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A Novel Power Control Strategy of Modular Multi-level Converter in HVDC-AC Hybrid Transmission Systems for Passive Networks

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Abstract—**With the development of High Voltage DC Transmission (HVDC) technology, there will be more and more HVDC-AC hybrid transmission system in the world. A basic challenge in HVDC-AC hybrid transmission systems is to optimize the power sharing between DC and AC lines, which become more severe when supplying power for passive networks, as the surplus power can only flow back to power grids through the AC lines. To deal with this issue, it demands not only accurate system capability design but also flexible power control strategy of power converters in VSC-HVDC. This paper proposes a novel power control strategy of Modular Multi-level Converter in VSC-HVDC, which can optimize converter output power according to passive network loading variation. Proposal method is studied with a case study of a VSC-HVDC AC hybrid project by PSCAD/EMTDC simulations.**

Keywords—Modular Multilevel Converter, VSC-HVDC, Power Control Strategy, Hybrid Transmission

I.   INTRODUCTION

With the development of full-controlled power devices such as Integrated Gate Controlled Thyristors (IGCT) and Insulated Gate Bipolar Transistor (IGBT), high-voltage and high-power voltage source converters (VSC) have been widely used in power system, for instance Voltage Source Converter - High Voltage Direct Current Transmission (VSC-HVDC). Comparing with the conventional line commutated converters based High Voltage Direct Current Transmission (HVDC) using thyristors, VSC-HVDC has the advantage of operating without reactive power support from weak or passive networks, therefore is suitable for connecting renewable energy sources, interconnecting weak power systems and power supplying for passive networks e.g. large cities without power plants [1].

Besides traditional two-level and three-level voltage source converter, modular multilevel converter (MMC) has also been utilized in VSC-HVDC and plenty of research has been devoted into this domain [2-5]. Since the first commercial project Trans Bay Cable was put into operation in 2010 [6], first MMC-HVDC demonstration project in China was put into operation in Shanghai Nanhui since July 2011. This project aims to validate the feasibility of wind power integration by MMC-HVDC. The power generated by 11 wind turbines is transferred into AC grid by +/-30kV DC converters through 8km XLPE cable. More than two years operation experience and experimental results exhibit a satisfactory performance of MMC-HVDC on wind power transmission [7].

In contrast to traditional two-level and three-level VSC with pulse width modulation and IGBT in series connection, MMC obtains the required high DC operating voltage by series-connecting of plenty of half-bridge or full-bridge sub-modules with dc-capacitors [8]. With the sub-modules, the MMC avoids directly connecting IGBT in series which is not reliable due to voltage sharing difficulties during transients. MMC can achieve high power and voltage as well as redundancy by adding more sub-modules. Furthermore, output voltage of MMC has low harmonic distortion so no additional shunt filters is needed, which can reduce whole system cost while increase reliability level [9].

There are more and more research efforts devoted to the study of VSC-HVDC in China [10-12]. Especially, a large-scale MMC prototype is recently constructed in Zhejiang University, which contains 264 submodules (SMs) [13]. With the promising future of VSC-HVDC lines in China, a complex VSC-HVDC AC hybrid transmission system will be conformed in near future [14]. The HVDC-AC hybrid system has several advantages, especially for passive networks, for instance the megacities, and island grids which have few power plants. First, it can increase power supply capability while saving construction cost with the HVDC system, because it only needs two DC poles instead of three phases AC lines and can be constructed by underground cables. Second, it can increase the reliability level of distributed systems, because VSC can support the AC voltage by operating as STATCOM. What's more, it can black startup when the distributed systems are collapsed. Therefore, there will be more and more HVDC-AC hybrid transmission lines in distributed system in the future.

One of the challenges in HVDC-AC hybrid systems is the power flow sharing control. Currently, the power flow sharing of VSC-HVDC AC hybrid system is normally set as constant, which may cause extra power loss. For instance, when the load demanding of passive network is less than the VSC-HVDC capability, the surplus power can only flow back by the AC system, which will lead to extra power loss on the transmission lines. In order to solve this issue, this paper proposes a power control strategy of MMC for VSC-HVDC AC hybrid power systems for passive networks, with a case study of a VSC-HVDC AC hybrid project, which is studied by the PSCAD/EMTDC simulation. The paper is organized as follows: Section II introduces the principle and typical configuration of the HVDC-AC hybrid transmission system.

Section III illustrates the principle and implementation of the proposed power control strategy of hybrid transmission system. Section IV presents the case study of control strategy by a $\pm$320 kV/1024 MVA - 230 kV HVDC-AC hybrid system. The comprehensive simulation results evidently demonstrate the capability of the control strategy in power sharing between AC and DC lines. Section V concludes the paper with brief discussions.

II. HVDC-AC HYBRID TRANSMISSION SYSTEM CONFIGURATION

The typical diagram of VSC-HVDC AC hybrid transmission system configuration is shown as Fig. 1. The power grids busbars connect with VSC-HVDC converter station and AC system, and the power is transmitted by both AC and DC lines. For the HVDC-AC hybrid transmission system, there are four operation modes:

1) DC and AC system parallel operation

By closing the busbar breaker between AC and DC lines, the power flow can transfer via AC and DC system simultaneously. The power sharing between AC and DC lines is an open issue. Currently, the power capability of DC system is set as constant, which is usually as full load demand, therefore when the load demanding is less than the design capability, the surplus power will flow back by the AC system, which will lead to extra power loss on the transmission lines.

2) DC and AC system independent operation

While the busbar breaker is open, the power flow will transfer via DC and AC system respectively. The main advantage of this configuration is the power flow can switch between DC AC systems in case of either system has faults.

3) Single DC system

This mode works normally when there is a permanent AC fault, which can be achieved by open the breaker on the parallel AC system.

4) Single AC system

In case of DC cable is under fault, DC line will be open, and the VSC in converter station will act as a STATCOM to support the AC system voltage.

This paper will discuss the coordinating control strategy of MMC power converters in VSC-HVDC converter stations for DC AC parallel operation.

The circuit configuration of a three-phase n+1 levels half bridge MMC is as shown in Fig. 2. The DC bus bar is composed of three phase units in parallel, which include upper
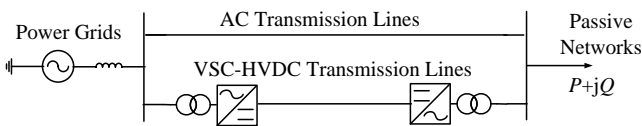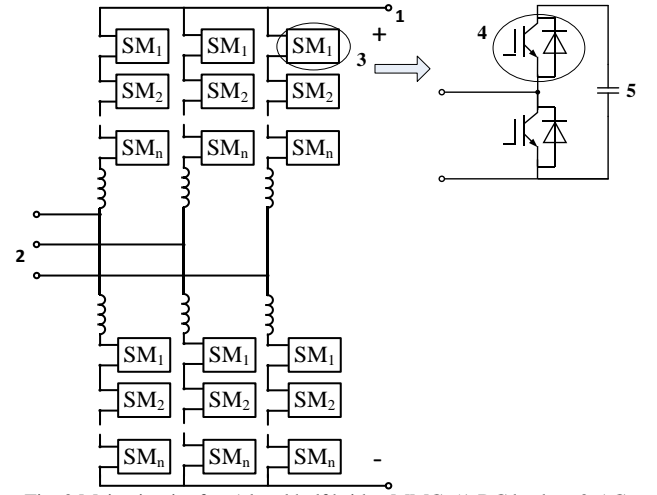

Fig. 2 Main circuit of n+1 level half bridge MMC. (1-DC busbar, 2-AC line, 3-sub-module, 4- full-controlled power devices e.g. IGBT IGCT, 5-high voltage capacitor)

bridge arm and lower bridge arm. Each arm has n sub-modules in series. One sub-module exemplary consists of two switches and provides either capacitor voltage or zero output voltage.

III. MODELING AND CONTROL STRATEGY OF MMC

The value of capacitor in the sub-module is normally high (usually several thousand uF), thus the voltage of the capacitor could be considered as voltage source. The output voltage of sub-module is switched by the switches. Thus each arm could be considered as a voltage source, and the output voltage is controlled by the control signal. The equivalent analysis circuit is as shown in Fig. 3, arm inductance L is connected with phase outputs u_a, u_b, u_c.

According to Kirchhoff's law, load output currents i_a, i_b, i_c are related to output voltages u_a, u_b, u_c as :

$$\begin{cases} L\dfrac{di_a(t)}{dt} = u_{a1}(t) - u_a(t) \\ L\dfrac{di_b(t)}{dt} = u_{b1}(t) - u_b(t) \\ L\dfrac{di_a(t)}{dt} = u_{c1}(t) - u_c(t) \end{cases}$$

$$(1)$$

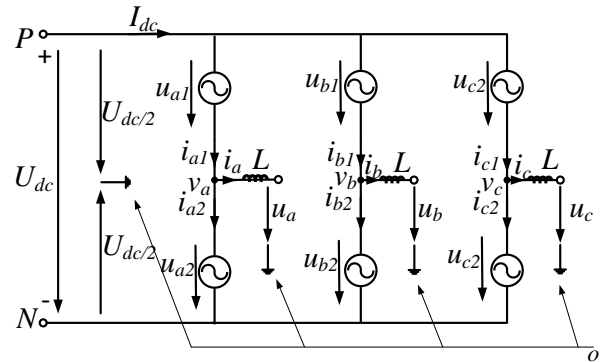Fig. 1.Typical diagram of VSC-HVDC AC hybrid transmission system.

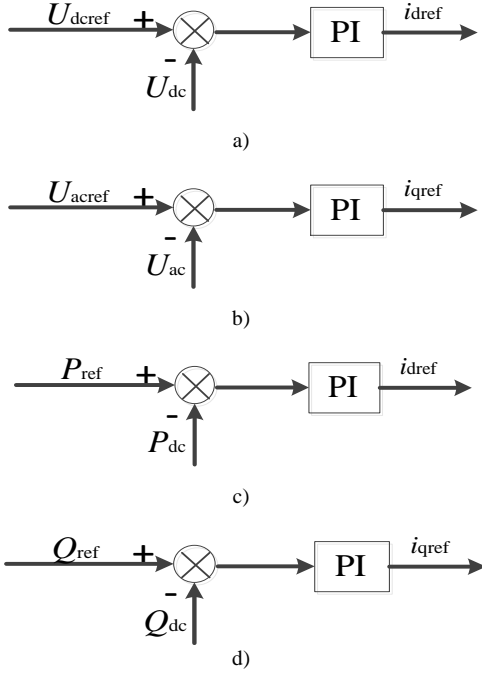Fig.3 Equivalent analysis circuit of MMC

Fig.4. a) i_{dref} control: DC voltage control, b) i_{qref} control: AC voltage control, c) i_{dref} control: Active power control, d) i_{qref} control: Reactive power control

With the d-q transformation, we can obtain:

$$\begin{cases} \dfrac{di_d}{dt} = \dfrac{1}{L}u_d + wi_q - \dfrac{1}{L}v_d \\ \dfrac{di_q}{dt} = \dfrac{1}{L}u_q - wi_d - \dfrac{1}{L}v_q \end{cases} \tag{2}$$

The instantaneous real and reactive power equation based on the d-q reference frame can be calculated, and under balanced steady state conditions, the d-axis coincides with the instantaneous system voltage vector (uq=0), thus

$$\begin{cases} P = 1.5u_d i_d \\ Q = -1.5u_d i_q \end{cases} \tag{3}$$

According to Eq. (3), the active and reactive power of MMC output can be set by controlling the d-q currents (i_d and i_q). The present outer control loop of MMC for supplying passive network is as shown in Fig. 4. At the rectifier side, the d-component current reference i_{dref} is controlled by the DC voltage regulator loops, and the q-component current reference i_{qref} is controlled by the AC voltage regulator loops. At the inverter side, i_{dref} is controlled by the active power regulator loops, and the i_{qref} is controlled by the AC Voltage regulator loops. Meanwhile, the i_{qref} also can be controlled by the
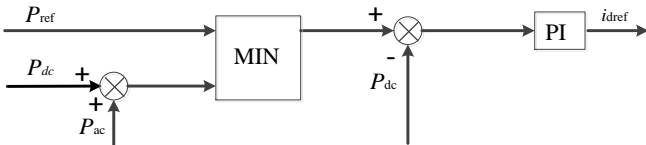

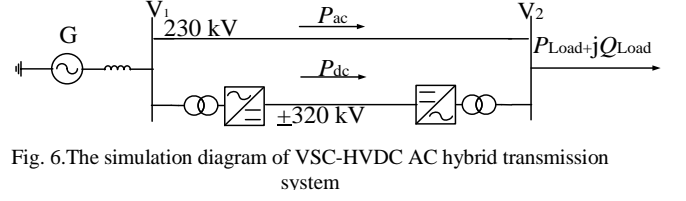Fig. 5.Proposal i_{dref} control: Active power control with the feedback of P_{ac}

Fig. 6.The simulation diagram of VSC-HVDC AC hybrid transmission system

reactive power regulator loops, shown in Fig. 4 d). As illustrated before, the active power of MMC output is set by the constant P_{ref} of the inverter side and controlling i_{dref}.

In the VSC-HVDC AC hybrid systems for passive networks, when the load of the passive network P_{load} is larger than the active power P_{dc} of the MMC output, the shortage of the power will flow by the AC transmission line from the power grids. The positive flowing power of AC transmission line P_{ac} is defined as power flow from power grids to passive networks. But if the P_{load} is less than the P_{dc}, the surplus power will flow back by the AC transmission line. Obviously the P_{ac} is negative then, and that will lead to extra power loss on the entire transmission systems, which is not desirable.

Therefore, the paper proposes a new control strategy of MMC with outer power control loop for the VSC-HVDC AC hybrid systems. In order to control the MMC output power, a power feedback loop is introduced in the outer control loop at the inverter side, as shown in Fig. 5, which feedbacks the AC power flow value. With the P_{ac}, modified reference power can be obtained for calculating the i_{def}. Through this proposal method, the MMC output power will decrease in case of power flow from passive networks to power grids through AC lines, which can decrease the power losses in the transmission lines.

IV. CASE STUDY AND SIMULATION RESULTS

In order to verify the proposed control strategies of MMC in VSC-HVDC AC hybrid system connected to the passive network, a hybrid transmission line model is established with the electromagnetic transient simulation software PSCAD/EMTDC. It consists of 230 kV/ 50 Hz AC transmission line and ±320 kV/1024 MVA HVDC transmission line, as shown in Fig. 6. The simulation diagram and the relative variables are also shown in Fig. 6. The MMC converters of VSC-HVDC have three phase 21-level, rated at 1024 MVA. The sub-module capacitor is 1800 µF and arm inductance is 0.05 H. DC cable length is set as 10 km, transformer is Yn/d type. The main parameters of the system are listed in Tab. I. Plenty of simulation results of the hybrid system under different conditions are obtained and shown in Fig. 7 to Fig. 11.

A. Simulation of HVDC Putting into Operation

The power sharing between AC/ DC lines when HVDC is putting into operation is shown in Fig. 7. At the beginning, the P_{load} is 1100MW, and the MMC is shutdown, and there is only the AC transmission line supplying the load of the passive network. The whole HVDC-AC hybrid system is working as mode 4 in Section II. Thus, the AC line power flow P_{ac} is 1100MW and the HVDC line power flow P_{dc} is 0 MW from beginning, as shown in the Fig. 7.

TABLE I THE MAIN PARAMETERS OF THE SYSTEM

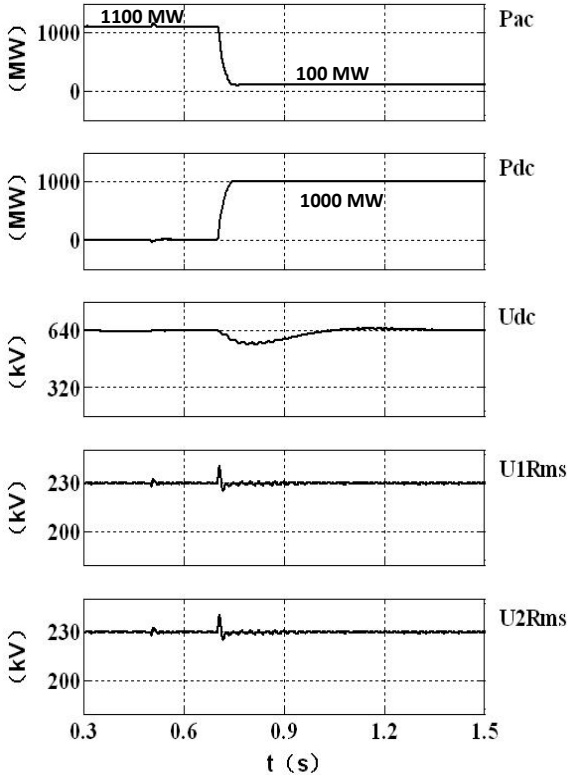| Items	Values	Remarks
Rated apparent power of MMC	1024 MVA	1.0 p.u.
AC system voltage U_{ac}	230 kV	
AC system frequency f	50 Hz	
Transformer ratio U_1/U_2	230 kV/370 kV	Yn /d
Transformer leakage reactance	0.01 p.u.	
DC cable Voltage $U_{dc}/2$	± 320 kV	
DC cable length	10 km	
Number of SMs per arm nSM	20	
SM capacitor C	1800 uF	
Arm inductance L	0.05 H	
SM capacitor Voltage Uc	32 kV	

Fig. 7.Simulation results of VSC-HVDC AC hybrid transmission system during the VSC-HVDC startup (0.3 s~1.5 s)
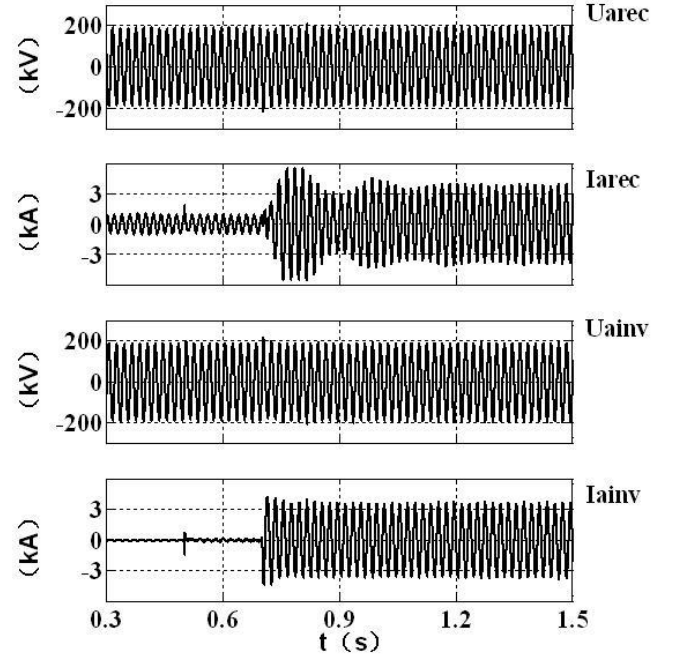

Fig. 8. Dynamic voltage/ current waveforms of VSC-HVDC AC hybrid transmission system during HVDC startup, with the proposal power control strategy (0.3 s~1.5 s)

At the 0.5 s, the MMC is starting up from the P_{ref} =0 MW, then there are tiny power fluctuations on the AC and DC transmission lines. At the 0.7 s, the P_{ref} of MMC is set as 1000 MW, then the DC power flow P_{dc} increases rapidly from 0 MW to 1000 MW and the AC power flow P_{ac} reduces to 100 MW. Finally, the hybrid system is working as DC/AC lines parallel operation, as shown in the Fig. 7. It can be seen that the AC line busbar voltage of both rectifier side (U_{1Rms}) and inverter side (U_{2Rms}) can be maintained constant during the HVDC startup.

Further details of the DC/AC system voltage and current waveforms during the transient are shown in Fig. 8. At 0.3 s, the MMC converter of rectifier side starts to operate, and output current (I_{arec}) increases. At 0.7 s, MMC on inverter side is putting into operation, and the currents increase on both sides corresponding to the power flow change. From Fig. 8, it could be clearly seen that the magnitude of the AC line voltages (U_{arec} and U_{ainv}) maintains constant during the transient state. Furthermore, it is worthy to note that both the AC voltages and currents are symmetrical with nominal frequency 50Hz.

B. Simulation of Proposal Power Control Strategy

In order to better showing the proposal control strategy, a simulation comparison between traditional control method and the proposal one is carried out in PSCAD based on the previous simulation.

At the 2s, the power consumption of passive network P_{load} reduces to 900 MW from 1100 MW. With the traditional common i_{dref} control strategy of MMC shown in Fig. 4, the HVDC transmission line power flow P_{dc} remains 1000 MW, and the AC transmission line has the negative power flow -100 MW, as shown in Fig. 9. This means 100 MW power is
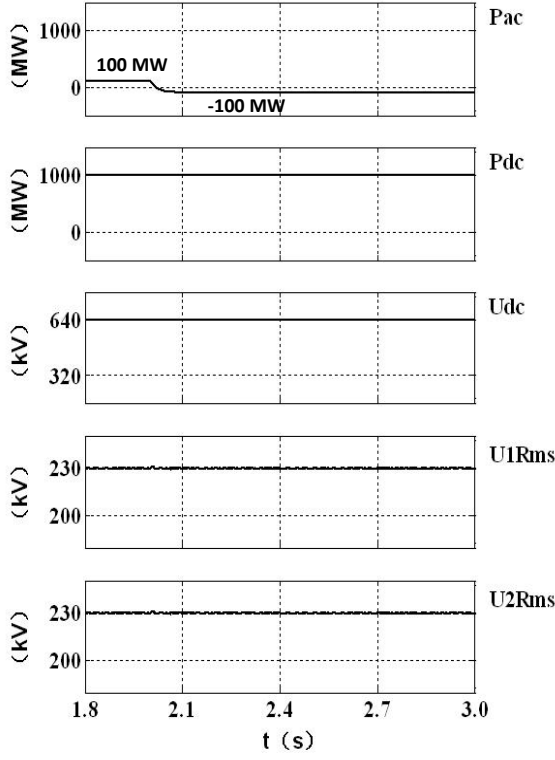
Fig. 9. Simulation results of VSC-HVDC AC hybrid transmission system during the passive network power consumption decreasing, with the traditional i_{dref} control strategy (1.8s~3s)
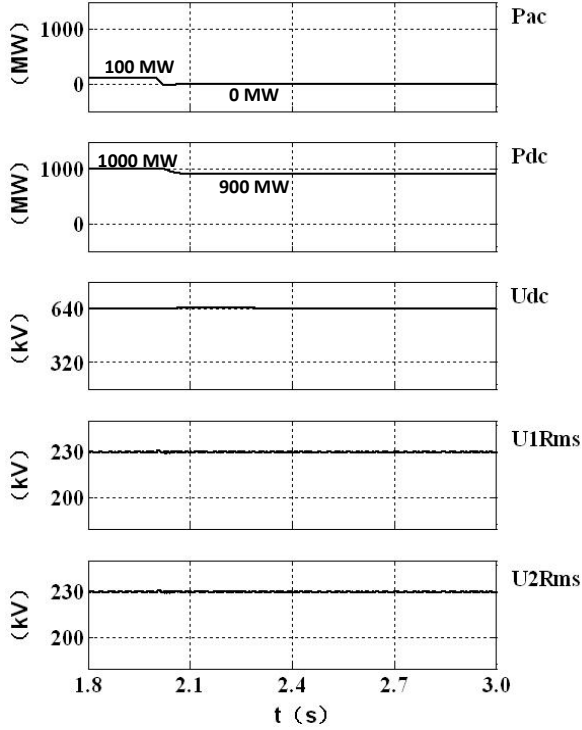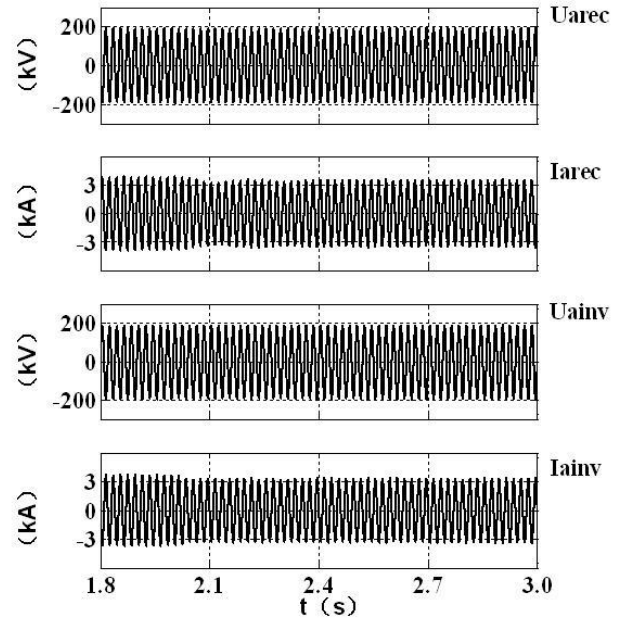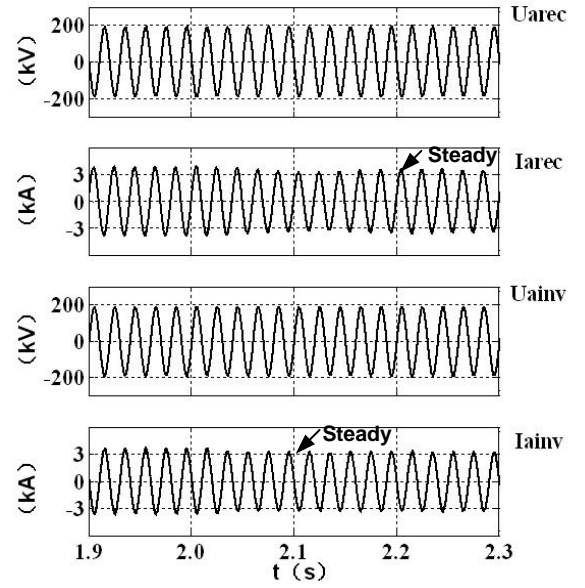

Fig. 10. Simulation results of VSC-HVDC AC hybrid transmission system when the passive network power consumption decreasing, with the proposal power control strategy (1.8 s~3 s)

a)

b)

Fig. 11. a) Dynamic voltage/ current waveforms during transient in Fig. 10, with the proposal power control strategy (1.8s~3s) b) further enlarge waveforms during 1.9 s~2.3 s.

flowing back to the supply grids through the AC line, which is not desirable and will unavoidably cause extra power loss to the whole system.

To solve this issue, the novel control strategy is utilized in the MMC control of HVDC line. With the proposal novel power (i_{dref}) control strategy of MMC shown in Fig. 5, the negative power flow through the AC line feedback to the MMC controller, and the MMC output power will be modified. As shown in Fig. 10, due to the proposal method, the HVDC transmission line power flow P_{dc} reduces to 900 MW from

1000 MW, and the AC transmission line has zero power flow, which means no power flow feedback to the supply grids. This shows that the proposed control strategy is effective and can eliminate the undesirable cycling power flowing.

The DC/AC system voltage and current waveforms during the power changing transient are shown in Fig. 11. At 2 s, the currents increase on both inverter and rectifier sides (I_{arec} and I_{ainv}) corresponding to the power flow change, while voltages on both sides (U_{arec} and U_{ainv}) keep constant due to the constant reactive power of the passive network, as shown in Fig. 11a). Further enlarge the waveforms, it could be clearly seen that the output current of the MMC quickly reaches the new stable value (within 0.1 s on inverter side while 0.3 s on the rectifier side) as shown in Fig. 11b). It can be noted that both the AC voltages and currents are stable with nominal frequency 50Hz during the transient.

V. CONCLUSION

The HVDC-AC hybrid system has several advantages for passive networks like the megacities, and island grids which have few power plants. It can increase power supply capability while saving construction cost by underground HVDC cables. It can also increase the reliability level of distributed systems, due to VSC's capability of supporting the AC voltage as STATCOM. There will be more and more HVDC-AC hybrid transmission lines in distributed system in the future.

This paper proposes a novel power control strategy of Modular Multi-level Converter in VSC-HVDC AC hybrid system for passive network, which can optimize HVDC converter output power according to passive network loading variation. With this method, the undesirable cycling power flowing through the AC line can be eliminated. The proposal control method is validated through the simulation in PSCAD/EMTDC, with a case study of a hybrid system consisting of 230 kV/ 50 Hz AC transmission line and $\pm$320 kV/1024 MVA HVDC transmission line. The simulation results well prove the effectiveness of the proposal method.

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