Accurate modeling and simulation analysis of modular multilevel converter system

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Abstract. Modular multi-level converter (MMC) mathematical analysis, including the main circuit parameter design, the main circuit electrical state, controller design and parameter tuning, and so on. From the external characteristics, MMC can be considered that the equivalence is reasonable and effective to some extent; but from the internal characteristics, the kind of equivalent will ignore the MMC some internal system characteristics, so the way modeling cannot reflect the constraints of voltage and current within the system. Therefore, it is necessary to carry on the system modeling research to the MMC converter to reveal the constraint relation of the internal electrical parameters of the MMC converter, and provide the theoretical basis for the system analysis and the complete set design..

1. Introduction
Modular Multilevel Converter-High Voltage Direct Current transmission (MMC-HVDC) is a kind of flexible DC transmission technology based on modular multilevel voltage source converter and self turn off devices, flexible DC transmission technology does not exist commutation failure, has better controllability and flexibility [1-3]. What's more, has a broad application prospect in the area of large-scale clean energy grid, island power supply, AC power synchronous/asynchronous DC interconnection and power grid construction etc.

At present, some key problems, such as operation mechanism, control and protection strategy, simulation modeling, and core equipment development, have been studied deeply at domestic and foreign, and a series of research achievements have been achieved in MMC[4-5]. In the MMC mathematical model above, the literature[6]based on switching function and instantaneous power theory established MMC analytical model of ABC under stationary coordinates, accurately calculate the relationship between the MMC internal dynamic variables such as DC voltage, bridge current problems and two fundamental frequency component. Document [7-9] based on switching function, the analytical expression of internal electrical quantity of MMC is established under ABC stationary coordinate system. By solving the critical equation of the bridge arm current, the values of other electrical quantities can be calculated at one time.

In this paper, the MMC system is modeled accurately, combined with mathematical analysis method and theoretical derivation, reveals the MMC constraint relationship between converter internal electrical parameters. The intrinsic relation between the bridge arm current and the bridge arm voltage is derived, get sub module voltage and harmonic voltage on the bridge arm (including fundamental frequency) of equal amplitude on the contrary, the phase, the upper and lower leg module input voltage and harmonic voltage amplitude is equal, so odd circulation without leg circulation, only with even circulation. Based on the electrical parameters of Yangshan and Sijiao converter stations in Zhoushan project, the comparison between the analytic value and simulation result shows that the analytical deduction is
2. MMC topology and modeling analysis

Theoretical derivation

According to the equivalent principle diagram of MMC shown in Fig. 2, it is assumed that the main circuit parameters of the system, this paper will solve the constraint relationship between the internal electrical quantities of the MMC. First assume that the bridge arm current contains DC, power frequency, double frequency, triple frequency and so on all the frequency components.

So you can get the bridge arm module capacitance voltage

\[ \text{upc} = \frac{1}{2\pi C} \int [p(1 - m \sin [tw])] \, dt \]  

(2)

Take (1) into the formula (2) to solve the solution

\[ \text{upc} = [12am(\cos(tw)) + 12atw + 3bm(\sin(\theta + 2tw)) - 6bmtw(\cos(\theta)) - 12b(\cos(\theta + tw))] 
- 6c(\sin(p + tw)) + 2cm(\sin(p + 3tw)) - 6c(\cos(p + 2tw)) / 24Cw + u0 \]

(3)

Similarly, the capacitor voltage of the lower bridge arm sub module can be as follows

\[ \text{unc} = \frac{1}{2\pi C} \int [(ip + Ia \cdot \sin \left[ w(t + \theta) \right]) \cdot (1 + m\sin[tw])] \, dt \]  

(4)

\[ \text{unc} = [-12am(\cos(tw)) - 12atw + 3bm(\sin(\theta + 2tw)) - 6bmtw(\cos(\theta)) + 12b(\cos(\theta + tw)) 
- 6c(\sin(p + tw)) + 2cm(\sin(p + 3tw)) + 6c(\cos(p + 2tw)) + 3lam(\sin(\theta + 2tw)) 
- 6lamtw(\theta \cos) + 12I(\cos(\theta + tw)))] / 24Cw + u1 \]

(5)

By the formulas (3) and (5) can be obtained: 2a = bm \cos(\theta)

(6)

On the upper arm into the sub-module voltage and for:

\[ \text{sum_upc} = \frac{1}{2} N_{sw} (1 - m(\sin[tw])) \left[ \frac{am(\cos[tw])}{2Cw} + \frac{b(\cos(\theta + tw))}{8Cw} \right. \]

\[ + \frac{cm(\sin(p + 3tw)) + c(\cos(p + 2tw))}{12Cw} \left. + \frac{cm(\sin(p + tw))}{4Cw} \right] + \text{upc}_0 \]
Similarly, the lower arm can be put into the sub-module voltage and for:
\[
\text{sum}_{\text{unc}} = \frac{1}{2} N_{\text{arm}} \left(1 + m \sin[n]\right) \times \left(-\frac{a m \cos[2n]}{2Cw} + \frac{c \cos[p + 2m]}{4Cw} - \frac{b \cos[n + \theta]}{2Cw} - \frac{c m \sin[p + tw]}{4Cw} + \frac{c m \sin[p + 3w]}{12Cw}\right)
\]

Respectively (7) (8) can be obtained:

The sum of the capacitor voltage of the upper bridge arm module is
\[
\text{sum}_{\text{upc}} = \frac{1}{2} \cos[2n]N_{\text{arm}} \left(\frac{a}{2Cw} + \frac{c \cos[p + 2m]}{4Cw} - \frac{b \cos[n + \theta]}{2Cw} - \frac{c m \sin[p + tw]}{4Cw} + \frac{c m \sin[p + 3w]}{12Cw}\right)
\]

The sum of the capacitor voltage of the lower bridge arm module is
\[
\text{sum}_{\text{unc}} = \frac{1}{2} \cos[2n]N_{\text{arm}} \left(\frac{a}{2Cw} + \frac{c \cos[p + 2m]}{4Cw} - \frac{b \cos[n + \theta]}{2Cw} - \frac{c m \sin[p + tw]}{4Cw} + \frac{c m \sin[p + 3w]}{12Cw}\right)
\]

From (9) and (10) can be obtained as follows:
- The odd harmonic (including the fundamental frequency) of the sum of voltage between the upper and lower bridge arm inputs to the submodule is equal, and the phase is opposite.
- The even harmonic of the sum of voltage between the upper and lower bridge arm inputs to the submodule is equal, and the phase is same.

According to the above formula can also derived, the bridge arm circulation does not contain odd circulation, only contains even current.

According to Kirchhoff voltage law for the secondary circulation, the above bridge, for example, to find the second harmonic components of the inductor voltage:
\[
u_l = L * \frac{d}{dt} [q, l] = L(2c w \cos[p + 2n] + b \cos[n + \theta])
\]

Simultaneous formula (11) and (12)
\[
\frac{c \cos[p + 2m]}{8Cw} - \frac{c m \sin[2n]}{12Cw} - \frac{3b m \sin[2n + \theta]}{16Cw} = 0
\]

To solve equation (13), three intermediate variables are required:
\[
a_2 = 2cLw + \frac{c N_{\text{arm}}}{8Cw} + \frac{c m^2 N_{\text{arm}}}{12Cw} \quad (14) \quad b_2 = -\frac{am^2 N_{\text{arm}}}{8Cw} \quad (15) \quad c_2 = \frac{3b m N_{\text{arm}}}{16Cw} \quad (16)
\]

Solving:
\[
c = \frac{3m N_{\text{arm}} \sqrt{9b^2 + 4a^2m^2 - 12abm \cos[\theta]}}{96CLw^2 - (6 + 4m^2) N_{\text{arm}}}
\]
\[
\sin[p] = \frac{3m(2a_m - 3b\cos[\theta])}{2c\left(48CLw^2 - \left(3 + 2m^2\right)N_{arm}\right)}
\]

(18)

\[
\cos[p] = \frac{9bm\sin[\theta]N_{arm}}{-96cCLw^2 + 2c\left(3 + 2m^2\right)N_{arm}}
\]

(19)

\[
\frac{am\cos[tw]N_{arm}}{4Cw} - \frac{bcos[tw + \theta]N_{arm}}{4Cw} - \frac{bm^2\cos[tw + \theta]N_{arm}}{32Cw} - \frac{3c\sin[p + tw]N_{arm}}{16Cw} - \frac{1}{2}m\sin[tw]N_{arm}u_0 + L*bw\cos[tw + \theta] + V*\sin[w*t + x] = 0
\]

(20)

The constraint equation can be written:

\[
\frac{d1^2 + c1^2 - a1^2 - b1^2}{2*1} \frac{\bar{\delta}}{\sin(x-\theta)}
\]

(21)

The simultaneous equations (14) and (6) can be solved \( \theta, m \). Take \( \theta, m \) into (1), (2), (11), (17), (18) and (19) respectively can be obtained by sub module capacitance current, capacitor voltage, average value, sub module voltage amplitude, phase angle and frequency of two circulation related expressions.

Through the above theoretical analysis and formula derivation, get mutual expressions between the sub module capacitor current, capacitor voltage, average value, sub module voltage amplitude, phase angle and frequency of two circulation, reveals the relationship between the electric quantity of the internal MMC, MMC provides a theoretical basis for the design of main circuit parameters, the control and protection strategy design, modeling and simulation study.

3. Simulation verification

In order to verify the correctness of the above theoretical derivation, a high-speed equivalent mathematical simulation model based on Zhoushan project is established. The main parameters of this model are as follows. See table 1:

| Parameter Item                  | Parameter Value | Parameter Item                  | Parameter Value |
|---------------------------------|-----------------|---------------------------------|-----------------|
| DC Bus Voltage (kV)             | 400             | Number of bridge arm modules    | 250             |
|                                 |                 | (without redundancy)            |                 |
| DC power (MW)                   | 100             | Sub module DC capacitor (mF)    | 2               |
| No load modulation              | 0.85            | Connection transformer capacity | 340             |
|                                 |                 | (MVA)                           |                 |
| Net side line voltage RMS (kV)  | 208             | Connection transformer ratio (kV) | 208/230         |
| Valve side line voltage RMS (kV)| 230             | Resistance of the bridge arm reactor (mH) | 350             |
Table 2 Electrical parameter theory and simulation data comparison between Si reef and Yangshan 100MW converter station

| Working condition | P=100MW, Q=0MVar | P=−100MW, Q=0MVar | P=35MW, Q=0MVar | P=−35MW, Q=0MVar |
|-------------------|-------------------|-------------------|-----------------|------------------|
| **Content**       | **Theoretical**   | **Simulation**    | **Theoretical** | **Simulation**   |
| Circulation amplitude | 64.764 64.79 | 64.64 64.71 | 29.10 29.11 | 30.42 30.45 |
| Phase angle of circulation | -88.9° -88.1° | 88.8° 88.9° | 180.03° 180.1° | 0.099° 0.2° |
| Module average voltage | 1598.8 1598 | 1598.7 1598 | 1627 1627 | 1571.86 1572 |
| Modulation ratio | 0.8416 0.8413 | 0.8466 0.847 | 0.8079 0.8081 | 0.88877 0.8888 |
| Power frequency phase angle | 0.97° 1.3° | 179.04° 179.1° | -89.8° -89.9° | 90.9° 90.1° |

Among them, P represents the active power of converter from AC converter to DC transmission. The Q value is positive, which represents the inductive reactive power of the converter, and the Q is negative, which represents the capacitive reactive power of the converter. In order to compare and analyze the theoretical and simulation data more intuitively, the theoretical derivation, analytical expressions and simulation waveforms are displayed in the same oscilloscope as shown in figure 3:

![Theoretical and Simulation Comparison](image)

Fig. 3 Comparison of theoretical analysis and simulation results
From the above analysis theory and simulation results, the premise known of the main loop system parameters and system operation condition, simulation results and the theoretical analysis value is consistent, verify the correctness of the theoretical analysis. Therefore, the theoretical analysis method has guiding significance for MMC operation characteristic analysis, control parameter setting and engineering application.

4. Conclusion
Through the system modeling of the MMC converter, the analytical expressions of the capacitor voltage, the sum of the input module voltage, the current amplitude, the phase and the modulation of the module are listed, more thorough understanding of the constraint relationship between the internal electrical parameters of MMC. The capacitor voltage DC bias for sub module, M modulation system does not agree with the theoretical regulation system, analytic expression of circulation amplitude, The circulation of the bridge arm contains only even harmonic components has a theoretical exposition, the simulation results verify the correctness of the theoretical analysis. According to the system main circuit parameters and operating conditions, you can give the system internal electrical parameters of the analytical expression.

References
[1] LU Xiaojun, LIN Weixing, AN Ting, et al. A Unified Dynamic Phasor Modeling and Operating Characteristic Analysis of Electrical System of MMC. Proceedings of the CSEE, 2016, 36(20): 5480-5491.
[2] Liu Pu, Wang Yue, Lei Wanjun, et al. Analysis of steady-state operating characteristics for modular multilevel converters[J]. Transactions of China Electrotechnical Society, 2015, 30(11): 90-99.
[3] YANG Yu1, SUN Dawei, XIE Xiaorong, et al. Comparative study on the accelerated models of MMC-based VSC-HVDC systems[J]. Power System Protection and Control, 2015, 45(6): 43-48.
[4] Xiao Huangqing, Xu Zheng, Xue Yinglin, et al. Theoretical analysis of the Harmonic Characteristics of modular multilevel converters[J]. Science China Technological Sciences, 2013, 56(11): 2762-2770.
[5] Liu Pu, Wang Yue, Lei Wanjun. Submodule capacitor parameter design of modular multilevel Converters to avoid system resonance. Proceedings of the CSEE, 2015, 35(7): 1713-1722 (in Chinese).
[6] Wang Shanshan, Zhou Xiaoxin, Tang Guangfu, et al. Selection and calculation for sub-module capacitance in modular multi-level converter HVDC power transmission system [J]. Power System Technology, 2011, 35(1): 26-32.
[7] Nademi H, Das A, Norum L. An analytical frequency domain modeling of a modular multilevel converter[C]. 2012 3rd Power Electronics and Drive Systems Technology (PEDSTC), Tehran, 2012: 86-91.
[8] Wang Shanshan, Zhou Xiaoxin, Tang Guangfu, et al. Modelling of modular multi-level voltage source converter[J]. Proceedings of the CSEE, 2011, 31(24): 1-8 (in Chinese).
[9] GAO Jian, SU Jian-hui, GAO Hang, et al. Capacitor voltage and circulation current control strategy in modular multilevel converter[J]. Power System Protection and Control, 2014, 42(3): 56-63.
[10] Cai Xinhong, Zhao Chengyong, Pang Hui, et al. A novel DC voltage control of MMC-HVDC power transmission system based on discrete mathematical model of MMC[J]. Power System Technology, 2013, 37(9): 2403-2409.
[11] Xu J Z, Gole A M, Zhao C Y. The use of averaged-value model of modular multilevel converter
in DC grid [J]. IEEE Transactions on Power Delivery, 2015, 30(2): 519-528.

[12] LI Tan, Aniruddha M.Gole, ZHAO Chengyong. Small-Signal Model of the Modular Multilevel Converter Considering the Internal Dynamics[J]. Proceedings of the CSEE, 2016,36（11）: 2890-2990.

[13] Antonopoulos A, Angquist L, Harnefors L, et al. Global asymptotic stability of modular multilevel converters[J]. IEEE Transactions on Industrial Electronics, 2014, 61(2): 603-612.

[14] Chen Yaojun, Chen Baichao, Tian Cuihua, et al. The system state equation and equivalent model of modular multilevel converters[J]. Proceedings of the CSEE, 2015,35(1):167-176.

[15] Kalcon GO, Adam G Pm, Anaya-Lara O, et al. Small-signal stability analysis of multi-terminal VSC-based DC transmission systems[J]. IEEE Transactions on Power Systems, 2012, 27(4): 1818-1830.

[16] GAO Hang, SU Jian-hui, WANG Jing-jing, et al. Study on control strategy for suppressing double fundamental frequency fluctuation of capacitor voltage of modular multilevel converter[J]. Power System Protection and Control, 2014,42(6):116-123.