Dynamic modelling of the VSC-HVDC for analytical studies

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Abstract: This study is aimed to present a dynamic model for the voltage source converter-based high-voltage DC (HVDC). The multi-modular converter (MMC) physical model is given and a linear control model for tuning the dynamic model is developed. MMC has a cascaded control structure, containing an outer loop and an inner loop. The reactive outer loop and the active outer loop could be designed and analysed independently. The average-value model of MMC for electromagnetic transient studies are given in this article. The average-value model and detailed model are built in electromagnetic transient simulation program (PSCAD/EMTDC) to verify the validity, precision, and high speed of the proposed method.

1 Introduction

In recent years, the developed voltage source converter-based high-voltage DC (VSC-HVDC) technology has a significant influence on the bulk capacity and long distance power transmission [1, 2]. The VSC-HVDC transmission system absorbs or generates reactive power and active power in an independent and rapid mode. Among VSC topologies, the two-level converter are extensively applied in early projects, which is characterised by simple circuit topology, fewer capacitors, and small footprint. The three-level converter appears afterwards with lower harmonics compared to the two-level converter. The high harmonics in those two topologies of converter and huge losses of valve hints their application in HVDC transmission. Compared to two-level and three-level converter, multi-modular converter (MMC) is famous for relatively easy modular manufacturing, lower losses, and high waveform quality, which is now widely accepted by most projects.

The analysis and design of the VSC-HVDC transmission system are heavily dependent on modelling and computer simulation. The procedure for design and analysis of such complex systems typically involve a large number of time domain transient studies as well as analysis in frequency domain for control purposes. The ever increases of the VSC-HVDC transmission system have motivated and lead researchers towards the development of fast and accurate electronic models.

At present, many simulation models of the VSC have been proposed: (i) detailed model [3–5]. The detailed model has the switching of all devices represented in full detailed and consumes extensive computing resources, and requires significant simulation time, especially for system-level studies. (ii) Switch function model [6, 7]. Switch function model adopts switch function equations to approximate the performance of real switch device. Controlled current sources are used, but the complex modulation still consumes huge computing resources. (iii) Average-value model [8–13]. Average-value model does not include pulse-width modulation part and its simulation step is free from carrier frequency. It approximates the original system by averaging the effect of fast switching within a prototypical switching interval. In addition, the averaged electrical quantities only contain fundamental component, so this model is not suitable for detailed electromagnetic transient research, such as harmonic analysis and protection setting. (iv) Thevenin equivalent model [7, 14].

Submodules on every arm of MMC are substituted by Thevenin equivalent circuit. Trapezoidal integration is applied to discrete switching process. Researchers need to program Thevenin equivalent in simulation software which is not friendly for users.

In time domain analysis, the transient behaviour of the system may be predicted with desired accuracy using the dynamic average models. This paper builds the average-value model and detailed model of a two-port VSC-HVDC system. The detailed system model and average-value model of MMC are introduced in Section 2. The dual closed-loop and controlled source value are also given in Section 2. Simulation results from steady state and transient state are given in Section 3.

2 System model

In order to solve commutation failure in traditional multi-infeed DC transmission, VSC-HVDC is excellent alternative in point-to-point transmission. The power can be transferred even if AC voltage drops to a large extent, which avoids large-scale power transferred to other AC lines and relieves the impacts on AC grids. The alternative transmission technology has no influence on increasing the short current and is free from the capacity and the number of receiving-end AC system. A generic two-port VSC-HVDC system layout is given in Fig. 1.

The converter topology is based on MMC. The submodules adopt half-bridge submodule. The model of a VSC-HVDC converter connected to the grid is shown in Fig. 2.

According to circuit theory, it can be deduced that

\[
\frac{d}{dt} \left( L_x i_{x,j} \right) + R_S i_{x,j} = u_{x,j} - u_{\text{diff},j}
\]

where \( j = a, b, c \); \( L_x \) is the sum of system reactance, arm reactance, and transformer reactance; \( R_S \) the sum of system resistance, arm resistance, and transformer resistance; \( i_{x,j} \) the AC current on the valve side; \( u_j \) the AC voltage at point of common coupling (PCC); \( i_{\text{diff},j} \) is upper and lower arm current of MMC, respectively; \( U_{dc} \) is DC voltage; \( C_0 \) the submodule capacitor; \( L_0 \) the arm reactance of.
MMC. Also

\[
\frac{u_{\text{diff}}}{2} = \frac{1}{2} (u_{up} - u_{down}) \tag{2}
\]

where \(u_{up}\) and \(u_{down}\) are upper and lower arm voltage, respectively.

From (2), the controller can control upper and lower arm voltage to adjust system operating condition. Transform \((1)\) from \(abc\) coordinates to \(dq\) coordinates by using Park’s transformation, we get

\[
\begin{align*}
L_s \frac{di_{d}}{dt} &= -R_s i_{d}(t) + \omega L_s i_{q}(t) - u_{\text{diff}}(t) + u_{w}(t) \\
L_s \frac{di_{q}}{dt} &= -R_s i_{q}(t) - \omega L_s i_{d}(t) - u_{\text{diff}}(t) + u_{w}(t)
\end{align*}
\tag{3}
\]

Also, Park’s transformation matrix is

\[
\begin{pmatrix}
P \\ Q
\end{pmatrix} = \begin{pmatrix}
\frac{3}{2} u_{ad} i_{ad} \\
\frac{3}{2} u_{aj} i_{aj}
\end{pmatrix}
\tag{5}
\]

Desired reactive power and active power can be obtained by controlling \(d\) current and \(q\) current independently. Thus, decoupling strategy is naturally applied in controller.

2.1 Control strategy

The dual closed-loop control scheme is adopted in VSC-HVDC to ensure fast current response. The outer loop can be either constant DC voltage control or constant power control. Sending end (system 2) in VSC-HVDC guarantees the DC voltage and system 1 adopts constant active power, and both converters adopt constant reactive power control. The control scheme is illustrated in Fig. 3. The nearest level modulation (NLM) strategy is applied in valve triggering control. In average-value model, the insulated-gate bipolar transistors are not explicitly represented and all internal variables in the MMC are perfectly controlled. Thus, SM capacitors voltage are balanced and circuit current around arms is no longer existed. Therefore, circuit current suppressing control and balancing control algorithm are not needed.

In the figure, \(R_s\) and \(L_s\) are the system resistance and reactance; \(R_i\) and \(L_i\) transformer resistance and reactance; \(i_s\) is the grid-side current; and \(E\) the grid voltage vector.

On the basis of model in the \(dq\) coordinate system, the paper applies decoupling feed forward control in the inner current loop. The reactive control loop and active control loop can be controlled independently. The NLM method lowers harmonics and valve losses to a large extent.

2.2 Dynamic modelling

The equations of average-value model derived from Fig. 2 for each phase is as follows:

\[
\begin{align*}
u_{p} &= \frac{U_{dc}}{2} - L_s \frac{di_{p}}{dt} + v_j \\
u_{q} &= \frac{U_{dc}}{2} - L_s \frac{di_{q}}{dt} + v_j
\end{align*}
\tag{6}
\]

Since the circuiting is assumed to be zero, the upper and lower arm currents are deduced by

\[
\begin{align*}
i_{pq} &= \frac{I_{dc}}{2} - \frac{i_{pj}}{2} \\
i_{pq} &= \frac{I_{dc}}{2} + \frac{i_{pj}}{2}
\end{align*}
\tag{7}
\]

The AC–DC converter is modelled as a current source on the DC side behind a capacitor. Each arm of MMC is modelled as a voltage source on the AC side. The average-value model of an MMC is presented in Fig. 4.

The reference value \(P_m\) for each arm is modulation waveform calculated by the inner controller. According to NLM theory, the
voltage of arm controlled voltage source is

\[ V_{AVM} = \text{Mod} \left( \frac{U_{dc}/2 - V_{m}}{V_{Cap}} \right) V_{Cap} \]  

(8)

where \( V_{Cap} \) is the rating voltage of submodule capacitor. The voltage generated by (8) is staircase waveform. Based on power balance, the controlled current source is

\[ I_{AVM,DC} = \frac{1.5U_{sd} \cdot i_{sd}}{U_{dc}} \]  

(9)

Modification of \( I_{AVM,DC} \) can be done if the losses of MMC are considered. Also the capacitor behind current controlled source is

\[ C_{AVM} = \frac{6C_0}{N} \]  

(10)

3 Simulation results

The detailed model and average-value model of the VSC-HVDC system shown in Fig. 1 are built in PSCAD/EMTDC. The AC system are represented as equivalent sources with a short-circuit level of 16,000 MVA. Simulation step is 20 \( \mu \)s and transmission line is cable modelled by frequency-dependent model. The system parameters are given in Table 1.

Several test cases are given to verify the effectiveness of average-value model.

Case 1: normal operation

During the steady state, the voltage of arm step voltage of detailed model and average-value model are depicted in Fig. 5.

Case 2: step change in reactive power

Power reference steps from \(-400\) to \(-350\) MW at \( t = 1.25\) s. The active power and AC current of system 1 of detailed model and average-value model are depicted in Figs. 6 and 7.

Case 3: performance during voltage sag

When \( t = 1.5\) s, three-phase grounding to 10 \( \Omega \) resistance are happened at PCC of system 1. The AC voltage of PCC, power, AC current of system 1, and DC current of detailed model and average-value model are depicted in Figs. 8–11, respectively.

In case 1, the step voltage of arm approaches sine wave which indicates \( N = 20\) submodules are enough to ensure low harmonics. In case 2, the power response follows the reference within 0.1 s with fast controller. In case 3, under voltage of PCC drops 20%, the power drops 7.5% at first but returns to normal value within 0.1 s. The DC current undergoes small perturbation and stays stable within 0.1 s. From case 1 to case 3, the waveform of detailed model are highly compatible with the average-value model not only in steady state but also in transient state.

Table 1 Simulation parameters

| Parameter                  | Value         |
|----------------------------|---------------|
| equivalent resistance \( R_\Sigma \), \( \Omega \) | 0.01          |
| equivalent reactance \( L_\Sigma \), mH      | 0.094 86      |
| \( C_0 \), \( \mu \)F          | 5000          |
| number of SM                | 20            |
| line length, km             | 100           |
| system voltage, kV          | 220           |
| transformer ratio           | 220/210       |
| system voltage \( E \), kV   | 220           |
| \( P_1^* \), MW             | -400          |
| \( Q_2^* \), Mvar            | 0             |
| \( Q_1^* \), Mvar            | 0             |
| \( U_{dc}^* \), kV           | 400           |

Fig. 4 Average model of MMC

Fig. 5 Step voltage of SM

\( a \) Detailed model

\( b \) Average-value model

Fig. 6 Active power of system 1 at PCC

\( a \) Detailed model

\( b \) Average-value model

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of average-value model is improved a lot compared to the detailed model, which verifies the correctness of average-value model.

4 Conclusion

The average-value model and detailed model of MMC are built in electromagnetic transient simulation program (PSCAD/EMTDC). The average-value model is valid in the low-frequency range up to and approaching the switching frequency of MMC. The average-value models are continued and can use much larger time steps and therefore typically execute orders of magnitude faster than the corresponding detailed switching models. On the one hand, the average-value model is characterised with high simulation speed and suitable for system level analysis. On the other hand, the average-value model is unable to simulate details in valve dynamics and DC fault. The large submodule capacitor is necessary for average-value model to support DC voltage within normal level. Improvements could be still made in follow-up research.

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6 References

[1] Hagiwara M., Akagi H.: ‘Control and experiment of pulsewidth-modulated modular multilevel converters’, *IEEE Trans. Power Electron.*, 2009, 24, (7), pp. 1737–1746

[2] Yan Z., Xue-hao H., Guang-Fu T., et al.: ‘A study on MMC model and its current control strategies’. The 2nd Int. Symp. on Power Electronics for Distributed Generation Systems, Hefei, China, 2010, pp. 259–264

[3] Saeedifard M., Iravani R.: ‘Dynamic performance of a modular multilevel back-to-back HVDC system’, *IEEE Trans. Power Electron.*, 2010, 25, (4), pp. 2903–2912

[4] Tu Q., Xu Z., Xu L.: ‘Reduced switching-frequency modulation and circulating current suppression for modular multilevel converters’, *IEEE Trans. Power Deliv.*, 2011, 26, (3), pp. 2009–2017

[5] Debnath S., Qin J., Bahrami B., et al.: ‘Operation, control, and applications of the modular multilevel converter: a review’, *IEEE Trans. Power Electron.*, 2015, 30, (1), pp. 37–53

[6] Han B.M., Jeong J.-K.: ‘Switching-level simulation model of MMC-based back-to-back converter for HVDC application’, 2014 Int. Power Electronics Conf. (IPEC-Hiroshima 2014–ECCE ASIA), Hiroshima, 2014, pp. 937–943

[7] Bhesamya M.M., Shukla A.: ‘Norton equivalent modeling of current source MMC and its use for dynamic studies of back-to-back converter system’, *IEEE Trans. Power Deliv.*, 2017, 32, (4), pp. 1935–1945

[8] Peralta J., Saad H., Dennetiere S., et al.: ‘Detailed and averaged models for a 401-level MMC–HVDC system’, *IEEE Trans. Power Deliv.*, 2012, 27, (3), pp. 1501–1508

[9] Mehrasa M., Pouresmaeil E., Zabihi S., et al.: ‘Dynamic model, control and stability analysis of MMC in HVDC transmission systems’, *IEEE Trans. Power Deliv.*, 2017, 32, (3), pp. 1471–1482

[10] Zhang H., Jovicic D., Lin W., et al.: ‘Average value MMC model with accurate blocked state and cell charging/discharging dynamics’, 2016 4th Int. Symp. on Environmental Friendly Energies and Applications (EFEA), Belgrade, 2016, pp. 1–6

[11] Gnanarathna U.N., Gole A.M., Jayasinghe R.P.: ‘Efficient modeling of modular multilevel HVDC converters (MMC) on electromagnetic transient simulation programs’, *IEEE Trans. Power Deliv.*, 2011, 26, (1), pp. 316–324

[12] Saad H., Peralta J., Dennetiere S., et al.: ‘Dynamic averaged and simplified models for MMC-based HVDC transmission systems’, *IEEE Trans. Power Deliv.*, 2013, 28, (3), pp. 1723–1730

[13] Xu J., Gole A.M., Zhao C.: ‘The use of averaged-value model of modular multilevel converter in DC grid’, *IEEE Trans. Power Deliv.*, 2015, 30, (2), pp. 519–528

[14] Beddard A., Barnes M.: ‘Modelling of MMC–HVDC systems – an overview’, *Energy Procedia*, 2015, 80, pp. 201–212