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PCC Voltage Compensation Scheme of MMC-MTDC System for Transient Stability Enhancement Under Communication Delay

XICHANG WEN, (Member, IEEE), JIANCHUN PENG, (Senior Member, IEEE), SADDAM AZIZ, (Member, IEEE), AND HUI JIANG
College of Mechatronics and Control Engineering, Shenzhen University, Shenzhen 518060, China

Corresponding author: Hui Jiang (huijiang@szu.edu.cn)

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ABSTRACT Multi-terminal High Voltage Direct Current (MTDC) with modular multilevel converter (MMC) is a promising technology, because it integrates diverse energy resources. However, there is still a risk for transient stability of a system with MMC in the case of communication delay. In order to improve the transient stability of hybrid AC/DC networks, the point of common coupling (PCC) voltage compensation scheme is proposed for MMC-MTDC to maintain stable operation when communication delay occurs. Based on the established closed-loop network control system (NCS) which the MMC-MTDC participates in, the proposed control strategy utilizes the multi-layer control according to the dynamic characteristic of MMC-MTDC, and compensates the PCC voltage in the controller input signal to reduce inaccuracy case by time delay, thus offset the negative effect of communication delay on power system transient stability. The proposed control method is fully investigated in a MMC-MTDC model based on 4-generator 10-node system model and the simulation results clearly indicate the proposed strategy can effectively enhance transient stability of system.

INDEX TERMS Modular multilevel converter (MMC), multi-terminal direct current (MTDC), transient stability, communication delay, multi-layer control, point of common coupling (PCC) voltage, compensation scheme.

I. INTRODUCTION

The increase of renewable energy sources has changed the operation of power system which required better stability. In order to cope with this change, the power technologies used in the transmission system need to become more flexible. Multi-terminal direct current (MTDC) grids can provide the possibility of meshed interconnections between regional power systems and various renewable sources of energy, which can potentially enhance reliability of the AC and DC systems, improve flexibility and economy of power dispatching [1], [2]. Future, dc grids are likely to be based on modular multilevel converter (MMC) which has become the most attractive converter topology for high power and medium/high voltage applications in recent years [3]. In comparison with the other multilevel converter topologies, the salient advantages include its modularity and scalability to meet any voltage level requirements, high efficiency, inherent fault-tolerance capability and excellent fault-blocking capacity. Therefore, the MMC has become the basic building block for MTDC systems and DC grids [4].

However, there are many challenges to resolve before MMC-MTDC grids are incorporated. To improve system performance, it is essential to improve the stability of MMC-MTDC systems [5], [6].

MMC-MTDC systems still applies the control strategies of the voltage-source converter-based multi-terminal high-voltage direct current (VSC-MTDC) systems currently. Their control strategy is layered upon two conditions: DC voltage control and AC-side auxiliary control. DC voltage control is used to stabilize DC grid operations, which balances the active power, and determines the power flow and

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sharing [7], [8]. On the other hand, the MMC-based AC-side auxiliary control of converter stations could provide auxiliary support to the AC systems, and it enhances stability of its operation [4]. The MTDC systems can also offer additional control function to improve system transient stability [6]. Such as, power oscillations control, which compensates the oscillations of AC system, by exchanging extra power, and modifying the DC power reference [9]. As in [10], it develops an electromechanical transient modeling of MMC based MTDC systems, for studying large-scale systems. Furthermore, the influence of the energy management of the MMC on the system dynamics is depth analysis, and compared by different types of MMC controllers [11].

To the best of our knowledge, the consequence of remote communication on the transient stability has not been considered prior in MMC-MTDC system modeling, and the network uncertainty in the process of information transmission is completely ignored. In reality, with the rapid development of information and communication technology, the traditional power system is gradually changing into Cyber physical power system (CPPS). CPPS consists of analog, interactive digital, power systems, and intelligent components designed for function through integrated logic and design. CPPS is the foundation of the future smart grid. However, CPPS relies heavily on network stability [12], which also brings network uncertainty of power system, such as communication delay, packet loss, etc. Communication delay has an important impact on the economic operation, and real-time control of power systems [13]. For example [14], analyzed the effect of communication delay, and packet loss on the stability of closed-loop control in wide-area power systems, and proposed an advanced damping control based on Q learning. New energy forecasting and distributed technology also provide a solution to network uncertainty [15]–[18]. However, the research related on this subject has trifle consideration. Therefore, it is critical for long distance MTDC transmission system to take into account communication delay problem, and propose a viable solution for aforementioned problem.

For this reason, a transient support scheme considering network uncertainty is proposed, which is based on combining MMC and MTDC. Compared with other articles, which improves transient stability, the contribution of this paper is as follows: to express the control problem, power system participate in transient stability as a general network control system (NCS) with network uncertainty (mainly refers to communication delay), and use this framework to quantify the influence of communication delay on NCS, for the improvement of transient stability. Secondly, the proposed control scheme which is based upon MMC-MTDC is designed such that it can efficaciously mitigate the network delay. The biggest advantage of this scheme is that it can take into account the two control layers of the MMC at the same time. Considering the communication delay, this scheme not only keeps the dc voltage control stability of the outer ring, but also considers the core control effect of the MMC output current to achieve the optimal control effect. Finally, the efficacy of the proposed model and scheme is widely verified in the constructed MMC-MTDC system with 4 generator, and 10 nodes.

The rest of the paper is organized as follows. In Section II, the dynamic process of converter based on MMC is introduced, and then state equation of controller is obtained. Then, in Section III, based on the assumption of generator set load model, an AC/DC hybrid system with 3 ports is proposed for a traditional 4-generator, and 10 nodes AC system. In Section IV, the controller and proposed scheme is incorporated to deal with the stability under Cyber uncertainty. Lastly, the computer generated simulation results considering AC, and DC system is carried out to verify the effectiveness of proposed controller approach to deal with the communication delay, and show the novelty of proposed scheme in realistic manners.

II. MMC-MTDC AND NETWORK MODEL

In order to facilitate research, this paper establishes MMC circuit model, and introduces its mathematical model in this section, and then adjoin it with the model of MTDC, generator, communication network, and introduces the operation of system.

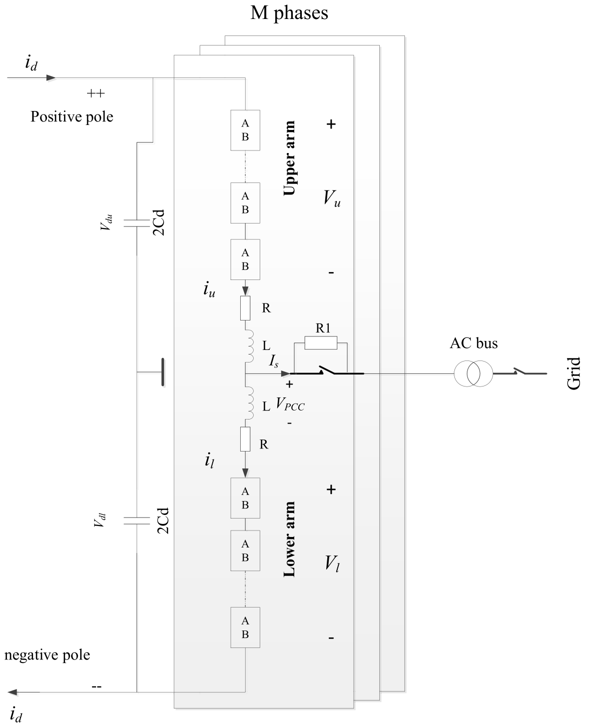


FIGURE 1. Circuit diagram.

A. MMC MODEL

A per-phase schematic of the MMC is shown in Fig.1 [19]. For the purpose of dynamic modeling, the dc bus can generally be understood as having pure capacitive characteristics, with a capacitance $2C_d$, from the neutral to the positive poles, and negative poles respectively, i.e. a pole-to-pole capacitance. V_{PCC} represents the point of common coupling voltage of MMC-MTDC and AC grid. These capacitances represent a lumped model of the pole-to-neutral capacitances of the positive and negative-pole dc cables interconnecting two MMC's in a high-voltage direct current (HVDC) transmission. The dc bus is assumed to be balanced, i.e. except where noted,

$$V_{du} = V_{dl} = V_d/2 \tag{1}$$

The subscript u represents the upper arm. and the subscript l represents the lower arm. For the same, the current is defined as i_u, i_l respectively. To make calculation easy and taking control perspective, following linear transformation is defined as follows:

$$\begin{aligned} V_s &= (V_l - V_u)/2 && (2)\\ V_c &= (V_l + V_u)/2 && (3)\\ I_s &= i_u - i_l && (4)\\ I_c &= (i_u + i_l)/2 && (5) \end{aligned}$$

Their physical meaning can be explained as: I_s refers to the phase current in the AC side, then V_s refers to the internal electromotive force (EMF) of each phase arm driven as I_s. I_c refers to the average current of each phase arm, then V_c is the voltage that driving this current.

Converter operating principle is the foundation on which the control designs of the subsequent sections are built. Assuming that the dc bus is balanced, the nodal equations governing the arms are:

$$\begin{aligned} V_d/2 - V_u - Ri_u - L\frac{di_u}{dt} &= V_{PCC} && (6)\\ -V_d/2 + V_l + Ri_l + L\frac{di_l}{dt} &= V_{PCC} && (7) \end{aligned}$$

Subtracting equation (6) and (7), and taking into account the output and circulating current relationships from equation (2) and (3), it results into

$$\begin{aligned} \frac{L}{2}\frac{di_s}{dt} &= \frac{-V_u + V_l}{2} - V_{PCC} - \frac{R}{2}i_s && (8)\\ L\frac{di_c}{dt} &= \frac{V_d}{2} - \frac{V_u + V_l}{2} - Ri_c && (9) \end{aligned}$$

The rationale approach for naming V_s as the output voltage now becomes obvious: V_s drives the output current I_s, as shown in the first relation. In a similar fashion, the internal voltage V_c drives the circulating current I_c(but with opposite sign).

One fundamental step in the design of the control system for a MMC is to find appropriate selections of the insertion indices n_u and n_u. $n_{u,l} = 0$, which implies that all sub-modules are by passed, then they will have $V_{u,l} = 0$. $n_{u,l} = 1$, which implies that all sub-modules are inserted, then there will be $V_{u,l} = V_{cu,cl}$. So n_u and n_l can be solved as follows:

$$n_u = \frac{V_c - V_s}{V_{cu}}, \quad n_l = \frac{V_c + V_s}{V_{cl}} \tag{10}$$

B. GENERATOR MODEL

This paper focuses on the electromechanical transient analysis of generator rotor; it uses the well-known classical fourth order generator model, which is considered to be sufficiently accurate for stability analysis. In this model, damp windings are ignored, but the effect of damping can be accounted for by increasing the damping constant D. The differential equations governed by this process are as follows:

$$\begin{aligned} \dot{\omega} &= \frac{\pi f}{H}(-D(\omega_0 - \omega) + P_m - P_e) && (11)\\ \dot{\delta} &= \omega_0 - \omega && (12)\\ \dot{E}_q &= \frac{1}{T'_{d0}}(E_{fd} - E'_q + (x_d - x'_d)I_d) && (13)\\ \dot{E}_d &= \frac{1}{T'_{q0}}(-E'_d + (x_q - x'_q)I_q) && (14) \end{aligned}$$

The algebraic equations are:

$$\begin{aligned} I_d &= (v_q - E'_q)/x'_d && (15)\\ I_q &= -(v_d - E'_d)/x'_q && (16)\\ P_e &= E'_q I_q + E'_d I_d + (x'_d - x'_q)I_d I_q && (17) \end{aligned}$$

And

$$v_d = -U\sin(\delta - \theta),\ v_q = -U\cos(\delta - \theta) \tag{18}$$

In differential equation δ is the angle of the rotor q axis of the generator relative to the synchronous rotating coordinate axis; ω is the angular speed of the generator rotor; H is the mechanical of the generator rotor's inertia constant; P_M is Mechanical output power of the turbine; P_e represents generator electromagnetic power; x_d, x_q represents d, q-axis reactance of generator; x_d, x_q is d, q-axis transient reactance; T_d, T_q is d, q-axis time constant. In algebraic equations E_d, E_q is d, q component of transient voltage behind reactance; v_d, v_q, θ, represents d, q-axis of stator voltage, and θ represents generator angle in degrees. In this paper, all loads in grid are modeled as constant admittances.

C. MODEL OF MTDC SYSTEMS

Based on the MMC-MTDC, the 4-generator 10-node AC/DC system is shown below in figure 2. The DC ports 1,2,3 (T1,T2,T3) are connected to nodes 2,10,8 respectively in the ac system through the converter 1,2,3(C1,C2,C3). The power flow of ac and dc system can be calculated separately.

The power system is represented by a system of differential-algebraic equations

$$\begin{aligned} \dot{X} &= F(X, Y, P) && (19)\\ 0 &= G(X, Y, P) && (20) \end{aligned}$$

where X represents the state variables, Y are the algebraic variables and P are parameters. In this paper, the set of differential equations F consists of the dynamic equations of the generators, while the algebraic equations contain the power flow equations, and the stator current equations of the generators.

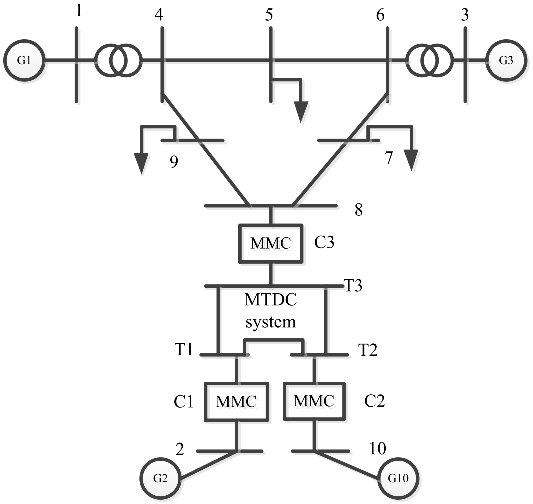


FIGURE 2. The framework of model MMC-MTDC.

The program flow uses MATPOWER obtain a power flow solution. It then calculates and constructs the augmented bus admittance matrix and proceeds with calculating the initial conditions of the generators, if the power flow converged. If the system is in steady-state, the main loop is started. The set of differential equations F is integrated, and the set of algebraic equations G is solved. If an event occurs, the augmented bus admittance matrix and the algebraic equations G are reconfigured, consisting of the network equations, and stator current equations are recalculated, until the system reaches a new equilibrium point or it deviates from equilibrium point.

In this model, the modified Euler method is used to solve the differential equation, which is often used in power system analysis computer programs. The variables are sent to the signal receivers in all parts of the grid, and the operation state is adjusted. At the same time, the power grid control system takes the *Y*, *X* that have changed (or hold state), as the input value at the next moment, until the simulation time is over.

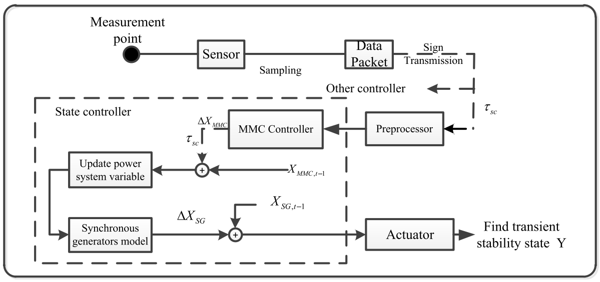


FIGURE 3. Framework of the NCS formulation for MMC-MTDC.

D. SIGNALTRANSMISSION OF COMMUNICATION NETWORK

The signal transmission problem of multi-terminal HVDC transmission system is expressed as a general network control system (NCS) problem, considering communication delay in this paper, there is network uncertainty. Figure 3 shows the entire framework of the closed-loop NCS in which the general MMC-MTDC participates in the stability of the system. As shown in the figure, the sensor first measures the data on each given bus at each control interval. A wide area measurement system (WAMS) is used to sample signals such as voltage, and current at a fixed sampling interval, and then packs the sampled digital signals into packets, which are transmitted to the corresponding controller along different communication network paths, and then they are utilized to generate control signals after processing at the front end of the controller. The reference control signal is transmitted to the corresponding actuator to realize the closed-loop control and stability support for the power system.

Apparently, the communication network part plays a vital role in the closed-loop control process. But unfortunately, network uncertainty, such as communication delay, and packet loss may occur during signal transmission. These network defects will affect the quality of signal transmission, and it turn affect the transient stability performance of power system. Specifically, assuming network defects exist, the signal received by the controller at *k-th* time is not the real-time corresponding signal transmitted by the sensor at *k-th* time, but the non-corresponding signal after the communication delay of the forward channel. Because the controller always lags the real-time signal and can't calculate the effective control signal in time, the performance of the control strategy is affected. Similarly, the network uncertainty also exists in the feedback communication channel from controller to actuator. In this paper, only the network uncertainty in the process of long-distance signal transmission channel is considered. As a result, it is pertinent to establish a model, which takes into account communication delay in MMC-MTDC system, and frame a control strategy which compensates it. A simple MMC-MTDC model considering communication delay is presented in Figure 3.

III. CONTROL MODEL WITHPCC VOLTAGE COMPENSATION SCHEME

In this section, by combining the proposed PCC voltage compensation scheme with control strategy is presented which can resolve the delay issues. In order to track and control the output and circulating current signals of MMC that are critical to system stability, MMC based multi-layer control is introduced in this part.

A. HIGHER-LEVEL CONTROL

The high-level is the dc bus voltage control, which adjusts the reference value of output current by changing the active power of the converter. Adjusting the output current reference is simple but critical.

$$dP = Kp^{*}(P_{ref} - P) \tag{21}$$

$$Cd'^{*}\frac{dV_d}{dt} = id - P/V_d \tag{22}$$

Available through conversion

$$\frac{Cd'^{*}}{2}\frac{dV_d^2}{dt} = P_d - P \tag{23}$$

$$I_{s\_ref} = (2^*(P+dP) + Kp^*Cd' \\ {}^*(V_d^2 - V_{d\_ref}^2)/2)/(3V_{PCC}) \quad (24)$$

P_d is the input power in DC side. P is the converter's active-power reference, K_P is the controller gain, V_{PCC} represents the PCC voltage.

B. OUTPUT-CURRENT CONTROL

In order to allow the output variables of the system controller to track the input reference value, in order to have control. The common method in the HVDC system is to decompose by *d, q*-axis, and then use the PI controller for tracking purpose. While in this paper, PR control is used, which is better for tracking specific frequency sinusoidal signals, and does not require to decompose DQ decoupling of complex MMC models, which is a suitable controller choice for MMC. Accordingly, the governing equations based on the PR controller are expressed as follows

$$V_s^* = K_o e + \frac{K_I s}{s^2+\omega^2} e + V_{PCC}^f e = i_{s\_ref} - i_s \quad (25)$$

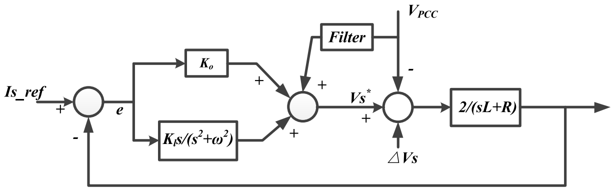


FIGURE 4. Output-current control loop.

The control-system block diagram is depicted in Figure 4. It can be seen that V_{PCC} plays an important role in output-current control, because the error is small relatively. Therefore, according to the higher-level and output current control, it is very significant to keep the accuracy of V_{PCC} for transient stability of system, when communication delay occurs.

C. CIRCULATING-CURRENT CONTROL

The circulating-current control is intimately linked to the voltage control. The circulating current controller must be adapted to some extent; to suit the voltage control scheme that is chosen. The circulating-current dynamics are governed by equation (9), after the Laplace transformation:

$$I_c = \frac{1}{sL+R}(V_d/2 - V_c) \quad (26)$$

In addition, a feed-forward term $V_d/2$-R^* I_c, can be added to compensate for the resistive voltage drop and term $V_d/2$ in equation (9).

Since the dc-bus voltage generally has a lower amount of harmonics than the ac-bus voltage, filtering of V_d is often not required. We obtain the control law

$$V_c^* = \frac{V_d}{2} - R^* I_c - R_a\left(1 + \frac{\alpha_1 s}{s^2+\omega^2}\right)(I_c^* - I_c) \quad (27)$$

and $I_c^* = I_d/M$, M represent number of phases, where R_a is the P gain. Controller block diagram illustrating this scheme is shown in Figure 5.

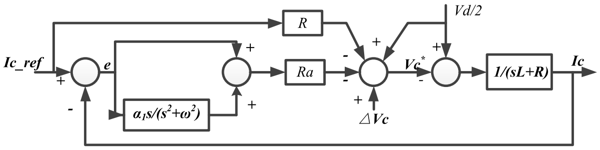


FIGURE 5. Circulating-current control loop.

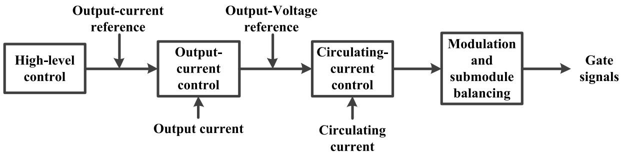


FIGURE 6. Overview of a MMC cascade control system.

In conclusion, an overall block diagram of a typical MMC control system without compensation scheme is showed in Figure 6. MMC has relatively complex internal dynamics than traditional converter topologies. It should be designed with care, as otherwise the performance of the entire converter may deteriorate. However, in order to solve the problem of transient instability caused by the communication delay, these control steps are not enough.

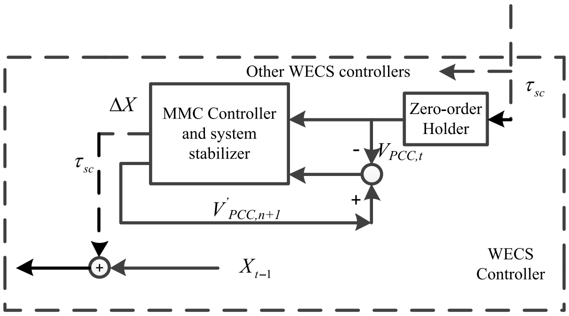


FIGURE 7. Proposed framework of the NCS formulation for MMC-MTDC.

D. COMPENSATION SCHEME

The main goal of this paper is to design an optimal scheme for transient stability under MMC control considering the existence of network uncertainty. For the performance of the control strategy, higher-level, output current control needs to ensure its own safe operation and accurate output signals after the event and delay happened. For this reason, an adaptive PCC voltage compensation scheme considering communication delay is proposed. Figure 7 shows the modified model to solve the problem of communication delay.

It flexibly adjusts the AC voltage signal parameters of the controller's input and its basic framework can be represented by the equation (28). This method not only considers the control regulation of the power by the high level control, but also considers the influence on the output voltage in the outer current control (the most critical), thus changing the output current of the controller, and finally affecting the transient stability of the power grid system.

$$V_s^* = (K_o + \frac{K_I s}{s^2 + w^2}) *(\frac{2^*(dP + \frac{3}{2}K_a^* \Delta V_{PCC}^* I_s/2)}{3^*(V_{PCC} + K_a^* \Delta V_{PCC})} - I_s) + V_{PCC}^f \quad (28)$$

ΔV_{PCC} represents the compensation of the system, $\Delta V_{PCC} = V'_{PCC,n+1} - V_{PCC,t}$, $V'_{PCC,n+1}$ represents the output of the controller at the previous moment $y_{n+1}^{(1)}$, K_a represents the gain of compensation. V_s^* express the MMC internal AC EMF reference signal with compensation.

IV. CASE STUDY AND DISCUSSIONS

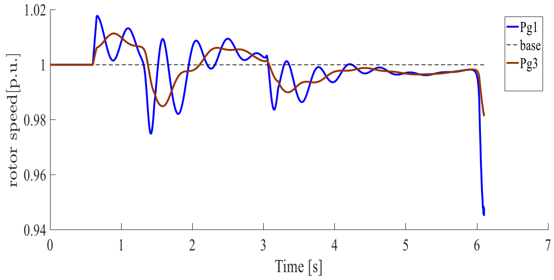
A. CASE STUDY

We use a step-by-step validation method to demonstrate our example. The test model shown in section II previously is presented as the study object. Both the original method, and the improved model are simulated on the MATLAB. The machine performance will affect the simulation time. The simulations in this paper were performed using MATLAB R2014a on a PC with an i7-6700 3.4 GHz CPU, and 32 GB RAM. The parameters of grid, MMC are shown in the following Table 1.

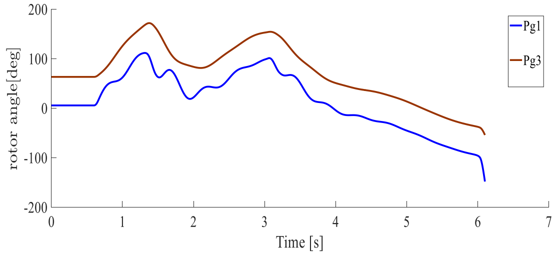
TABLE 1. The parameters of gridandmmc.

M	3
N	12
V_d	140kV
Rated power	210MVA
ωl	2π*50 rad/s
C_d	100μF
L	50mH
R	0.1Ω
Rdc	100km dc cable: 13.9 mili-Ohm/km
Pg2,Pg3,Pg10 (100MVA)	80,85,81
Pd5,Pd7,Pd9 (100MVA)	90,100,125
K_P, K_o, K_I ,R_a	300,1800,9,20

A series of simulations were conducted. Considering the proposed MMC-MTDC model, we first assumed that a three-phase fault occurs in 0.6s for the model in the third part, a communication delay occurs. The main grid network sends the new state variables because reconstructed augmented bus admittance matrix Y_t in addition with the generator nodes 2 and 10 that are connected to the remote MMC rectifier. A change signal is received by the MMC signal receiver after 40 calculation steps, and then rectifier's mmc controller responds to the new input quantity, changes its own running state. The controller solves the new steady-state value and continuously receives a signal with 40 step delay thereafter. At this time, the change produced in generator rotor angle and speed changes are shown in the following Figure 8.



(a). The speed changes of generator rotor in AC side in case 1.



(b). The angle changes of generator rotor in AC side in case 1.

FIGURE 8. (a). The speed changes of generator rotor in AC side in case 1. (b). The angle changes of generator rotor in AC side in case 1.

Because the generator nodes 2 and 10 are connected to the main network through the DC grid and not affected by the fault of the main grid. Therefore, its dynamic process doesn't change when this fault occurs. Figure 5 clearly describes that during the transient process, the oscillations of the rotor speed of each generator does not show an attenuation inclination, and the rotation angle does not reach a stable state.

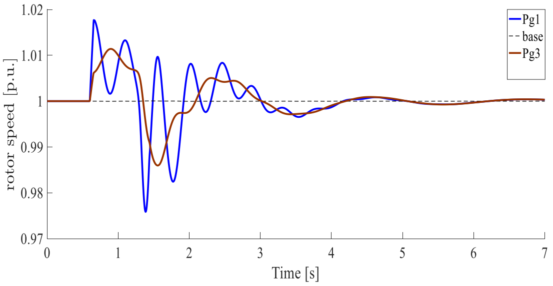
When the control action as proposed in this paper is incorporated, the motion of the rotor and speed of the generator under same conditions (when control action is not inserted) are shown in the following Figure 9.

It can be seen from the simulation diagram that, unlike the original control model, the proposed compensation method can make the generator to return in its stable operating condition at the same time instant, without impeding generator rotor speed variance.

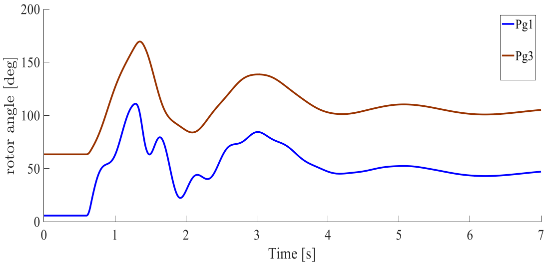
When a three-phase fault occurs at node 5 farther from the MTDC side, and the operating state of the network changes such as the generator connected to the converter changes its output power, And the communication signal delay is 70 steps, the change of rotor angle, and rotational speed of each generator during the same time period is shown below in Figure 10.

B. DISCUSSION

Compensation control method takes into account the MMC-MTDC signal transferability, using equivalent compensation to minimize the impact of communication delay in the communication network. In this paper, the feedback technique without the controller is used to calculate the equivalent compensation. Firstly, record the data sent by the controller

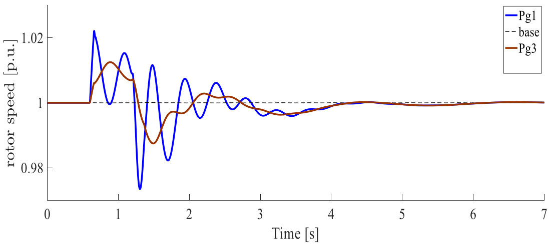


(a). The speed changes of generator rotor in AC side in case 2.

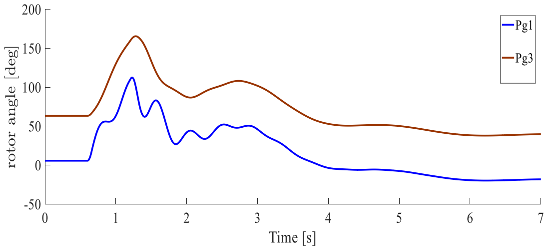


(b). The angle changes of generator rotor in AC side in case 2.

FIGURE 9. (a). The speed changes of generator rotor in AC side in case 2. (a). The angle changes of generator rotor in AC side in case 2.



(a). The speed changes of generator rotor in AC side in case 3.



(b). The angle changes of generator rotor in AC side in case 3.

FIGURE 10. (a). The speed changes of generator rotor in AC side in case 3. (b). The angle changes of generator rotor in AC side in case 3.

to the MMC rectifier, and calculates the difference between the data sent by the rectifier, and the recorded data through the communication network. After that, the gain difference signal passed into the controller. The controller uses the current time and time-independent compensation signal to estimate the state quantity for the next time, to carry out the above hierarchical control, and repeats the above procedure until the goal of delay error elimination is achieved. After the failure of the system, the compensation ΔV_{PCC} acts in the input signal to make the system gradually recover to a stable state even in the presence of delay fault.

V. CONCLUSION

Obviously, the simulation results in case 1-3 show that the proposed additional compensation signal scheme based MMC can effectively improve the transient stability under fault events in power systems, even considering the existence of communication delay. The established system model in this paper considers MMC-MTDC state characteristics and transient behavior of the generator. And the proposed PCC voltage compensation scheme can effectively solve the problem of transient instability occurs in the generation of power system when the fault signal transmission is delayed. It indicates that MMC-MTDC system can effectively alleviate the problem of weak transient stability by compensating the state of the input controller.

During the process of MMC complex dynamic change, this scheme can ensure the stable operation of AC and DC parts in power system. The transient stability of AC/DC system is obtained by ensuring that the system can be restored to a stable state in a short time after the failure occurs. To sum up, the proposed scheme can maintain good control performance under communication delay. Therefore, the proposed scheme has high tendency for practical application in various fields of control.

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XICHANG WEN (Member, IEEE) received the B.S. degree from the Guangdong University of Technology, Guangzhou, China. He is currently pursuing the Ph.D. degree with the Department of Optoelectronic Engineering, Shenzhen University, Shenzhen, China. His main research interests include modular multilevel converter and multi-terminal DC system operation, optimization, and planning.

JIANCHUN PENG (Senior Member, IEEE) received the B.S. and M.S. degrees in electrical engineering from Chongqing University, Chongqing, China, in 1986 and 1989, respectively, and the Ph.D. degree in electrical engineering from Hunan University, Hunan, China, in 1981. He was a Visiting Professor with Arizona State University, Tempe, AZ, USA, from November 2002 to November 2003, and Brunel University London, U.K., from May 2006 to August 2006. He is currently a Professor with the College of Mechatronics and Control Engineering, Shenzhen University, Shenzhen, China. His current research interests include electricity markets and power system optimal operation and control.

SADDAM AZIZ (Member, IEEE) received the M.Eng. degree in electrical engineering from Chongqing University, Chongqing, China, in 2015, and the Ph.D. degree in optoelectronics engineering from Shenzhen University, Shenzhen, China, in 2019. He was declared as a Professional Electrical Engineer by Engineers Australia in 2017. He was a Visiting Professor with China University Summer School Association, China, from 2018 to 2020. He is currently a Research Associate Professor with the College of Mechatronics Engineering, Shenzhen University. His research interests include cyber physical power systems, artificial intelligence, renewable energy integration, and multiterminal HVDC multiterminal DC system operation, optimization, and planning.

HUI JIANG received the B.S. degree in electrical engineering from Chongqing University, Chongqing, China, in 1990, and the M.S. and Ph.D. degrees in electrical engineering from Hunan University, Hunan, China, in 1999 and 2005, respectively. From November 2005 to November 2006, she was a Visiting Scholar with Brunel University London, U.K. She is currently a Professor with Shenzhen University. Her research interests include power system economics and power system planning and operation.

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