Abstract—The electromechanical model of modular multilevel converter (MMC) based high voltage dc (HVDC) transmission network in transient stability (TS) simulator is proposed in this paper based on the MMC average arm model and the submodule (SM) equivalent capacitance approach. The accuracy of the TS model is verified by comparing the simulation results with that of the PSCAD/EMTDC model subject to different grid contingencies, including the controller reference step change, the remote three-phase ground fault and the close three-phase ground fault.

Index Terms—electromechanical modeling, DSAtool, MMC-HVDC, PSCAD/EMTDC, transient stability

I. INTRODUCTION

The high voltage dc (HVDC) transmission system has been regarded as a highly efficient alternative for bulk transmission of electrical power over a long distance. Among which the power electronic (PE) based HVDC configuration, such as the voltage source converter (VSC) based HVDC, has been widely accepted due to its distinguishing characteristics, e.g., flexible control of power flow direction, less reactive power injection to the grid, and black start capability [1]–[4]. In recent years, the number of modular multilevel converter (MMC) based HVDC projects has been increasing worldwide considering its advantages over VSC-HVDC, including high scalability, lower switching loss, smaller harmonic filtering burden, etc. The integration of MMC-HVDC into the conventional ac network will affect transient stability (TS) of the system, and therefore it is of great necessity to investigate the dynamic performance of such systems.

The MMC-HVDC system, as many other PE based facilities, has been modeled and analyzed in electromagnetic transient (EMT) simulators, such as PSCAD/EMTDC. EMT simulation models can accurately specify fast switching dynamics of PE devices and the high control bandwidth of corresponding regulators [5], [6] with a short simulation time step, which is typically selected as 0.05 ms. However, it is computationally prohibited to study the large-scale transmission network with MMC-HVDC systems in the EMT simulator for a considerable period of time.

Compared with the EMT simulation, the TS simulation focuses on the electromechanical transients and oscillations between 0.1 ∼ 3 Hz neglecting system unbalance, and the simulation time step is usually selected as around 5 ms. Therefore, a TS simulator can process a large-scale network with thousands of buses in a relatively short time. The commonly used commercial positive sequence TS simulation tools include GE PSLF, Simens PIT PSS/E, PowerWorld Simulator, and PowerTech Labs TSAT (Transient Security Assessment Tool) [7].

Therefore, it is of importance to develop models of MMC-HVDC systems for transient stability studies in the context of the large-scale power network, which emphasizes the relatively slow dynamics of PE components. The electromechanical models of PE based power facilities have been investigated in existing studies [8]–[11]. However, the MMC-HVDC model applied in commercial TS simulators has not been sufficiently studied to the best of the authors’ knowledge. Specifically, the TS model created in PowerTech Labs TSAT is not available.

In this paper, the point-to-point MMC-HVDC electromechanical model is developed in TSAT. The proposed MMC-HVDC model is derived based on the MMC average model which can reflect the electromechanical transients of the MMC-HVDC. Meanwhile, the MMC-HVDC model specifies the vector control which includes the power regulation and ac grid voltage support. The TSAT in DSATools is selected as the TS simulator since the MMC-HVDC model can be easily customized by the User-Defined Model (UDM) editor included in the TSAT standard package [12].

The paper is organized as follows: Part II introduces the
 MMC circuit topology and the general modeling approach. Part III explains the realization of the MMC-HVDC model in the TS simulator, including the MMC average model, the controller model, and the model representation in the phasor domain. Part IV presents the simulation verification of the MMC-HVDC electromechanical model considering various testing conditions, and conclusions are drawn in section V.

II. MMC-HVDC Modeling Considering Electromechanical Transients

As illustrated in Fig. 1, the point to point MMC-HVDC network connects two remote ac grids through dc transmission cables. The vector control based on the Parker Transformation is commonly used to regulate the energy balance and provide grid support, which is similar to the VSC-HVDC controller.

The MMC topology diagram is illustrated in Fig. 2. There are N submodules (SM) in each MMC phase arm, where the half-bridge dc-dc converter is the most frequently used SM configuration. The arm inductance $L_{\text{arm}}$ and the arm resistance $R_{\text{arm}}$ are placed in each phase arm for current spike suppression. The MMC EMT dynamics have been widely studied and simulated using the commercial EMT simulators where the PE switching characteristics and sophisticated controller are fully considered [13], [14].

According to the existing studies [9], [15]–[19], the MMC-HVDC electromechanical model is divided into the following 3 parts:

- The ac side dynamic model, which includes the point of common coupling (PCC), the decoupling inductance, and the equivalent MMC ac model which is usually specified as an equivalent voltage source as illustrated in Fig. 3.

- The dc side dynamic model, which specifies the dynamic performance of the dc transmission network, includes the equivalent dc link capacitor, the effect of the arm inductance/ resistance, and the dc transmission line capacitor.

- The dynamic controller model, which combines the ac and dc side model. The vector control is the most commonly used control algorithm in the MMC-HVDC, which can be basically divided as: 1) the outer control loop which is designed according to the particular application requirement, e.g. regulate the power flow, support the terminal bus voltage; 2) the inner current control loop which closely follows the reference current in $dq$ axis by regulating the MMC output voltage.

In this paper, the developed MMC-HVDC model is also classified into three parts as above, details of which are discussed in section III.

III. MMC-HVDC Realization in TSAT

As explained in section II, the MMC-HVDC fast dynamics have to be simplified to guarantee only the electromechanical transients are included in the TS simulator. The MMC-HVDC dynamic equivalent modeling approaches are explained as follows:

A. MMC SM Capacitor Equivalent Method based on the Arm Average Model

It can be observed in Fig. 2 that the MMC configuration is similar to that of the two-level VSC except that the MMC should consider the voltage balance of each SM capacitor and the circulating current suppression in each phase leg. In order to simplify the MMC model, the voltage across each SM is assumed to be equal and the circulating current is assumed to be well suppressed. The MMC Arm Average Model (AAM) is proposed in [13], [20] based on the aforementioned assumptions. Due to the simplicity and good dynamic performance considering the fundamental frequency of the ac network, the AAM has been widely used in related studies, including the MMC stability analysis, impedance modeling, controller design, etc.
According to the configuration of AAM proposed in [18], the aggregated energy storage effect of all SM capacitors is simplified into one equivalent capacitor across the dc transmission line, which is similar to the real VSC capacitor placed between the dc and ac grid. Since the individual SM dynamic performance is out of the scope of electromechanical transient studies, the aggregated effect of the SM capacitors can be equivalent to that of one capacitor connected across the dc bus [9], which is expressed as:

\[
C_{eq} = 6 \cdot \frac{C_{SM}}{N_{SM}}
\]

(1)

where \(C_{eq}\) represents the MMC equivalent capacitance, \(N_{SM}\) represents the number of SMs in each phase arm, and \(C_{SM}\) represents the capacitance of each SM.

Therefore, the MMC is equivalent to the configuration of VSC by this simplification approach. It should be noticed that this equivalent method is only effective when the MMC dc link current is not regulated [18], [21], [22], otherwise, the dc link voltage is not equal to the total average voltage across the MMC phase arm. The cases that include the dc link current controller is out of the scope of this paper. The MMC dynamic equivalent circuit in the \(dq\) coordinates is illustrated in Fig. 5 based on this constraint, where \(L_{eq,ac}\), \(R_{eq,ac}\) and \(L_{eq,dc}\), \(R_{eq,dc}\) represent the MMC ac and dc equivalent line impedance respectively; \(i_{gd}\) and \(i_{gq}\) represent the current injection into the ac network; \(v_{gd}\) and \(v_{gq}\) represent the ac terminal voltage at PCC; \(m_d\) and \(m_q\) represent the MMC modulation index.

The inner current loop control bandwidth is too high to be characterized by the TS simulator. So the MMC ac current injection is assumed to closely follow the current reference, regarding the inner current loop dynamic as a time delay.

C. Electrical Variables Transformation between TS and EMT

The ac terminals of an MMC-HVDC system should be represented in the phasor domain considering the TS simulator requirement. Therefore, the transformation between the \(dq\) axis and the phasor domain is necessary. The phasor domain coordinate is illustrated in Fig. 7 by solid black line, where the real and imaginary axises are used to represent the phase angle and the amplitude of the electrical variables. The corresponding phasor variables remain static at the steady state operating point in the static \(RI\) coordinates, while the \(dq\) axis, which is illustrated by the black dash line in Fig. 7, rotates at the fundamental frequency of the adjacent ac grid. The \(V\) and \(I\) are illustrated in Fig. 7 as an example of the voltage and current in the \(RI\) coordinates. In this paper, the PCC voltage measured at the MMC terminal is aligned with the \(d\) axis, so the transformation between the phasor domain and the \(dq\) coordinates is expressed as follows:

\[
\begin{align*}
    i_d &= \sqrt{I_d^2 + I_q^2} \cdot \cos (\theta_2 - \theta_1) \\
    i_q &= \sqrt{I_d^2 + I_q^2} \cdot \sin (\theta_2 - \theta_1)
\end{align*}
\]

(2)
\[ \theta_1 = \arctan \left( \frac{V_I}{V_R} \right) \]
\[ \theta_2 = \arctan \left( \frac{I_I}{I_R} \right) \]

\[ I_R = \sqrt{I_d^2 + I_q^2} \cdot \cos(\theta_2) \]  \hspace{1cm} (4)
\[ I_I = \sqrt{I_d^2 + I_q^2} \cdot \sin(\theta_2) \]

\[ \theta_d = \theta_2 - \theta_1 = \arctan \left( \frac{i_d}{i_q} \right) \]
\[ \theta_2 = \arctan \left( \frac{V_I}{V_R} \right) + \theta_d \]  \hspace{1cm} (5)

where \( i_d \) and \( i_q \) represent the current \( I \) in the \( dq \) coordinates; \( V_R \) and \( V_I \) represent the voltage \( V \) in the \( RI \) coordinates; \( I_R \) and \( I_I \) represent \( I \) in the \( RI \) coordinates; \( \theta_1 \) and \( \theta_2 \) represent the \( V \) and \( I \) phase angle; \( \theta_d \) represents the angle difference between \( \theta_1 \) and \( \theta_2 \).

D. MMC AC Terminal Specification

The MMC ac-terminal voltage expressed as phasor is used to represent the MMC-HVDC performance in the TS simulator. The circuit diagram of the MMC ac-terminal connected to the PCC is illustrated in Fig. 3. With the line current \( I_d \) and \( I_q \) derived by the controller model in Fig. 6, the MMC terminal voltage in phasor domain is calculated as:

\[ V_M^* = V_S - jX_LI_{L,ref} \]  \hspace{1cm} (6)

where \( V_M^* \) represents the MMC terminal voltage in phasor domain, \( V_S \) represents the PCC voltage in phasor domain, \( X_L \) represents the line reactance, \( I_{L,ref} \) represents the current flowing through the transmission line derived by the controller model, of which the phasor expression is derived by (4), (5).

IV. MMC-HVDC Model Benchmark

The MMC-HVDC model is created in TS simulator based on the modeling process expressed in section II, and the accuracy of the electromechanical model is verified in this section. As illustrated in Fig. 8, the MMC-HVDC model is integrated into the IEEE 3-machine 9-bus transmission network between Bus 6 and 4. Bus 10 and 11, which are directly connected to the MMC terminals, are created additionally and located adjacent to Bus 4 and 6 respectively. The right-side MMC terminal is regarded as the rectifier, while the left-side one is regarded as the inverter as illustrated in Fig. 1.

The MMC-HVDC model is integrated into the IEEE 3-machine 9-bus system.

The detailed EMT model of the aforementioned network under study has also been developed in the PSCAD/EMTDC to evaluate the accuracy of the TS model. The step response, the remote three-phase ground fault and the close three-phase ground fault are simulated and analyzed respectively in the following subsections.

A. Controller Reference Step Response

The TSAT model is built based on the average model in Fig. 5 and the control model in Fig. 6. The step response is performed on the electromechanical model characterizing a step change of the controller reference to evaluate the model’s dynamic response subject to the small system disturbance. Four independent simulation cases are illustrated in Fig. 9 including the decrease of MMC power reference \( P_{ref}, Q_{ref} \), the increase of ac terminal voltage \( V_{ac} \), and the increase of dc link voltage \( V_{dc} \). In each case, the controlled variable reference experiences a step change at \( t = 3 \) s respectively while the other references remain constant. In Fig. 9 red curves represent the simulation results in PSCAD while blue curves represent those in the TS simulator. It can be observed in Fig. 9 that the electromechanical model simulation results show a good agreement with the PSCAD model at the reference value step response.

B. Ground Fault Remote from the MMC Terminal

A three-phase ground fault at Bus 8 is applied to evaluate the performance of the model during grid contingency. The ground fault occurs at \( t = 3 \) s and lasts for 0.1 s. Both the MMC ac side and dc side performance are evaluated, where the following variables are recorded respectively: the active power consumption \( P \) and the voltage at two MMC ac terminal buses \( V_{ac} \), the dc link voltage at two dc transmission line terminals \( V_{dc} \). Simulation results are illustrated in Fig. 10. It can be concluded that the ac side performance of the MMC TSAT model achieves a good match with that of the PSCAD model. Regarding the dc link voltage, the dynamic performance before
and during the fault shows a better match than the performance after the fault. The high-frequency oscillation at dc link voltage cannot be observed in the simulation results from TS simulator.

C. Ground Fault Close to the MMC Terminal

In this case, a three-phase ground fault at Bus 4 is applied to the testing network. Compared with the last case, the ground fault is closer to the MMC terminal, so the impact on the MMC-HVDC is more severe. The low-voltage ride-through control is applied to the MMC at Bus 10 to withstand the low terminal voltage. The ground fault occurs at $t = 3$ s and lasts for 0.1 s. The simulation results are illustrated in Fig. 11. Compared with the PSCAD simulation results, it is observed that the performance of the MMC electromechanical model achieves a relative good match with that of the accurate model before and during the fault. After the fault is cleared, the ac terminal voltage raised back faster than that of the PSCAD model, which also leads to the mismatch in the active power. However, TSAT simulation results after 3.3 s show a good agreement with the EMT simulation results, indicating relatively accurate dynamic performance.

V. Conclusion

This paper proposes an electromechanical model for MMC-HVDC system in the widely used commercial TS simulator TSAT. The MMC-HVDC analytical model is created based on the MMC AAM and the equivalent dc link capacitor, and meanwhile realized in TSAT by using the UDM editor which can customize the dynamic performance of the HVDC power converters. The accuracy of the TSAT model has been evaluated by comparing the simulation results with those of the PSCAD/EMTDC model subject to different grid contingencies, including the controller reference step change and the three-phase ground fault. According to the simulation results, the MMC-HVDC model developed in TSAT can accurately reflect the dynamic performance regarding the electromechanical transients when the HVDC network is subject to both small grid disturbances or grid contingencies.

REFERENCES


(a) MMC rectifier side: Response to ground fault.

(b) MMC inverter side: Response to ground fault.

Fig. 11. MMC model subject to the three-phase ground fault at Bus 4: active power, dc link voltage, ac terminal voltage.


