Comparison of Current Control Strategies in Modular Multilevel Converter

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***Abstract*— There is a need to transmit the power generated from windfarm in remote locations to the residential and industrial load. One of the suitable and economic solution for such long distance transmission of power is the High Voltage DC (HVDC) transmission. The Modular Multilevel Converter (MMC) based HVDC transmission is a proven technology with very high power quality.**

Results show that traditional method has better steady state performance, while MPC based method has much faster dynamic response and has the advantage of involving less control strategies in controlling systems with multiple control aspects. Different control strategies for capacitor voltage balancing and CC elimination are also simulated and compared.

Keywords—Modular Multilevel Converter, HVDC, Current control strategies, Capacitor voltage balancing, Circulating current suppression

I. INTRODUCTION

With the increasing demand of large capacity and long distance energy transmission, such as that for offshore wind farm, the HVDC transmission technology becomes more preferable and it is believed that HVDC will be the technology for future energy system[1]–[4]. In comparing with High Voltage Alternating Current (HVAC) system, the advantages of HVDC include: 1) the length of transmission not limited by surplus of reactive power as no shunt capacitance exists, 2) low losses and voltage drop on transmission lines, 3) being able to connect two asynchronous system, 4) fast and accurate control of power flow and quick fault isolation, 5) cheaper cost for long distance transmission.

The high power, high voltage transmission demands also increase the requirement for power converters. The MMC proposed in 2002 [5], [6] has offered the solution. It uses modular structure to achieve high voltage levels and less harmonics, thus is widely promoted, especially in HVDC applications[7]–[11]. Intense research has been done on MMC during past few years. Two main technical challenges about control of MMC are addressed due to the modular structure of topologies.

The first challenge is the capacitor voltage balancing[12], [13]. As Sub-Modules (SM) are inserted or bypassed at different parts of the power cycle, leading to asymmetric charging or discharging of individual capacitors, the capacitor voltage variation will occur, which make control system inaccurate and unstable[14]. Therefore, keeping SM capacitor voltage at constant value is key issue.

The second problem is about CC [15], [16], which is caused by the voltage differences among the three phases (here, CC only refers to AC components). Because CC only flows in three phase legs, they will not affect the AC-side voltages and currents, however, if they are not properly reduced, they will increase the RMS values of arm currents, thus increase the losses and give more stress on components[13]. So effective algorithms are needed for CC suppression.

In addition, for MMC based HVDC system, the active and reactive power control are necessary for energy transmission purpose[17], [18]. The main purpose of this paper is to review the recent control strategies of MMC associated with all these three control aspects and compare different algorithms by simulation based on the application of HVDC system. In order to focus more on control algorithms, only one side MMC of HVDC system will be studied.

The rest of the paper is organized as follows. Section II introduces some background knowledge about MMC including MMC structure and mathematical model. In Section III, voltage balancing algorithms, circulating current suppression algorithms and AC side current control algorithms are reviewed. After that, different strategies chosen to be simulated and compared will be introduced in Section IV. The simulation results are presented in Section V. Section VI includes conclusions and remarks.

II. STRUCTURE OF MODULAR MULTILEVEL CONVERTER

A. MMC structure

Fig.1 shows the structure of a three-phase MMC. Three phases are also called three legs. Each leg consists of an upper arm and a lower arm, both of which comprise N series-connected identical SM, which is shown in dotted box. There are different structures for SMs of MMC, the one shown in Fig.1 is half-bridge structure, which is the most popular one [13], [19] and will be used in this paper. The other types are summarized in [13]. In addition, each arm has a series inductor, which is used to limit high frequency components in the arm current.

As illustrated in Fig. 1, each SM has two switches and one capacitor. By controlling the switches, the output voltage of SM V_{SM} can be equal to capacitor voltage or zero, which are called SM inserted state or bypassed state respectively. The desired output AC voltages are achieved by choosing correct state combinations of all SMs. More detailed operation principle can be found in [5], [6], [20].

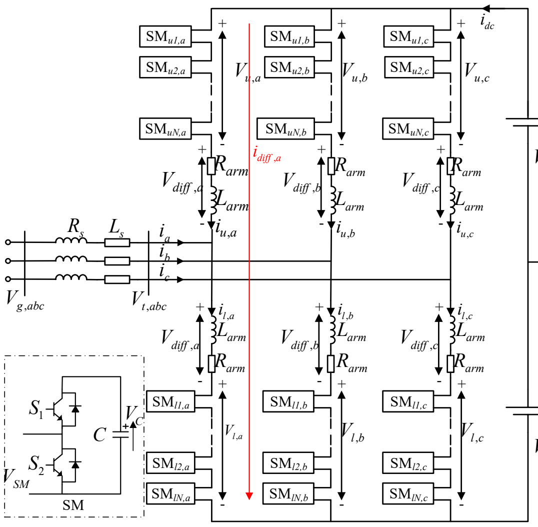

Fig. 1 The detailed diagram of MMC

B. Mathematical Model of MMC

As shown in Fig. 1, the total voltage on each arm is defined by $V_{k,j}$, where subscript k represents arms ($k=u, l$, representing upper and lower arm respectively); subscript j represents phases ($j= a, b, c$). $V_{diff,j}$ is the voltage drop on the arm impedance. CC of phase A shown by red line uses symbol $i_{diff,j}$. In AC side, the converter is connected to the grid with voltage $V_{g,j}$ and grid impedance R_s and L_s. The DC side of converter is connected to voltage sources with midpoint grounded. The directions of all quantities are shown in the diagram.

Based on Fig. 1 and Kirchhoff voltage law, the dynamic equations of MMC in phase j can be expressed by:

$$\frac{V_{dc}}{2} - V_{u,j} - R_{arm} i_{u,j} - L_{arm}\frac{di_{u,j}}{dt} + R_s i_j + L_s \frac{di_j}{dt} - V_{g,j} = 0 \qquad (1)$$

$$-\frac{V_{dc}}{2} + V_{l,j} + R_{arm} i_{l,j} + L_{arm}\frac{di_{l,j}}{dt} + R_s i_j + L_s \frac{di_j}{dt} - V_{g,j} = 0 \qquad (2)$$

Because of the symmetry between upper arm and lower arm, the AC side current will be equally divided into two parts flowing to upper and lower arm respectively. Similarly, due to the symmetry between three phases, the DC current will be equally divided into three parts for three phases. Therefore, the arm current can be expressed as:

$$i_{u,j} = \frac{I_{dc}}{3} + i_{diff.j} - \frac{i_j}{2} \qquad (3)$$

$$i_{l,j} = \frac{I_{dc}}{3} + i_{diff.j} + \frac{i_j}{2} \qquad (4)$$

where the $i_{diff.j}$ only represents the AC components.

Adding (1) and (2), and substituting i_j in (3) and (4), the outer dynamic equation for MMC is yielded:

$$(L_{arm} + 2L_s)\frac{di_j}{dt} = -(R_{arm} + 2R_s) i_j + V_{u,j} - V_{l,j} + 2V_{g,j} \qquad (5)$$

Subtracting (2) from (1) and substituting $i_{diff,j}$ in (3) and (4), the inner dynamic equation for MMC is yielded:

$$V_{diff,j} = L_{arm}\frac{di_{diff,j}}{dt} + R_{arm} i_{diff,j} + R_{arm}\frac{I_{dc}}{3} = \frac{V_{dc}}{2} - \frac{V_{u,j}+V_{l,j}}{2} \qquad (6)$$

where $V_{diff,j}$ is difference voltage.

According to equation (5), the AC side current can be directly controlled by $V_{u,j} - V_{l,j}$ and according to equation (6) $V_{u,j} + V_{l,j}$ (or $V_{diff,j}$) can be used to control the CC. These will be the basic theories for most of control algorithms for MMC introduced.

In addition, the equations for dynamics of SMs can be derived as discussed in [13]:

$$C\frac{dV_{cu,j}}{dt} = i_{u,j}\frac{n_{u,j}}{N} \qquad (7)$$

$$C\frac{dV_{cl,j}}{dt} = i_{l,j}\frac{n_{l,j}}{N} \qquad (8)$$

where $V_{ck,j}$ is the individual SM capacitor voltages, $n_{k,j}$ is the inserted number of SMs in upper and lower arms.

Equation (3) to (8) gives a generalized dynamic model of MMC.

III. MMC Control Schemes

In this section, the MMC control schemes for capacitor voltage balancing, circulating current suppression and AC side current control are reviewed.

A. Voltage balancing Algorithms

The sorting method is most widely used for SM capacitor voltage balancing control. The basic principle is that all the SM capacitor voltage are measured and sorted first, then if arm current is positive, the SMs with lowest voltages are inserted, so that they will be charged and voltages increase; otherwise, the SM with highest voltages are inserted, so that the capacitors will be discharged and voltages decrease [21]. This algorithm is simple and effective, however, unnecessary switching will occur and switching frequency increases. Many methods were proposed to solve the problem[12], [22]–[25]. In [26] a method based on carrier rotation is proposed. By rotating the carriers of PWM for each SM, the energy will be equally distributed to all SMs and voltage will be balanced. However, for more precise control, the capacitor voltages still need sorting. In [27] a method based on averaging control and balancing control is proposed. Two close-loop control are used to force individual SM capacitor voltage to follow the reference value. This method is more complicated than sorting method but can achieve flexible control on SM voltages. In [28], MPC is used to balance the SM voltages. By measuring the arm current, the SM capacitor voltage can be predicted according to equation (7) and (8) and desired performance can be achieved by minimizing the cost function.

B. Circulating Current Suppression Control (CCSC)

In [14], [29], methods based on energy control are proposed to suppress the CC by controlling the total energy and energy difference between upper and lower arm. In these papers, CC includes both AC and DC components and only AC components need suppressing as the conclusion is made that the AC component of CC will break the energy balance between upper and lower arm, while DC component is responsible for energy transfer between AC side and DC side of MMC. Based on same idea of controlling energy, a similar approach using mathematical optimization is proposed in [30] and shows better performance by simulation. Based on the idea of controlling the AC and DC component of circulating current separately, more methods are proposed [31], [32]. These methods suppress CC indirectly by controlling the energy or voltages of SMs. In addition, they can achieve single phase control, which is more flexible. Different from that, the CCSC proposed in [22] suppresses CC directly and treat three phases as a whole. It is built on the conclusion that the circulating current is in the form of negative sequence with double line frequency. As there are not only double line frequency component in the circulating current, but also even harmonics, [16], [33], [34] use Proportional-resonant (PR) controller and repetitive controller to eliminate these even harmonics. Hysteresis control is also used to suppress CC in defined band[15]. In addition, MPC is used to eliminate circulating current by adding related constraints to cost function in [28].

C. AC side current control

PI based control algorithm is the traditional method for AC side current control of voltage source converter. According to [17], [35], the control scheme for MMC applied in HVDC system is almost the same as that for 2-level converters [3], [36]–[38]. It is usually divided into two control loops: fast inner control loops and relatively slower outer control loops. Inner loop is current control in d-q frame and outer loop can achieved by active power or DC voltage control and reactive power control. It has the advantage of simplicity and robustness. Recently, MPC method is proposed as an alternative method for controller AC side current for 2-level VSC [39]–[43], as well as MMC [8], [28], [44]. Different from PI based method, MPC highly depends on the mathematical model introduced in Section II B. All three control terms are added into a single cost function, the desired performance is achieved by minimizing cost function. In addition, hysteresis current control method is proposed to control MMC [45], [46]. It is straightforward, but more effort is made on choosing voltage levels as the number of voltage level increases. Because of the inherent nonlinear dynamics of the MMC, nonlinear modelling and control are proposed to achieve more precise performance in [47], [48]. But they involve high computational effort.

IV. Comparison of Various Control Scheme

For each control aspects reviewed in last section, at least two methods with same control purpose are chosen and simulated in Matlab/Simulink environment for comparison. In addition, the study of MMC was based on the application of HVDC transmission system and the system diagram is shown in Fig. 2, in which the symbols have the same meaning as that in Fig. 1. Only one side converter is studied through simulation. The DC side was represented by DC voltage sources, or when DC voltage control is applied two resistors were connected to DC side to represent the rest of system.

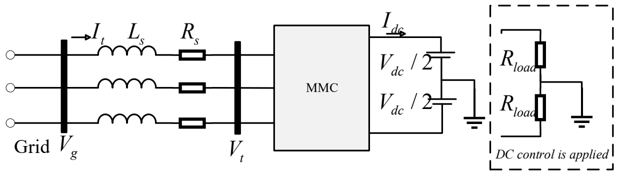

Fig. 2 The overall diagram of studied the system

In order to verify and compare different control algorithms, two cases are defined. Case 1 compares two CCSC methods and Case 2 aims to compare AC side current control algorithms and voltage balancing algorithms. Simulation results are shown in Section V.

A. Case 1: CCSC Comparison

In this case, two CCSC methods for comparison are defined (sorting method is used for both cases to balance voltages):

1) M1: Based on double line frequency negative sequence d-q frame [22].

The arm currents are measured and circulating current is calculated based on equation (3) and (4), which then are transferred to d-q frame but by setting the transfer angle double of fundamental one and input sequence to be negative. Two control loop are built for d and q axis respectively and the reference current is set to zero. The circulating currents before and after using the method are compared.

2) M2: Based on Energy control [14].

The voltages of SM capacitors on each phase are measured and the energy stored in upper and lower arm is calculated. Two control loops are built to control the total energy and difference energy respectively. The steady state performance and dynamic response will be tested and the circulating current before and after using the methods are compared.

As mentioned in review section, *M1* is a direct method, while *M2* is indirect for CCSC, which makes the comparison more meaningful.

B. Case 2: Two overall control scheme comparison

Either of two overall control scheme includes all three control strategies. The traditional PI based method and relative modern MPC based method will be compared. The control diagrams are shown below.

1) M3: PI based method[3], [17]

In this method, AC side current control is achieved by PI controller, *M1* in Case 1 is used to suppress the CC and sorting method is used for SM capacitor voltage balancing. Here the DC voltage control is used. The overall control scheme is shown in Fig. 3.

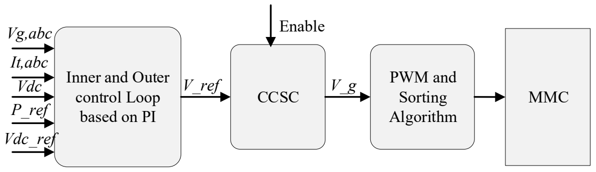

Fig. 3 Overall control Scheme of *M3*

2) M4: MPC based method[28]

In this method, all three control strategies are achieved by using MPC algorithm as shown in Fig. 4. The current reference is calculated by power equations according to desired active power and reactive power. In addition, the capacitor voltage balancing performance by using sorting algorithm and MPC is also compared.

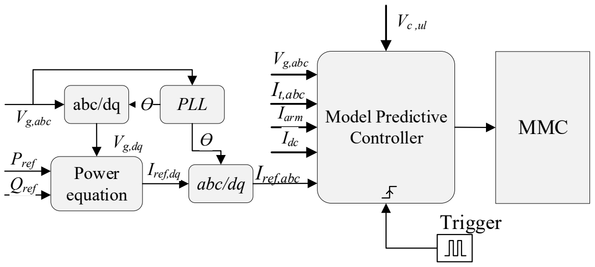

Fig. 4 Overall control Scheme of *M4*

C. Parameter Value

TABLE I
PARAMETERS FOR SIMULATION

Symbol	Meaning	Value
P	Active power	20 MW
Q	Reactive power	6.6 MVAr
V_g	Grid voltage (phase, peak)	14.14 kV
L_s	Grid side inductance	3.17 mH
R_s	Grid side resistance	0.062 Ω
$V_{dc}/2$	DC bus voltage	17.68 kV
N	Number of SMs per arm	6
C	SM capacitance	0.01 F
L_{arm}	Arm inductance	1.59 mH
R_{arm}	Arm resistance	0.1 Ω
V_c	SM capacitor voltage	5892 V
F_s	Carrier frequency	600 Hz
T_s	Sampling period (for MPC)	100 µs

The model parameters are summarized in TABLE I, which are mostly based on those used in paper [22], the modified parameters such as SM capacitor and inductance are chosen according to [49].

V. SIMULATING RESULTS

The cases defined in Section IV are simulated in Matlab/Simulink environment. All the results are shown in P.U. based on the value shown in TABLE I. In order to demonstrate the results better, the time periods from start up to steady state (0-0.4s) are ignored in the figures.

A. Case 1

1) M1

The simulating results are shown in Fig. 5. The CCSC algorithm was enabled at 0.5s as shown in Fig. 5(a). The CC is shown in Fig. 5(b) (the DC component was got rid of).

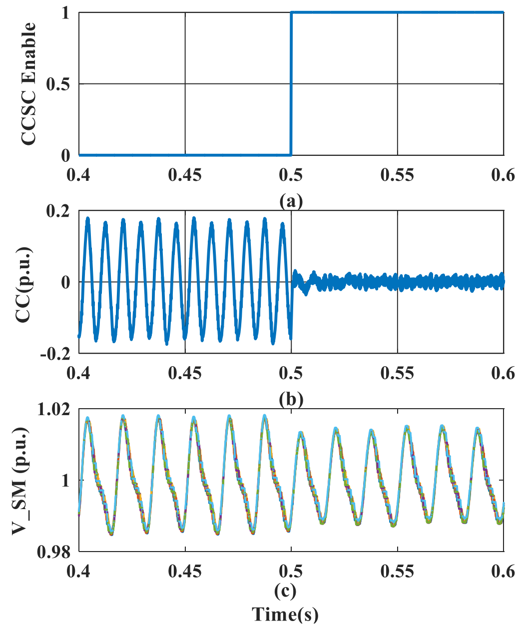

Fig. 5 (a) enable signal of CCSC; (b) circulating current (c) the capacitor voltages of phase A

As we can see, before CCSC was enabled, the circulating current was about 0.18 p.u. for peak value at double line frequency as expected. After enabling CCSC, it is reduced to less than 0.03 p.u. Figure 5(c) shows the voltage of all SMs on phase A, it is found that the CCSC also reduce the SM capacitor voltage ripple from about 3.25% to 2.75%. These clearly show well performance of this algorithm. The SM capacitor voltages are well balanced due to the usage of sorting method.

2) M2

The simulating results are shown in Fig. 6. The energy control is enabled from the beginning. At first, total energy and balance energy reference were at 1p.u. and 0 respectively until t=0.8s and t=1.3s, step changes were added to references one after another as shown in Fig. 6 (a) and (b). The total energy reference is upper limited by the SM capacitor voltage limitation, and lower limited by the maximum allowed modulation index otherwise it can be freely selected, while the balance energy reference should always be zero[14]. Here a step is added only for testing purpose.

From Fig. 6(c) and (d), the capacitor voltages in both upper and lower arm reached the new references in less than 0.1s with no steady state error, which show good responses of both control loops. As shown in Fig. 6(e), the circulating current is well suppressed from 0.15 p.u. as shown in Fig.5(b) before t=0.5s to less than 0.1 p.u. The ripple of SM voltages in Fig. 6(c) or (d) are about 3%. Compared with that shown in Fig.5(c), it reduces by 0.25% of rated AC side voltage.

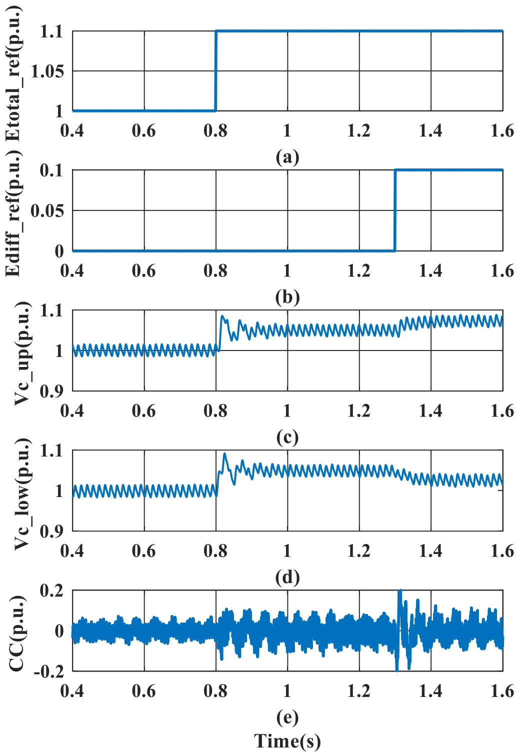

Fig. 6 (a) reference for total energy control (b) reference for balance control (c) upper arm capacitor voltages (d) lower arm capacitor voltages (e) circulating current

3) *Comparison between M1 and M2*

The comparisons between two methods are summarized in TABLE II. As we can see, the method *M1* is better than *M2* both in circulating suppressing and reducing capacitor voltage ripples. In addition, *M1* is easy to tune and synchronize with other controllers. One good advantage of energy control is that the DC energy can be controlled flexibly.

TABLE II
COMPARISON BETWEEN TWO CCSC METHODS (IN P.U. VALUE)

	No Controller	With M1	With M2
CC(peak)	0.18	<0.03	0.08
Voltage Ripple (p-p)	3.25%	2.75%	3%
Tuning		Easy	Hard
Other Function		No	Energy Control

B. *Case 2*

1) *M3*

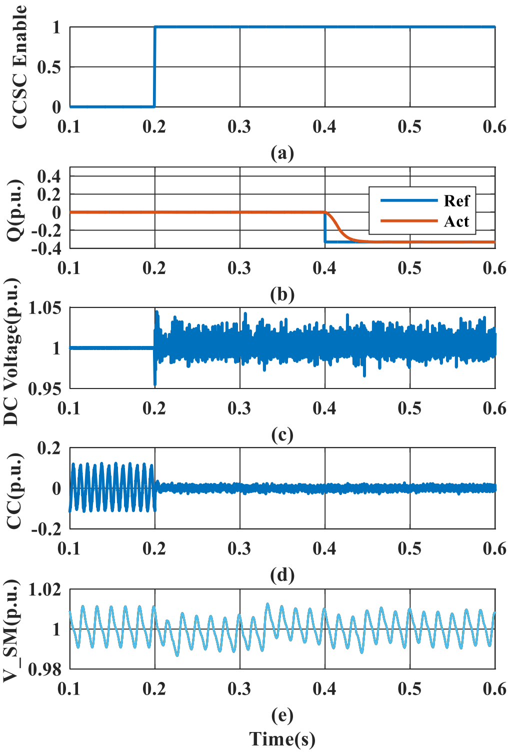

Fig. 7 (a) enable signal of CCSC (b) reactive power and reference value (c) DC bus voltage (d) circulating current (e) SM capacitor voltages in upper arm of phase A

The simulation model block diagram is based on Fig. 3. The results are shown in Fig. 7. At t=0.2s the CCSC is enabled as shown in Fig. 7(a) and at t=0.4 the reactive power has a step change from 0 p.u. to 0.33 p.u as shown in Fig. 7(b). It can be seen that the reactive power followed reference in Fig. 8(b) without steady state error and transient process lasted for about 0.03s with no overshoot. The DC bus voltage in Fig. 7(c) was not affected by the step change of reactive power and kept at 1p.u. by DC control. From Fig. 7(d) and (e), the CCSC effectively reduced CC from about 0.15p.u. to almost zero both before and after the reactive power change. However, it brought about 3% noise on DC bus voltage as shown in Fig. 7(c). In addition, CCSC also injected oscillation on SM voltages with period about 2.5s, which is slow and the cause needs further study. Besides that the results verify the good performance of target control scheme. Also, it is proved that all three controllers can operate together well without unacceptable mutual effect.

2) *M4*

Based on Fig. 5, all three constraints are added to cost function. The tuning of weighting factors is based on the empirical method presented in [50] and value of them chosen in the following simulation is λ_v= 6, λ_{cir}=1 and λ_{ac}=1 for voltage balancing control, CCSC and AC side current control respectively.

A trigger block was used in the model to force the MPC function executing only once every 100 μs. In this way, the switching frequency was fixed and could be varied according to requirement.

Simulation results are shown in Fig. 8. As the time period from start up to steady state is longer than *M3,* the time starts from 1.5s.

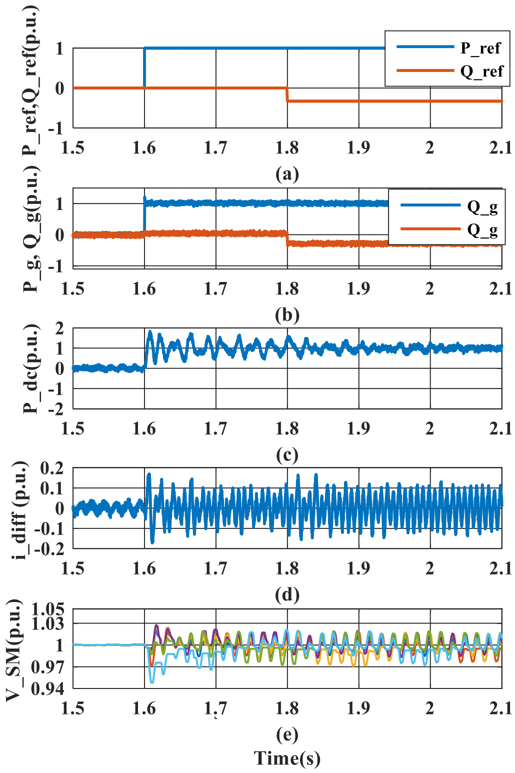

Fig. 8 (a) active and reactive reference (b) measured active and reactive power at grid bus (c) active power transferred to DC side (d) circulating current (e) SM capacitor voltages in upper arm of phase A

Initially, the system operated with both active and reactive power reference being zero as shown in Fig. 8(a) and (b) from t=1.5s to 1.6s and both capacitor voltage balancing and circulating current control were enabled. At t= 1.6s, a step change was assigned to active power reference to transfer 1p.u. active power from AC side grid to DC side. At t= 1.8s, reactive power command was step changed to transfer 0.33 p.u. power from DC side to AC side as shown by Fig. 8(a). Fig. 8(b) are the measured power. Comparing these two diagrams, it could be seen that both active and reactive followed the reference with very fast dynamics responses, the rising time is in the orders of switching period and about 300μs. The steady state error is zero, but the ripples of active and reactive are about 5%, which is a little bit high. Fig. 8(c) illustrated the power transferred to the DC side, which changed from zero to 1p.u after step change of active power reference as expected. But there were oscillations observed during transient, the overshoot reached almost 100%, which will increase the stress for DC bus capacitor. Fig. 8(d) and (e) show the CC and SM capacitor voltages respectively. The CC were suppressed to about 0.1p.u. and the ripple of SM capacitor voltage is kept under 5%. However, the SM capacitor voltages are not strictly balanced, the differences are up to 3% of rated value.

3) Comparison between M3 and M4

Two method are compared and summarized below:

1) **Performance of circulating current elimination and voltage balancing.** Comparing Fig. 8(d), (e) and Fig. 7(d), (e) respectively, it is found that both method controlled the CC and capacitor voltage in an acceptable range, but traditional method had an obvious better performance on both of them. Using traditional method, the CC was suppressed to almost 0 compared to 0.1p.u.(peak value) by MPC; the voltages were in perfect balance in each arm and the ripple was about 2% compared to 3% SM voltage difference and 5% ripple by using MPC.
2) **Performance on reference following and dynamic response.** Comparing Fig. 8(b) and Fig. 7(b), for steady state performance, traditional method resulted in less error between reference and real power, which was almost zero, while MPC resulted in about 5% ripples. However, MPC had considerably faster dynamic respond. It took about 300μs for MPC to reach the new reference value after step changes, comparing 30ms for PI based method.
3) **The simplicity of the system.** Using MPC, the model of entire system must be known, which makes control system complex and reduces the robustness. However, MPC can control the AC side current, SM voltages and circulating current at the same time, while for traditional method, three separate controllers are needed for three control purposes. In this aspect, MPC based system is more succinct as less algorithms involved and less parameter adjustment needed, also no special care needed for synchronizing different controllers.

VI. Conclusion

In this paper, control strategies in SM voltage balancing control, circulating current control and AC side current control for MMC are reviewed. In addition, some of the control strategies were simulated and compared in Simulink by applying MMC in HVDC system. It is concluded that method based on double line-frequency d-q coordinate for CCSC has superior performance over energy control method in circulating current suppression, while the advantage of energy control is that it can control the arm energy flexibly. In addition, Compared to MPC in circulating current control part, both double line-frequency d-q coordinate and energy control methods performed better. As for AC side current control, traditional PI based method has better performance on reference tracking, while MPC results higher ripple around references. However, much faster dynamic responses were achieved by MPC. Also, MPC can achieve all three control purposes at the same time, which is an advantage for MPC in controlling the system with multiple control aspects.

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