International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 3 Issue 11 ǁ November. 2015 ǁ PP.49-54

Variable Voltage Source Equivalent Model of Modular Multilevel Converter

WANG Qingzhen[1], ZENG Guohui[1,2], ZHAN Xing[1]
[1]*(School of Electronic and Electrical Engineering, Shanghai University of Engineering Science, Shanghai, China)*
[2]*(School of Electronic Information and Electrical Engineering, Shanghai Jiao Tong University, Shanghai, China)*

ABSTRACT*: The structures of modular multilevel converter module (MMC) are very complex, and the numerous sub-modules and output level number bring difficulties for the analysis and simulation. In this paper, assuming the sub-capacitor voltage instantaneous value of a single arm is the same value, the switching frequency of the switch is much higher than the output voltage frequency, the system harmonics were ignored, the system state equations are deduced about the intermediate variables as circulation current and the capacitor voltage between the upper and lower arms. On this basis, a variable voltage source continuous equivalent model is proposed, which may replace the system physical simulation model with the actual simulation study. At the same time, the model reflects the relationship between the output voltage and circulation current，which provide a way to analyze the formation mechanism of circulation and the capacitor voltage fluctuations, and make system analysis simple and intuitive. The simulation results validate that this continuous model is rationality and correctness.*

Keywords -*Modular multilevel converter (MMC), Continuous model, State equation, Variable voltage source continuous equivalent model (VVSCEM)*

I. INTRODUCTION

Applications of the modular multilevel converter (MMC) in HVDC transmission and high-voltage motor drives have received more and more attention, which bring increasingly demands on power electronic conversion devices. In recent years, MMC obtain a better attention and promotion among several high-voltage converters for its great flexibility, easiness to implement redundancy, a modular structure, and direct back-to-back connection.

Paper [1] analyzes the operation mode and features, deducing equivalent circuit between output voltage and circulation current by analytical methods, summarizing the various sub-module topology applications for the various sub-module topology of MMC. However, the proposed equivalent circuit has its own advantages and disadvantages in different applications and limited applications. Papers [2-3] discussed MMC real-time model on the basis of mathematical equations, but these methods have overlooked the switching characteristics of the system. The system is equivalent to a continuous system that has brought convenience to the system analysis, but the physical concept is not very clear and the internal variables relationship cannot be observed visually.

Because MMC AC side step waveform voltage output was obtained by sub-module capacitor DC voltage, the keeping capacitor voltage transformer balanced become an important condition for stable operation. Paper [4] keep the same sub-module capacitor voltage value by voltage ranking method and bridge arm current polarity. But when the MMC number of levels change for a long time, this method will make the problem becomes very complex and not easy to control system analysis and steady. It necessary to establish a simple model, it becomes very simple and intuitive to analysis system.

II. MMC STRUCTURE AND OPERATIONAL PRINCIPLE

The main circuit topology diagram of modular multilevel converter shown in Fig.1. Each phases (upper arm and lower arm) contain 2N sub-modules and a current limiting inductors. Each sub-module consists of a half-bridge and a DC storage capacitor. If the input DC voltage is Ud, the average voltage of each capacitor is Ud/N and the capacitor average voltage of each phase is 2 times the DC input voltage.

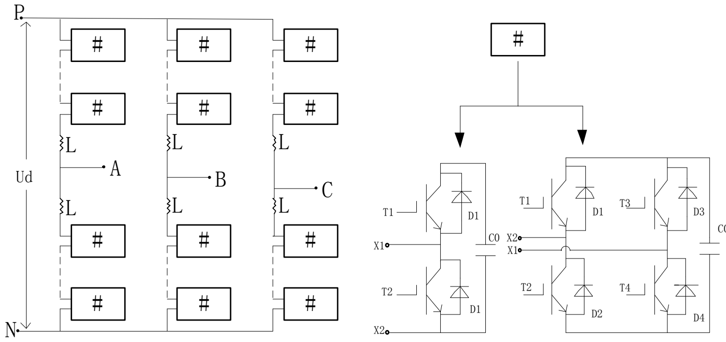

Fig.1MMC main circuit topology diagram

There are three operating states of each sub-module that can output zero level and capacitor voltage two levels at work. The first state occurs the sub-module to join in its output capacitor voltage, then T1 will be opened and T2 be closed. The sub-module as "open "state that each sub-module switches T1, T2 complementary work charge and discharge for circuit capacitance, which adds a capacitor voltage. The second state occurs the sub-module output zero voltage, then T1 will be closed and T2 be opened. The sub-module as "close "state that sub-module capacitance is bypassed, which reduced a level output. The third state occurs the switch to be closed, then T1 and T2 will be closed. Under normal circumstances, this state does not occur. Tab.1 shows the three sub-module operating state. When the switch T1 is "open" state, the sub-module output voltage is capacitor voltage Uc; when the switch T2 is "open" state, the output voltage is zero.

Tab.1 Three sub-module operating state

operating states	switchT1	switchT2	output voltage
1	open	close	Uc
2	close	open	0
3	close	close	0

In this way, by controlling the switch of sub-module, we can choose whether to put the module capacitance into the arm, so as to change the output level. In order to ensure stability of the DC voltage and to avoid the circuit does not generate a larger circulation, the average number of modules is usually guaranteed to be the same or the average number of modules is N. For example, the number of the “open” state sub-modules is N1 in upper arm of A phase, and the number of the lower arm is N2, so each time shall meet:

$$N_1 + N_2 = N \text{(2-1)}$$

If the A phase was analyzed as an example. Suppose the same bridge arm sub-modules capacitor voltage are the same, according to Kirchhoff's voltage law can be obtained:

$$u_{a0} = \frac{1}{2}U_d - u_{aP} - L\frac{di_{aP}}{dt} - r_d i_{aP} \text{(2-2)}$$

$$u_{a0} = -\frac{1}{2}U_d + u_{aN} + L\frac{di_{aN}}{dt} - r_d i_{aN} \text{(2-3)}$$

In formula,i_{aP}、i_{aN}: Current through the upper and lower arms. u_{aP}、u_{aN} : Voltage of upper and lower arms.u_{a0} : A phase-phase AC voltage. U_d : DC voltage.$r_d(r_d = R_{aP} = R_{aN})$: Equivalent DC resistance of upper and lower arms.

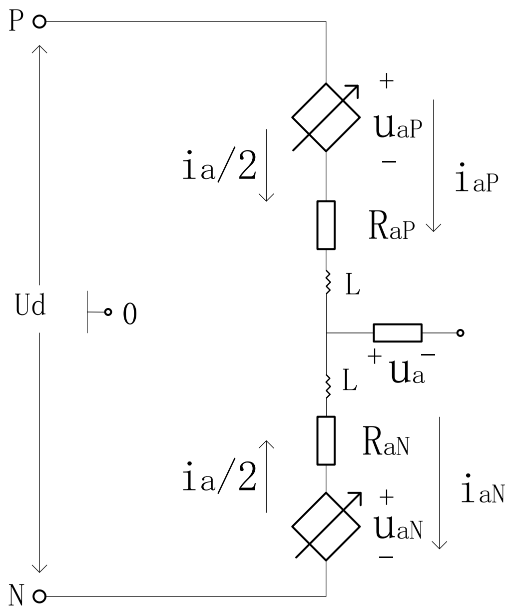

Fig.2 Variable voltage source equivalent model

Under normal operating conditions of the converter, limiting inductor voltage drop is much less than the DC side and AC side output voltage. If the voltage is ignored, each arm can be considered as a controlled voltage source. The equivalent circuit model is established, as shown in Fig.2. Kirchhoff's voltage law:

$$u_{aP} = \frac{1}{2}U_d - u_{a0} \quad (2\text{-}4)$$

$$u_{aN} = \frac{1}{2}U_d + u_{a0} \quad (2\text{-}5)$$

In formula, U_d : Converter DC voltage. u_{aP}、u_{aN} : Voltage of controllable voltage source on the A phase. u_{a0} : Voltage of DC side neutral point.

By theformula（2-4）and（2-5）can be obtained

$$U_d = u_{aP} + u_{aN} \quad (2\text{-}6)$$

$$u_{a0} = \frac{1}{2}(-u_{aP} + u_{aN}) \quad (2\text{-}7)$$

By the formula（2-6）and（2-7）can be obtained, the sum of DC-side voltage is equal to the sum of the upper and the lower arm voltage and AC-side voltage is equal to the difference between the upper and the lower arm voltage. Taking the A phase arm as an example, the AC side output voltage is:

$$u_{a0} = \frac{1}{2}mU_d \sin(\omega t + \varphi) \quad (2\text{-}8)$$

By theformula（2-4）and（2-5）can be obtained

$$u_{aP} = \frac{1}{2}U_d\,[1 - m\sin(\omega t + \varphi)] \quad (2\text{-}9)$$

$$u_{aN} = \frac{1}{2}U_d\,[1 + m\sin(\omega t + \varphi)] \quad (2\text{-}10)$$

In formula, m、φ: Amplitude modulation ratio and modulation wave phase.

By the MMC topology structure,the threebridgearm havethe samesymmetryand the correspondingDCvoltageU_d.ThentheDC voltage$U_d$whohave the sameimpedanceand the DCcurrent isuniformly distributed in the threebridgearms and the current of each phase is $\frac{I_d}{3}$;Similarly, each phaseAC outputcurrenti_a、i_b、$i_c$are also distributed in the upper and lower arm of each phase, shown in Figure 2-2. FromKirchhoff's current law:

$$i_{aP} = \frac{i_a}{2} + \frac{I_d}{3} \quad (2\text{-}11)$$

$$i_{aN} = -\frac{i_a}{2} + \frac{I_d}{3} \quad (2\text{-}12)$$

III. STATE EQUATION AND EQUIVALENT MODEL

FromOhm's Law, anycapacitancecan be expressed as(3-1).

$$i_{ci} = C_i \frac{du_{ci}}{dt} \quad (3\text{-}1)$$

In formula, u_{ci} is the instantaneous value of the capacitor voltage.

For a phase, if it is assumed that capacitor voltage is the same each phase. The sub-module capacitor voltage sum wereu_{aP}^{Σ}、u_{aN}^{Σ}, so its differential equation is:

$$i_{aP} = C_{defP} \frac{du_{aP}^{\Sigma}}{dt} \quad (3\text{-}2)$$

$$i_{aN} = C_{defN} \frac{du_{aN}^{\Sigma}}{dt} \quad (3\text{-}3)$$

In formula,u_{aP}^{Σ}、u_{aN}^{Σ}: sub-module capacitor voltage sum of upper and lower arm;C_{defP}、C_{defN}: Equivalent capacitance value at any time. Under normal operating conditions, the average value of u_{aP}^{Σ}、u_{aN}^{Σ} is approximately equal to the DC input voltage U_d. Therefore, the formula (2-9) and (2-10) can be written as

$$u_{aP} = \frac{[1-\text{msin}（\omega t+\varphi）]}{2} u_{aP}^{\Sigma} \quad (3\text{-}4)$$

$$u_{aN} = \frac{[1+\text{msin}（\omega t+\varphi）]}{2} u_{aN}^{\Sigma} \quad (3\text{-}5)$$

In formula，msin （ωt + φ）is fundamental component of A phase switching function.

If, $n_P = \frac{[1-\text{msin}（\omega t+\varphi）]}{2}, n_N = \frac{[1+\text{msin}（\omega t+\varphi）]}{2}$, so

$$u_{aP} = n_P u_{aP}^{\Sigma} \quad (3\text{-}6)$$

$$u_{aN} = n_N u_{aN}^{\Sigma} \quad (3\text{-}7)$$

In formula，n_P、n_N: Controlled modulation wave of upper and lower bridge arms, its value range is [0, 1].
For A phase, if each capacitor value is C_0, the upper and lower arm equivalent capacitance value:

$$C_{defP} = \frac{C_0}{Nn_P} \quad (3\text{-}8)$$

$$C_{defN} = \frac{C_0}{Nn_N} \quad (3\text{-}9)$$

By the formula（3-2）、（3-3）、（3-8）and（3-9）can be obtained

$$\frac{du_{aP}^{\Sigma}}{dt} = \frac{i_{aP}}{C_{defP}} = \frac{Nn_P i_{aP}}{C_0} \quad (3\text{-}10)$$

$$\frac{du_{aN}^{\Sigma}}{dt} = \frac{i_{aN}}{C_{defN}} = \frac{Nn_N i_{aN}}{C_0} \quad (3\text{-}11)$$

Kirchhoff's current law, upper and lower arm current i_{aP}、i_{aN} as follows:

$$i_{aP} = \frac{i_a}{2} + i_h \quad (3\text{-}12)$$

$$i_{aN} = -\frac{i_a}{2} + i_h \quad (3\text{-}13)$$

By the formula（3-12）and（3-13）can be obtained

$$i_a = i_{aP} - i_{aN} \quad (3\text{-}14)$$

$$i_h = \frac{i_{aP} - i_{aN}}{2} \quad (3\text{-}15)$$

Kirchhoff's voltage law:

$$u_a = \frac{U_d}{2} - R_{aP} i_{aP} - L\frac{di_{aP}}{dt} - u_{aP} \quad (3\text{-}16)$$

$$u_a = -\frac{U_d}{2} + R_{aN} i_{aN} + L\frac{di_{aN}}{dt} + u_{aN} \quad (3\text{-}17)$$

Due to equivalent resistance are the same for A phase，so $R_{aP} = R_{aN} = R$.

By the formula (3-14) 、 (3-16) and (3-17) can be obtained

$$u_a = -\frac{R}{2} i_a - \frac{L}{2}\frac{di_a}{dt} + \frac{1}{2}(u_{aN} - u_{aP}) \quad (3\text{-}18)$$

By the formula (3-15) 、 (3-16) and (3-17) can be obtained

$$U_d - 2Ri_h - 2L\frac{di_h}{dt} - (u_{aN} + u_{aP}) = 0(3\text{-}19)$$

United（3-6）、（3-7）、（3-10）、（3-11）、（3-12）、（3-13）and（3-19）can be obtained the state equation:

$$\mathrm{Dx} = \mathrm{Ax} + \mathrm{Bu}(3\text{-}20)$$

In formula，$A = \begin{bmatrix} -\frac{R}{L} & -\frac{n_P}{2L} & -\frac{n_N}{2L} \\ \frac{Nn_P}{C_0} & 0 & 0 \\ \frac{Nn_N}{C_0} & 0 & 0 \end{bmatrix}$, $B = \begin{bmatrix} \frac{1}{2L} & 0 & 0 \\ 0 & \frac{Nn_P}{2C_0} & 0 \\ 0 & 0 & -\frac{Nn_N}{2C_0} \end{bmatrix}$, D is a differential operator，

$x = [i_h u_{aP}^{\Sigma} u_{aN}^{\Sigma}]^T$， $u = [U_d i_a i_a]^T$。

IV. SIMULATION

In order to verify the correctness and feasibility of the model. According to the analysis of the third section, the experimental platform of MMC is established based on state equation. The simulation and experimental parameters are shown in Tab.2.

Tab.2The simulation and experimental parameters

parameter	value	parameter	value
DC voltage/V	200	Inductance/mH	8
Sub-module capacitor /mF	3	Output frequency/Hz	50
Resistance/Ω	15	Modulation ratio	0.8

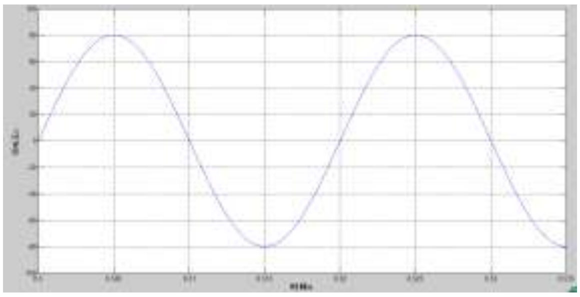
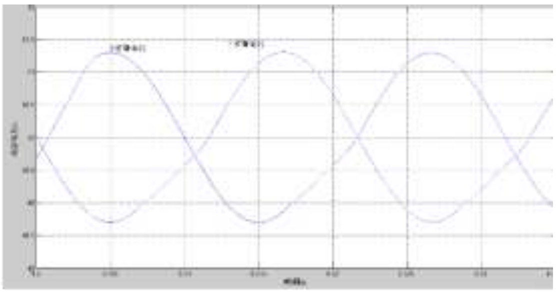

Fig.3 Output phase voltage waveform Fig.4 Sub-module capacitor voltage waveform

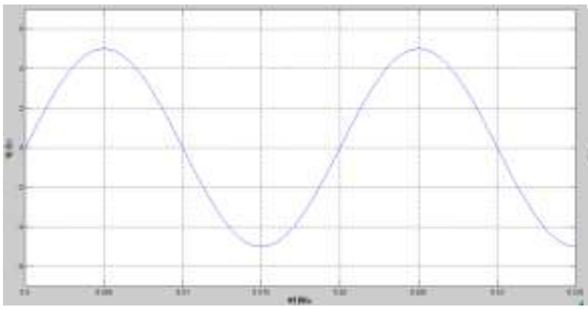
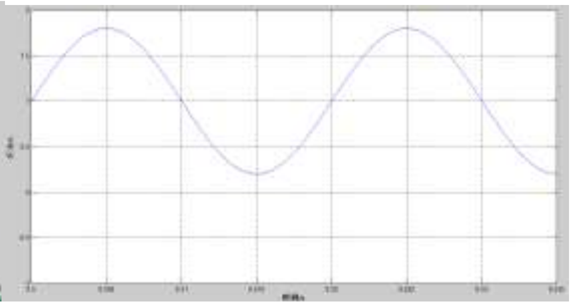

Fig.5 Output current waveformFig.6Circulating current waveform

From Fig.4 and Fig.6, in the upper and lower arm of the converter, the average value of each sub-module capacitor voltage is about 50V and the current of the bridge is mainly composed of DC component, fundamental component and harmonic component. From Fig.3 and Fig.5, Due to the continuous model does not exist in inverter switching devices, so that the output voltage amplitude is 80V smooth sinusoidal and the current amplitude is about 5A. Compared with the physical model which is controlled by the switch device, the simulation results of the continuous model can better approximate the physical model. In the study of steady state and control system homeostasis, the continuous model can be used in place of a physical model to simplify the analysis and accelerate simulation speed.

V. CONCLUSIONS

In this paper, assuming the sub-capacitor voltage instantaneous value of a single leg is the same value, the switching frequency of the switch is much higher than the output voltage frequency, the system harmonics were ignored, the system state equations are deduced about the intermediate variables as circulation current, the capacitor voltage between the upper and lower arms. By system state equation, we can get the output variable expression of MMC system, which can calculate other variables. According to the state equation, we propose a variable voltage source continuous equivalent model. The simulation confirms the correctness and validity of the proposed continuous model. We can get the following conclusions:

- λ In the context of the proposed model assumptions, the model may replace the MMC system physical simulation model with the actual simulation study, regardless of the complexity of the switching device;
- λ The continuous simulation model better approximation of the physical model, in the study of the control system steady, the continuous model can be used instead of physical models to simplify the analysis and accelerate simulation speed;
- λ The model reflects the relationship between the output voltage and circulation current. It provides a way to analyze the formation mechanism of circulation and the capacitor voltage fluctuations.

REFERENCES

[1] Wei Chenhua, Yang Yan, Xie Yang, Wei Chao. Research on key issues of modular multilevel converter [J]. Electronic Design Engineering, pp.182-186, Mar., 2014.

[2] Harnefors L, Antonopoulos A, Norrga S. Dynamic analysis of modular multilevel converters [J]. IEEE Transactions on Industrial Electronics, pp. 2526-2537, 2013.

[3] Ahmed N, Ängquist L， Norrga S， et al. Validation of the continuous model of modular multilevel converter with blocking/deblocking capacity[C]. The 10th IET International Conference on AC and DC Power Transmission 2012(AC/DC 2012). Birminhan，UK：IET, pp.1-6, 2012.

[4] Wang Siyun. Research on control method of modular multilevel converter [D]. Zhejiang University, 2013.

[5] Zhang Lanhua. Research on design and control strategy of modular multilevel converter [D]. Shandong University, 2012.

[6] G. P. Adam, S. J. Finney, K. Bell, and B. W. Williams, Transient capability assessments of HVDC voltage source converters, in Power and Energy Conference at Illinois (PECI), 2012 IEEE, 2012, pp. 1-8.

[7] S. P. Teeuwsen, Modeling the Trans Bay Cable Project as Voltage-Sourced Converter with Modular Multilevel Converter design, in Power and Energy Society General Meeting, 2011 IEEE, 2011, pp. 1-8.

[8] R.MarquardtandA.Lesnicar,Anewmodularvoltagesourceinverter topology ， presentedattheRec.Eur.Conf.PowerElectr. Appl. [CD-ROM],Toulouse,France,2003.

[9] M.Hiller,D.Krug, R. Sommer and S.Rohner, Anewhighlymodularmediumvoltageconvertertopologyforindustrialdriveapplications,inProc.Rec.EPE [CD-ROM],Barcelona,2009,p.1-1-0.

[10] HM.Pirouz and M.T.Bina,New transformer less STATCOM topology for compensating unbalanced medium-voltage loads, in roc.Rec.EPE[CD-ROM],Barcelona,2009,pp.1–10.

[11] Makoto Hagiwara, Ryo Maeda, and Hirofumi Akagi. Control and Analysis of the Modular Multilevel Cascade Converter Based on Double-Star Chopper-Cells (MMCC-DSCC). IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL.26, NO.6, JUNE 2011.