

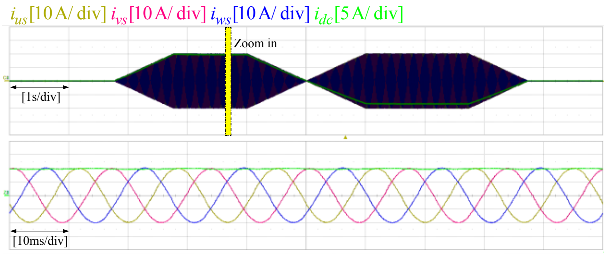


Figure 16. Experimental waveforms of three-phase AC current of the MMC and the transmission line current.

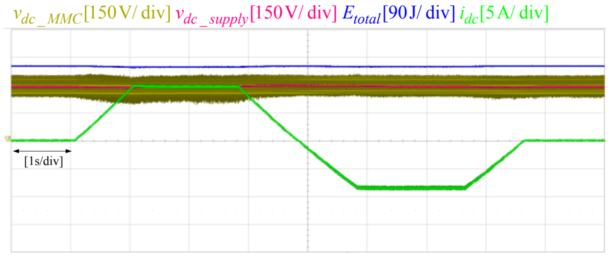


Figure 17. Experimental waveforms of DC link voltage of both stations, MMC total capacitor energy and the transmission line current.

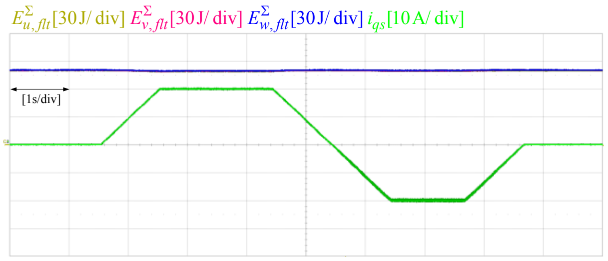


Figure 18. Experimental waveforms of sum of three phase leg capacitor energy and AC side active current of the MMC.

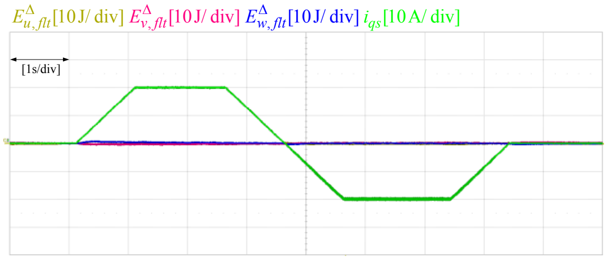


Figure 19 Experimental waveforms of three phase upper and lower arm capacitor energy differences and AC side active current of the MMC.

power as shown in Fig. 13. At 3.0s a SLG fault occurs at the Gird II and the fault is cleared at 3.1s. In such a light load condition, the AC grid side current of the PD inverter increases to maintain the original transmitted power. It can be observed that during the SLG fault, the transmission line current tracks its reference with enough dynamics and the sums of the sub-module capacitors of six arms are regulated as its rated value well by the proposed control strategy.

E. Comparison of AC Grid Current Regulation Performance

Performances of the AC grid current regulation by the conventional DSRF-based controller and the proposed SRF-PR controller are compared during SLG fault at 200MW light load. In Fig. 14(a), it can be observed that the AC grid side current cannot track its reference during transient by the conventional controller. However, there is no steady state error in the case by the conventional DSRF-controller. In Fig. 14(b), the AC grid current tracks its reference with excellent performance during transient without any steady state error.

V. EXPERIMENTAL RESULTS

A seven-level MMC prototype has been constructed in the laboratory to verify the proposed control strategy. The MMC converter operates as the PD converter and a two-level converter based DC supply is built up to emulate the VR converter. The transmission line is emulated by series connection of inductors and resistors. Fig. 15 shows the down scale experimental setup of the emulated point-to-point HVDC transmission system. Detailed parameters of the experimental setup are shown in Table II.

The transmission system varies the power flow from 2.7kW to -2.7kW in the experiment. Fig.16 shows three phase currents of the MMC and the transmission line current. The PD regulator, namely the MMC starts to draw current from the DC transmission line as long as it starts to export active power into the AC grid. While the power flows from the MMC into the AC grid varies from 2.7kW to -2.7kW, the transmission line current varies from 10A to -8.5A (Loss of the down scale MMC prototype is not negligible).

In Fig. 17, it's shown that during the power flow variation, the DC link voltage of the MMC varies slightly to regulate the transmission line current actively and no voltage fluctuation occurs. Since the MMC total capacitor energy is fully decoupled from the DC link voltage by the proposed control strategy, it's kept constant during power flow variation.

Fig. 18 shows the leg capacitor energy of three phases of the MMC, namely the sums of upper and lower arm capacitor energy of three phases. It's shown that by the proposed control strategy each sum of the leg capacitor energy is well regulated as its reference value 81J well during the power flow variation. Fig. 19 shows the upper and lower arm capacitor energy differences of three phases of the MMC. It's shown that the upper and lower arm capacitor energy are always balanced for three phases by the proposed control strategy during power flow variation. The results of Fig. 18 and the Fig. 19 mean that each arm capacitor energy of six arms is well regulated to reference value 40.5J by the proposed method during power flow variation.

VI. CONCLUSION

In this paper, a novel control concept of the MMC-based VSC-HVDC transmission system has been proposed. By the proposed control method, the DC bus side of the MMC is fully decoupled from the AC grid side and the energy stored in the sub-module capacitors. The DC bus side of the MMC acts as an active high bandwidth voltage source instead of a passive capacitor in the conventional method. In contrast to the conventional control strategy, the transmission line current can be controlled directly and actively and the voltage fluctuation in the transmission line has been fully suppressed by the proposed method even during a sudden power flow variation.

Different from the conventional control strategy, the twice line frequency fluctuation in the transmission line voltage is inherently avoided at unbalanced AC grid condition. A novel stationary reference frame based AC grid current regulator has also been proposed to improve current regulation performance in case of the sudden AC grid voltage unbalance such as a SLG fault. The validity and the advantages of the proposed method are verified by both full scale simulations and down scale experiments.

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