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Start Control for the MMC-HVDC

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Abstract. This paper designs the control strategies and start procedure of MMC-HVDC. The start procedure consists of three stages, uncontrollable charging stage, controllable charging stage and power-raising stage. The current circuit is analysed and the equivalent circuit is obtained in uncontrolled charging stage. The computational formula of current-limit resistor is obtained in the uncontrollable stage. Two different control strategies to further charge the capacitors to the rated voltage in controllable charging stage are designed. Strategy one makes use of DC voltage control and balancing strategy of capacitor voltage while Strategy two divides the capacitors of one arm into two groups. In power-raising stage, to avoid the impact of power step, slope control is used in power outer loop. Finally, a simulation model is established in the PSCAD/EMTDC. The simulation results show that the effectiveness and rationality of the designed start procedure and control strategies

1. Introduction

VSC-HVDC refers to HVDC based on voltage source converter (VSC), and it is suitable for the technical fields, such as the integration of renewable energy and the connection of asynchronous AC grids because it can control the active power and the reactive power independently and quickly and commutate without the need of power grid [1-6]. In 2001, A. Lesnicar proposed modular multilevel converter (MMC) [7]. HVDC based on MMC (MMC-HVDC) not only possesses the above advantages of VSC-HVDC but also can output voltage waveform with low harmonics. Besides, MMC-HVDC doesn't need any filters and has good expansibility due to its modular structure. For all the advantages above, MMC-HVDC has been becoming the research hotspot in the field of HVDC [8-12].

Every arm of MMC consists of a series of serial submodules and every submodule contains one or more capacitors which are used to store energy. Before the start of MMC, the capacitors are uncharged. Because the trigger circuit of the submodules needs to take energy from the capacitors, the capacitors of the submodules need to be pre-charged during the start of MMC before the trigger circuit can work properly [13-17].

During the initial stage of pre-charging, the voltage of capacitors is low and the charging current will be too high to burnout the devices if the MMC is charged directly by the power grid. So it is need to insert a resistor into the charging circuit, which is called limit-current resistor. The resistance of limit-resistor is dependent on the maximum charging current the devices can tolerate. The reasonable and economical selection of limit-resistor needs to analyse the charging current loop in detail. The charging current is the result of the interreaction between three-phase voltage of power grid and all the arms of MMC, but the existing research about the relationship between limit-resistor and charging current just considers the charging current under the action of two-phase voltage, so the computational formula of limit-resistor obtained is wildly inaccurate.

This paper concludes the previous research and redesigns the start procedure of MMC-HVDC. The start procedure consists of three stages, uncontrollable charging stage, controllable charging stage and power-raising stage. The current circuit is analysed and the equivalent circuit is obtained in uncontrolled charging stage. The computational formula of current-limit resistor is obtained in the uncontrollable stage. Two different control strategies to further charge the capacitors to the rated voltage in controllable charging stage are designed. Strategy one makes use of DC voltage control and balancing strategy of capacitor voltage while Strategy two divides the capacitors of one arm into two groups. In power-raising stage, to avoid the impact of power step, slope control is used in power outer loop. Finally, a simulation model is established in the PSCAD/EMTDC. The simulation results show that the effectiveness and rationality of the designed start procedure and control strategies

2. The topology of MMC

The topology of single-ended MMC is shown in Figure 1. The MMC is made up of three phase units and every phase unit consists of two arms. Every arm consists of n serial half-bridge submodular and a reactor L_0 [18].

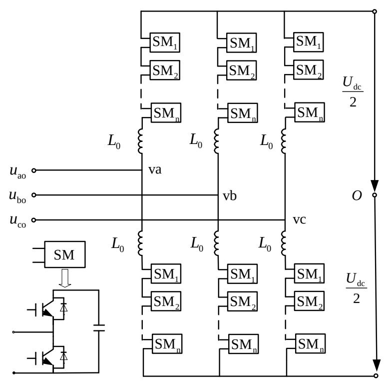


Figure 1. The typology of MMC

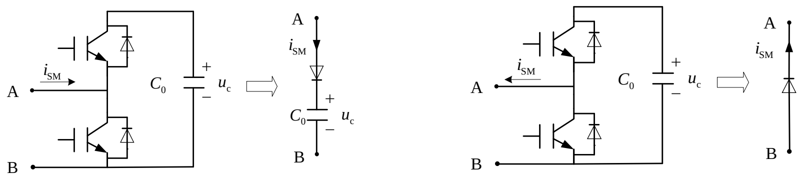
3. The start procedure of MMC-HVDC

3.1. The start procedure of MMC-HVDC

The start procedure of MMC-HVDC can be divided into three basic stages, i.e., uncontrolled charging stage, controlled stage and power-raising stage. In the initial start stage of MMC, the capacitors of submodular are uncharged so the MMC is uncontrollable, so this stage is called uncontrolled stage. During the uncontrolled stage, all the IGBTs are turned off, the capacitors are charged by the power grid through diodes. Due to the restriction of the voltage of power grid and the structure of MMC, the capacitors cannot be charged to the rated voltage in the uncontrolled stage. After uncontrolled stage, the voltage of capacitors has reached the working voltage of trigger circuit of MMC, so the MMC is controllable. In the controlled stage, the capacitors are charged to the rated voltage. After the controlled stage, the power-raising stage begins and the power transmitted by MMC-HVDC increases gradually from zero to the rating. Then the whole start procedure is finished.

3.2. Analysis of the uncontrolled stage

As described above, in the uncontrolled stage, the submodules are blocked and the capacitors can only be charged by diodes. In this stage, the equivalent circuit of submodular is decided by the direction of charging current. Suppose the direction of current from A to B is positive. When the charging current is positive, the submodular can be equivalent to a diode in series with a capacitor. When the charging current is negative, the submodular can be equivalent to a diode. The equivalent circuit is shown in Figure 2.



(a) The charging current is positive (b) The charging current is negative

Figure 2. The equivalent circuit of submodular

The simple equivalent circuit of MMC in the uncontrolled stage is shown in Figure 3. The three-phase upper arm is listed as the ap, bp and cp, three-phase lower arm as an, bn and cn respectively. R_s is the equivalent system resistor , L_s is the equivalent system reactor, $R_{\lim}$ is the limit-current resistor.

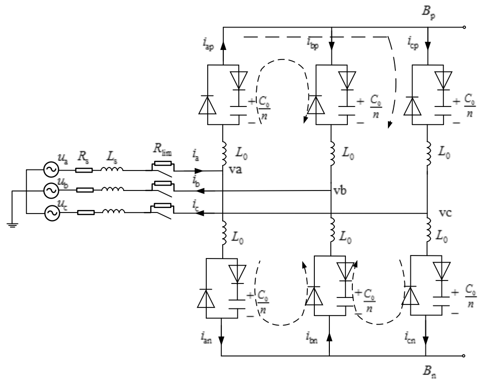


Figure 3. The simple equivalent circuit in uncontrolled stage

In the uncontrolled stage, the voltage of capacitors of submodules increases gradually, which will block the charging current, so the maximum charging current generally appears within the half circle after the charging beginning. Suppose the voltage of phase a is the highest and the initial phase angle is zero and that of phase b is the lowest, then the expression of the phase-a voltage is shown in (1), where *U* refers to effective value of phase voltage of power grid.

$$u_a(t) = \sqrt{2}U\sin(\omega t) \tag{1}$$

The current directions of all the phases and arms are shown in Figure 3. Based on KCL and KVL, the following equations can be obtained for phase a, b and phase a, c.

$$i_a = i_b + i_c \tag{2}$$

$$i_{ap} = i_{bp} + i_{cp} \tag{3}$$

$$i_{an} = i_{bn} - i_{cn} \tag{4}$$

$$u_{ab} = i_a(Z_s + R_{\lim}) + i_{ap} \cdot Z_L + i_{bp}(Z_C + Z_L) + i_b(Z_s + R_{\lim}) \tag{5}$$

$$u_{ab} = i_a(Z_s + R_{\lim}) + i_{an}(Z_C + Z_L) + i_{bn} \cdot Z_L + i_b(Z_s + R_{\lim}) \tag{6}$$

$$u_{ac} = i_a(Z_s + R_{\lim}) + i_{ap} \cdot Z_L + i_{cp}(Z_C + Z_L) + i_c(Z_s + R_{\lim}) \tag{7}$$

$$u_{ac} = i_a(Z_s + R_{\lim}) + i_{an}(Z_C + Z_L) - i_{cn} \cdot (Z_C + Z_L) + i_c(Z_s + R_{\lim}) \tag{8}$$

$$u_a + u_b + u_c = 0 \tag{9}$$

Considering the capacitive reactance of the capacitors is much less than resistance of the limit-current resistor, (10) can be obtained from (2)-(9).

$$6u_a = 6i_a(Z_s + R_{\lim}) + 3i_a \cdot Z_L + i_a \cdot Z_C + (i_{ap} - i_{cn})Z_C \approx 6i_a(Z_s + R_{\lim}) + 3i_a \cdot Z_L + i_a \cdot Z_C \tag{10}$$

Where $i_m(m=a,b,c;k=p,n)$ refer to the instantaneous value of three phase current, $i_{mk}(m=a,b,c;k=p,n)$ refer to the instantaneous value of six arm current, u_{ab} and u_{ac} refer to the instantaneous value of line voltage of phase a and b and phase a and c, $u_m(m=a,b,c)$ refer to the instantaneous value of three phase voltage, $Z_s=R_s+j\omega L_s$ refers to the system impedance, $Z_L=j\omega L_0$ refers to inductive reactance of arm inductor, $Z_C=1/j\omega(C_0/n)$ refers to the capacitive reactance of arm capacitor. (11) can be obtained from (10).

$$u_a=i_a\left[(R_s+R_{\lim})+j\omega\left(L_s+\frac{L_0}{2}\right)+\frac{1}{j\omega(6C_0/n)}\right] \tag{11}$$

Based on (11), the charging loop of the initial stage in uncontrolled stage can be further equivalent to the circuit shown in Figure 4, where $u_s=u_a$, $R_e=R_s+R_{\lim}$, $L_e=L_s+L_0/2$, $C_e=6C_0/n$.

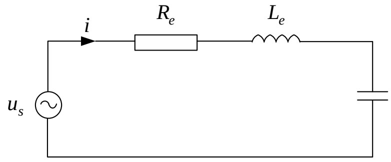


Figure 4. The equivalent circuit of MMC in initial stage of the uncontrolled stage

The capacitor and inductor are uncharged in the initial stage of the uncontrolled stage, so the equivalent circuit can be regarded as a second order RLC series circuit with zero state response. (12)-(14) can be obtained from Figure 4, where i_p refers to the steady component of the charging current and i_h refers to the transient component of the charging current [19].

$$i=i_p+i_h \tag{12}$$

$$i_p=I\sin(\omega t-\varphi) \tag{13}$$

$$i_h=I\mathrm{e}^{-\frac{R_e}{2L_e}}\sin\left[\sqrt{\frac{1}{C_eL_e}-(\frac{R_e}{2L_e})^2}t+\varphi\right] \tag{14}$$

Where $I=\frac{\sqrt{2}U}{\sqrt{R_e^2+\left[\omega L_e-1/(\omega C_e)\right]^2}}$ and $\varphi=\tan^{-1}\left\{\left[\omega L_e-1/(\omega C_e)\right]/R_e\right\}$. Because the R_e is far greater than L_e, the c decays very fast. So the maximum charging current mainly decided by the steady component.

$$i_{\max}\approx i_{h(\max)}=\frac{\sqrt{2}U}{\sqrt{R_e^2+\left[\omega L_e-1/(\omega C_e)\right]^2}} \tag{15}$$

When the allowable maximum charging current is known, the resistance of limit-resistor can be calculated by (16).

$$R_{\lim}=\sqrt{\frac{2U^2}{i_{\max}^2}-\left[\omega L_e-1/(\omega C_e)\right]^2}-R_s \tag{16}$$

3.3. The control strategy of MMC in the controlled stage

As analysed above, the capacitors cannot be charged to the rated voltage in the uncontrolled stage. After the uncontrolled stage, the submodular become controllable, so the capacitors can be charged to the rated voltage through related control strategies. This paper designs two different control strategies in the controlled stage based on the characteristic of half-bridge submodular.

Strategy one: After the uncontrolled stage, the decoupling controller of the inner and outer loop is put into operation immediately. The outer-loop controller adopts constant dc voltage control strategy and constant ac-side reactive power control strategy and balancing control strategy of capacitor voltage is put into operation simultaneously. To reduce the time from the inner and outer loop controller are put into operation to the capacitors are charged to the rated voltage, the capacitors should be charged to a high voltage. However, in the later stage of uncontrolled stage, the rise of capacitor voltage becomes slower and slower. Considering the both two factors above, the capacitor voltage is set to 70% of the rated voltage after the uncontrolled stage being finished in this strategy.

Strategy two: This strategy divides the capacitors of the same arm evenly into two groups and then charge the capacitors belonging to different groups separately. When charging the capacitors of the first group, the capacitors of the second group are bypassed. After the first group is charged to the rated voltage, the second group begins to be charged. When all the capacitors are charged to the rated voltage, the controlled stage is finished. Considering the charging speed becomes slower and slower in the later period of uncontrolled stage, this strategy need not charge the capacitors to the 70% of the rated voltage. In practical engineering, when the voltage of capacitors reaches 30% of the rated voltage, the trigger circuit can work properly, so the capacitor voltage is set to 30% of the rated voltage after the uncontrolled stage being finished in this strategy.

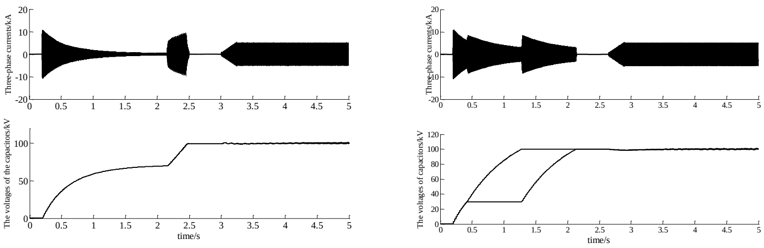
4. Simulation verification

4.1. The establishment of simulation system.

A two-terminal digital model is established in the PSCAD/EMTDC. Every arm has eight submodules, whose capacitance is 10000uF and the rated voltage of the capacitor is 100kV. The line voltage of the power grid is 500kV and the ratio of the transformer is 500:420. The rated dc voltage is 800kV and the inductance of arm inductor is 45mH.

4.2. The establishment of simulation system.

Based on the model above, the simulation study about the start control of MMC-HVDC is conducted and the simulation waveforms are shown in Figure 5.



(a) Strategy one (b) Strategy two

Figure 5. The waveforms of three-phase current and the voltage of capacitors in strategy one and two

All the charging stages of strategy one can be figured out clearly from Figure 5. The ac-side breakers are closed at 0.2s and the MMC station begins to be charged by the power grid. With the voltage of capacitors rising, the charging current becomes smaller and smaller, so the charging speed becomes slower and slower. At 2.2s, the voltage of capacitors reaches 70kV (70% of the rated voltage), so the uncontrolled stage ends and controlled stage begins. In the controlled stage, under the control of the outer and inner loop controller, the capacitors are gradually charged to the rated voltage (100kV). Because the current-limit resistor is cut off immediately after the uncontrolled stage, the charging current will increase suddenly in the beginning of the controlled stage. However, the charging current will not exceed the tolerant current of the devices because the voltage of the capacitors is enough high after the uncontrolled stage. After the capacitors are charged to the rated voltage, the MMC stations are blocked and the power exchange between power grid and the MMC station decreases to zero. After that, the related on-off operations can be conducted. Then the MMC stations are unblocked and the transmitted power between two MMC stations are gradually raised to the rating.

All the charging stages of strategy two are shown in Figure 6. Different with strategy one, after the capacitors being charged to 30kV, the capacitors of the same arm are divided into two groups to be further charged. The ac-side breakers are closed and all the capacitors are charged simultaneously at 0.2s. At approximately 0.4s, the uncontrolled stage is finished. Then the first groups of all the arm capacitors are charged furtherly whose voltages continue to increase while the second groups are bypassed and their voltages remain unchanged. At around 1.3s, the first groups are charged to the rated voltage and then the second groups continue to be charged. The rest procedures are same with strategy one.

To verify the validity of the above derivation about the limit-current resistor, the calculated values by (11) and the simulation values of the maximum charging current are obtained by changing the resistance of the limit-resistor and the results are shown in Figure 6. We can see that the calculated values are little bigger than the simulation values when the limit-current resistor is small. When the limit-current resistor is bigger than 30 ohm, the calculated values are almost equal to the simulation values. In practical engineering, the limit-current resistor is generally several hundred ohm or even bigger, so (11) and (12) possess enough accuracy

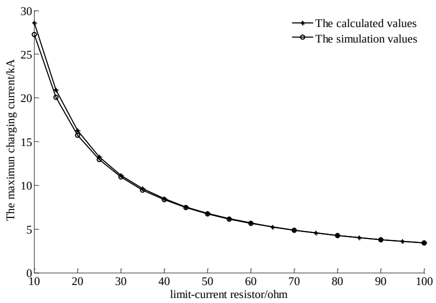


Figure 6. The relationship between the maximum charging current and the limit-current resistor

5. Conclusion

This paper designs the control strategies and start procedure of MMC-HVDC. The start procedure consists of three stages, uncontrollable charging stage, controllable charging stage and power-raising stage. The current circuit is analysed and the equivalent circuit is obtained in uncontrolled charging stage. The computational formula of current-limit resistor is obtained in the uncontrollable stage. Two different control strategies to further charge the capacitors to the rated voltage in controllable charging stage are designed. Strategy one makes use of DC voltage control and balancing strategy of capacitor voltage while Strategy two divides the capacitors of one arm into two groups. In power-raising stage, to avoid the impact of power step, slope control is used in power outer loop. Finally, a simulation model is established in the PSCAD/EMTDC. The simulation results show that the effectiveness and rationality of the designed start procedure and control strategies

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References

[1] Zili Y, Genyin L and Guangkai L 2007 Analysis on operational mechanism of VSC-HVDC and relevant parameter design of its main circuit *Power System Technology*. **31** 16-26.
[2] Zheng X and Hairong C 2007 Review and applications of VSC HVDC *High Voltage Engineering* **33** 1-10.
[3] Xinming F, Lin G and Chengjun X 2014 Control of VSC-HVDC in AC/DC hybrid transmission with wind farms integrated *Proceedings of the CSEE*. **34** 4781-90.

[4] Zhixin W, Jie W and Lie X 2013 Key Technologies of large offshore wind farm VSC-HVDC converters for grid integration *Proceedings of the CSEE*. **33** 14-26
[5] Jing L, Gang S and Xu C 2015 Control strategies of large wind farms integration through AC/DC parallel transmission system based on VSC-HVDC *Power System Technology*. **39** 639-646.
[6] Chungang C, Chengyong Z and Xiaofang C 2012 Mathematical model and control strategy of MMC-HVDC *Proceedings of the CSU-EPSA*. **24** 13-18
[7] Lesnicar A and Marquardt R 2003 *Proceedings of IEEE Conference on Power Tech* Bologna, IEEE 24, 23-26.
[8] Minyuan G, Zheng X and Qingrui T 2010 Nearest level modulation for modular multilevel converters in HVDC transmission *Automation of Electric Power systems* **34** 48-52.
[9] Qingrui T, Zheng X and Xiang Z 2010 Mechanism analysis on the circulating current in modular multilevel converter based HVDC *High Voltage Engineering* **36** 547-552.
[10] Shanshan W, Xiaoxin Z and Guangfu T 2011 *Modeling of modular multilevel voltage source converter Proceedings of the CSEE* **31** 1-8.
[11] Zhongqi L, Qiang S and Wenhua L 2010 VSC-HVDC system based on modular multilevel converters *Automation of Electric Power systems* **34** 53-58.
[12] Minyuan G and Zheng X 2010 Modeling and control of modular multilevel converter in HVDC transmission *Automation of Electric Power systems* **34** 64-68.
[13] Jian Z, Jianhui S and Xinying W 2014 Pre-charging control of modular multilevel converter *High Voltage Apparatus* **50** 103-107.
[14] Ming K, Yufeng Q and Zhiyuan H 2011 Pre-charging Control strategies of modular multilevel converter for VSC-HVDC *Power System Technology* **35** 67-73.
[15] Gaopeng G, Xuehao H and Jialiang W 2014 Precharge control strategies for modular multilevel converter *Power System Technology* **38** 2624-30.
[16] Minyuan G and Zheng X 2010 Modeling and control of modular multilevel converter in HVDC transmission *Automation of Electric Power Systems* **34** 64-68.
[17] Fayou Y, Guangfu T and Ming K 2015 Pre-charging control strategy for MMC-based DC grid *Proceedings of the CSEE* 35 5147-5153.
[18] Yunbo L, Yunfei X and Xiangning X 2015 Pre-charging control for unified power quality conditioner based on modular multilevel converter *Automation of Electric Power Systems* **39** 182-187.
[19] Yinlin X and Zheng X 2013 Start control for the MMC-HVDC system based on clamp double submodule *Power System Protection and Control* **41** 1-7