THE SUB-MODULE CAPACITANCE AND ARM INDUCTANCE SELECTION IN MODULAR MULTI-LEVEL CONVERTER

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ABSTRACT

Arm inductor and sub-module capacitor are two key components in the modular multilevel converter. Optimizing the selections of arm inductance and sub-module capacitance is thus critical for the converters design. This paper aims to developing the selection principle for arm inductance and sub-module capacitance in modular multilevel converter. The sub-module capacitance in MMC is selected mainly based on the capacitor Voltage fluctuation constrains. The voltage unbalance among sub-module capacitors is revealed to have a significant impact on the sub-module capacitance selection, as the unbalanced voltage would increase the total capacitor voltage fluctuation. The impact of sub-module capacitors' unbalanced voltage on the total voltage fluctuation is evaluated. An analytical expression of the unbalanced voltage is derived; it can be used to calculate the maximum capacitor voltage fluctuation, and thus used for the sub-module capacitances election. Arm inductors in MMC are used to limit the circulating current which flows within the converter. The switching frequency harmonic is found to be the dominant component in the circulating current when an active circulating current suppressing controller is implemented. The analytical relationship between the arm inductance and switching frequency circulating current is derived, based on which the arm inductance requirement is obtained by limiting the circulating current to meet the defined specifications. A simulation has been carried out in the MATLAB, and the simulation results verify the theoretical analysis. A scaled-down MMC prototype has been built, and the experimental results validate part of the analysis.

KEYWORDS: MMC-Modular multilevel converter, IGBT- Insulated gate bipolar transistor, SM- Sub module, HVDC- High voltage direct current, MVDC- Medium voltage direct current.

1.1 INTRODUCTION

For over a period of 10 years, Modular Multilevel Converter is flattering wide pronounce, that is the reason a lot of researchers have been attracted to attempt or to suggest to discover a possible way of remodeling it [1]. This results mainly due to the effort of a competent alternative means of energy generations, which comparatively has a less negative impact for the environment if it's compared to the energy generation for the means of current. Additionally, the MMC generates very low distortions of the output voltage and also decreased switching stress on power electronic switching devices when using more switches compared with ordinary converters. With the modular multilevel converter a new era for high-power voltage source converter was entered. Since the MMC, which was first presented in combines excellent output voltage waveforms with very high efficiencies it is ideal for high-voltage high-power applications such as high-voltage direct current transmission, high-power motor drives and electric railway supplies. Advanced Voltage Source Converters (VSC) are a key component of future HVDC-transmission systems [2], while bulk power transmission remains to be well suitable for line commutated thyristor converters, the most important future application fields share demanding requirements, which are best met by self-commutated converters. Examples of these applications are the integration of large solar thermic and wind farms into the grid, the upgrading of the power supply for mega cities and the stabilization of existing AC-networks. Main requirements are fast and independent control of active and reactive power flow, operation without bulky passive filters, black start capability and the option of extending the DC network to more than two stations (multi-terminal).

Severe fault conditions and disturbances including short circuits at the DC side must be managed fast and safely. Modular multilevel converters seem to have great potential in energy conversion in the near future. High power applications, such as DC interconnections, DC power grids, and off-shore wind power generation are in need of accurate power flow control and high efficiency power conversion in order to reduce both their operating costs and their environmental impact. The multilevel concept provides lower losses due to a considerably lower switching frequency compared to a 2-level equivalent. Apart from the lower switching frequency, the quality of the output voltage waveform is higher. This implies that smaller and simpler harmonic filters are required. To take this thought one step further, a modular multilevel converter provides simplicity of design and control, as well as scalability to various voltage and or power levels. [3] Moreover, the concept of a modular converter has the potential to improve the reliability, as a faulty module can be bypassed without significantly affecting the operation of the whole circuit. A great advance in the design of modular topologies was made when Marquardt and Lesnicar suggested their design of the Modular Multilevel Converter in 2003 a design being investigated by several research teams lately. In fact the basic circuit, using voltage sources instead of capacitors, was already proposed by Alesina et al. in 1981. The basic component of the MMC, here called a ”sub module”, is a simple half bridge with a capacitor bank, as stated in structure. Each phase leg of the converter has two arms, each one constituted by a number of series connected sub modules. The number of the output steps depends straightly on the number of modules available in each arm. There is also a small inductor in each phase in order to take up the voltage difference, which is produced when a module is switched in or out. A diagram of this converter with *N* modules per arm is shown in Figure 1. By applying a simple modulation scheme, the converter operates as expected when viewed from the output, but a closer look inside the converter reveals high currents circulating between the phase legs.[4]

The existence of these currents implies that the sub modules have to be rated for a higher current, but the most important effect is the energy transfer between the arms. Unless controlled, they can lead to instabilities, as the energy stored inside the converter will not be balanced. [5]

2.0 MODULAR MULTILEVEL CONVERTER

The MMC could be use anywhere when a high power is compulsory, this result for a wide acceptance in system of energy and industrial as long as authorize to scheme the system of high and medium voltage, in which has a qualitative output of the voltage. For this result it is typical for the new approaching by using the medium voltage direct current MVDC distribution and high voltage direct current HVDC transmission will expand the automation. Although even the ‘‘HVDC system may likely continue to deployed in the feature especially as technological improvements are making them cost competitive with alternative AC schemes at decreasing power levels; and their unique control characteristic can be exploited to enhance the capacity, level of interconnection, and availability of existing AC systems’’.[6]

2.1 GENERAL CONVERTION

The electrical energy conversion from one system to another is called power conversion. And it is differentiated by its input and output of AC or DC. Power conversion system generally classified in to 4 pigeonholes. The conversion from AC to AC is considered as transformation of which have the same frequencies of input and its output. Another power conversion is from DC to AC consistently considered as inverting, means that it converts a DC to AC. In the inverter circuit there is three stages as: Oscillation, switching and transformation stage. [7] Then converter can be designed as rectifier to perform a rectification (changing quantities from AC to DC by using the diodes results a current to flow in only one direction. Also another power conversion is changing quantities from DC to DC, which is called regulations usually refers to the boosting as a results of using maximum power point tracker MPPT, in which conventionally has a current ripple usually at the input as a result of colossal power losses if its connected to nonlinear device. [7][8]

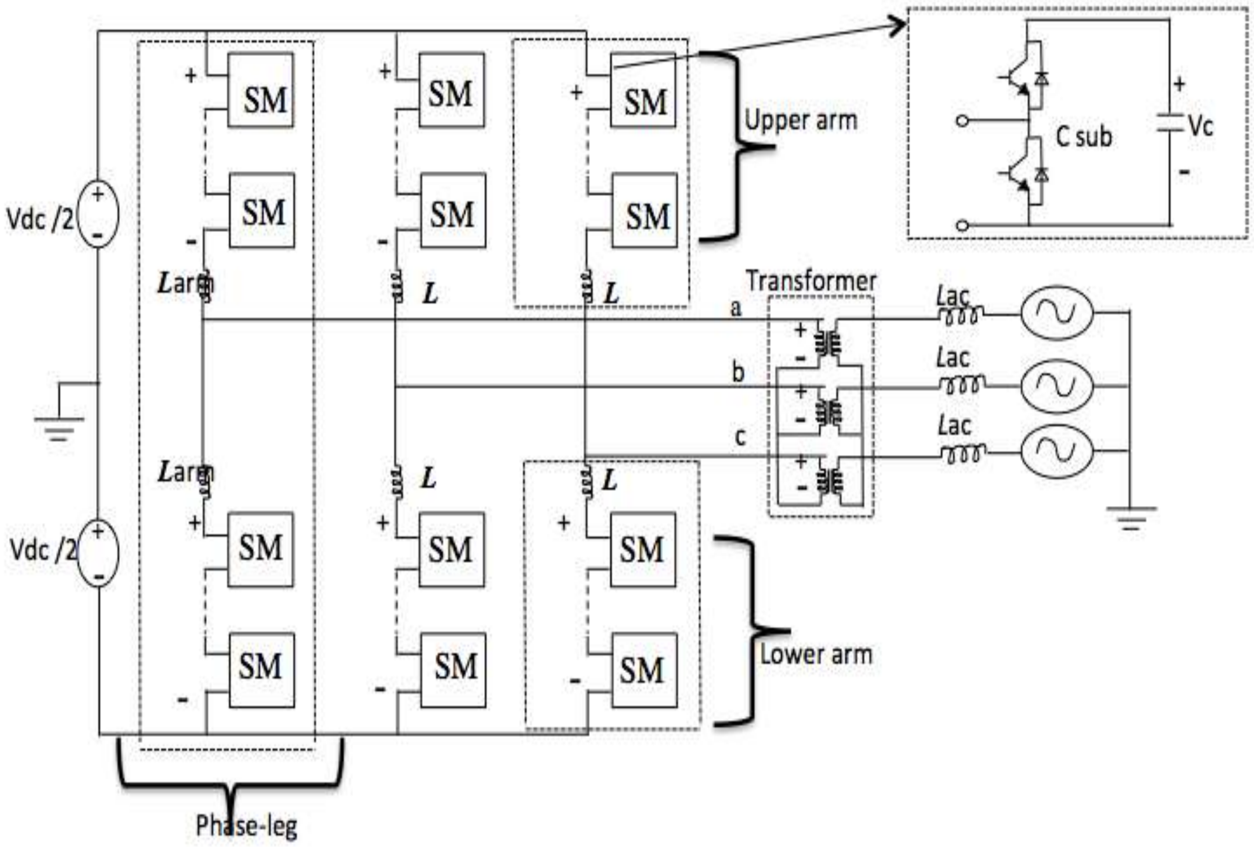
2.2 MODULAR STRUCTURE

Modular multilevel Converter having receiving accrual deliberation in all along and a recent year not only in industrials but also even from academic. By construction, MMC has two periphery; AC side and DC side and also has two major elemental sub module capacitor and arm inductor.

The higher structure of the modular afford simple adaptable, less forfeit for excess and operation for tolerant of fault, lofty possibility, standard implementation of the components, and the output waveform's quality is certified. [9]

Apart from all aforementioned advantages, modular converters then depend upon an arrangement of control which has a bounteous convoluted operation and configuration for the reason that it necessary contain complex control mission concurrently. Likewise, because of the huge number of signals to be advanced, it requires the higher performance control platform. Afore interrogation result the reason for just out and extant a lot of experimentation from variance side all over the world. The main characteristics of MMC are the existence of arm inductors. It is known that series connection with sub modules in each arm as it's depicted in Circuit diagram. The arm inductor used to compensate for the differences of voltage between DC side voltage and the phase-leg voltages. And the voltage differences are caused by the current circulation.[10] The arm inductance has the major impact on a magnitude of the circulating current. In many applications for example HVDC transmission system, ac side for the MMC is being connected to the voltage sources. Arm inductor and sub module capacitor ensure the desired arm voltage achieve as well as adequate voltage balance control, arm balancing control and individual balancing control that proposed for phase-shifted modulation scheme.[9][10]

2.3 CIRCUIT DIAGRAM



3.0 REVIEW OF THE SYSTEM

For an appropriate feature, the MMC retains to capture the minds of power and electronic engineers all over the world especially in industries of higher and medium power. This results to give a chance for its execution of improvements. A lot of researchers knuckle down for comparison between high and medium power semiconductor converters as illustrated in Figure 1.0, [11] to finding out the simplest way for strategies of their control, then by optimizing an available algorithm of modulation it caused bettering output harmonic distortions levels of the inverters, capacitor voltage levels remodeling also currents ripples levels deprecated.

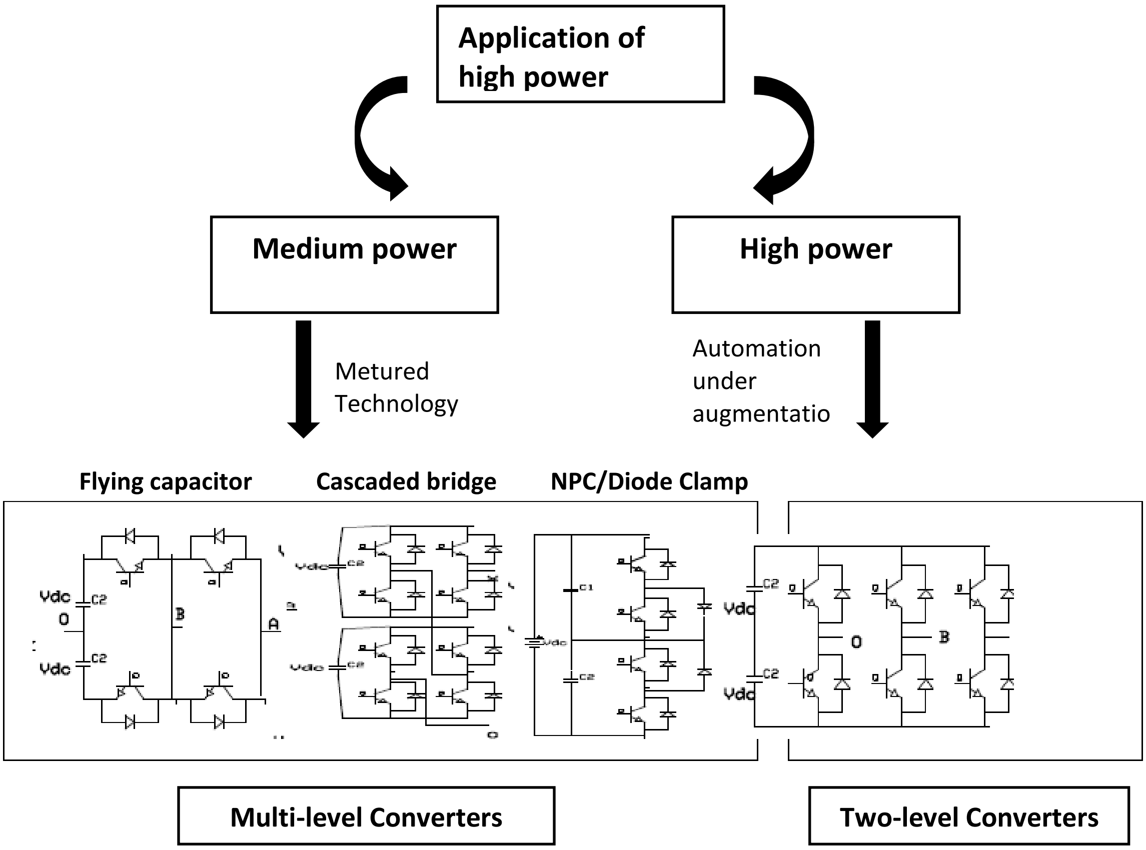


Figure1.0 Comparison between high and medium power semi-conductor converter technology.

Modular Multi-level converters offer great number of advantages over the conventional available converters. It provides a better quality output voltage step that is more closely to sinusoidal waveform and an improved power transformation. To further ascertain the claim, on the output quality improvement of converter, eleven levels and twenty-nine level output waveforms were generated and compared as Figure 1.1, shows the two waveforms.

The amount of harmonic distortions (THD) reduces drastically for the steps of voltage increased, improving the output voltage quality for the overall efficiency of the system. [9]

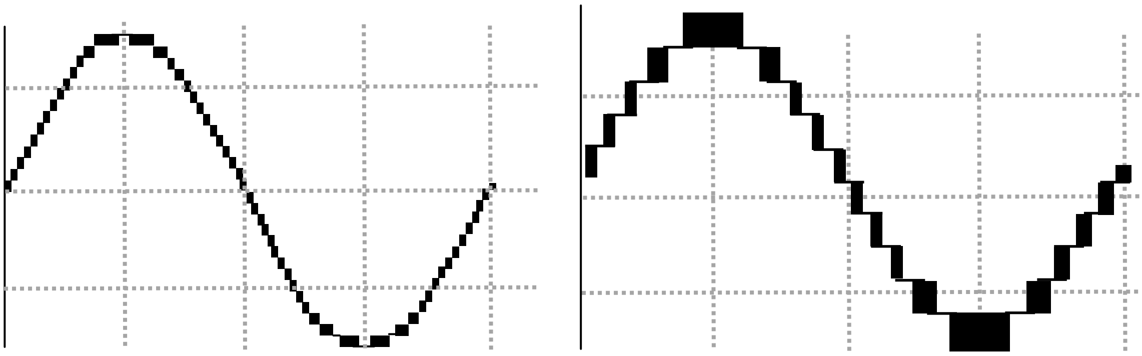


Figure1.1 (a) 29 levels voltage waveforms. (b) 11 level voltage waveform

For instance, a lot of advancing of investigation counseled fronting beat down harmonic output of converter by use of premeditated points of control and envisaging configurations for new converter. The widely known and popular topology converters are: Neutral point, cascaded high bridge and flying capacitor converters. The aforementioned converter can be considered as high power converters. [12] Figure 1.2, summarizes the various classifications of available high power converters sooner of MMC. Back to the early 1970's the exploration related the 3 intimated topology interested to advance power handling of the converter potentiality publication as (high Voltage and current) then at as current source inverter (CSI) for improvement of its current rating.

Afterward, analyst begins for ripen mean alternatively of voltage control in lieu of currents; this known as voltage source inverter (VSI), heading to MMC. [13]

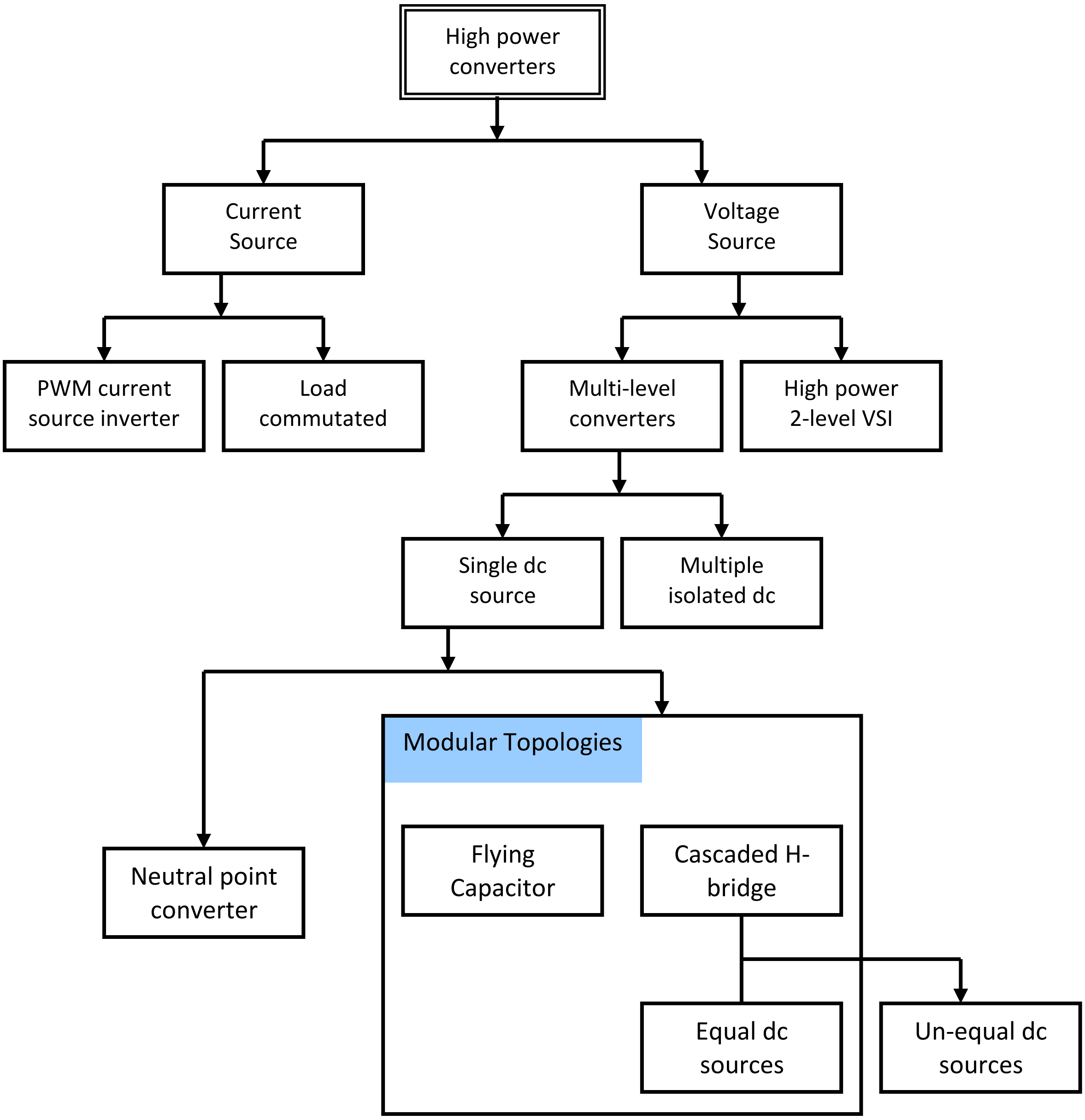


Figure 1.2, classification of High Power Converters

Choice for high power converter like NPC, FC and CHB Converter is governed by a factor number as for comparison of some converters topologies as delineated in the Table1.

Table 1. Comparison of some converters Topologies			
	NPC	**FC**	**CHB**
Specification	Clamping diode	Additional of capacitor	Isolation DC Source
Modularity	Is Low	Is High	Is High
Design and Implementation	Is Low	It has a Medium (Capacitors)	It has a High (Transformer input)
Control Concern	Voltage balancing	Voltage setup	Sharing of power
Fault Tolerance	Is very Difficult	Is Easy	Is Easy

Table1. Comparison of some converters Topologies

As known, there are a numbers of industrial accomplished modular multilevel converters delude for different appositeness high and medium voltage, this shows it is potentiality of domineering market in the near feature.

3.1 MAIN APPLICATION OF MODULAR MULTILEVEL CONVERTER

Because of the capability of higher voltage and quality of higher power provided by the Modular multilevel Converters, their major application is in high voltage direct current (HVDC) transmission system, other applications like medium voltage drive and active filters and also used in micro grid, or renewable energy application. [13]

3.2 ADVANTAGE OF MODULAR MULTILEVEL CONVERTER

- Due to the harmonic cancellation among multiple sub-modules (SM) its AC voltage has low harmonic contents, and therefore the need for a filter is eliminated. [21]

- In the MMC arms the currents and DC link are continued, and a DC link capacitor can be omitted.

- For MMC, the losses in power electronic switches are reduced, and the PWM carrier frequency is low. [2][6]

- Only some of the SM capacitors discharged and the discharging currents are limited by the protection choke in the arms in a DC link short circuit fault, therefore the system recovery is very fast.

- The system of the MMC can remain operating for a certain period even when few sub-modules are out of order. Nevertheless, modular multilevel converter topology alone has some else requirements of control in addition to the consistent VSC, and also requires more sophisticated controller. For instance, the controller of MMC needs to balance SM capacitor voltages and eliminate circulating current. [2][13]

4.0 DEFINITION OF OPERATION CONDITIONS

Some currents and voltages need to be defined first just is in order to assist the following analysis. The direction of voltage and current are shown in figure 1.3

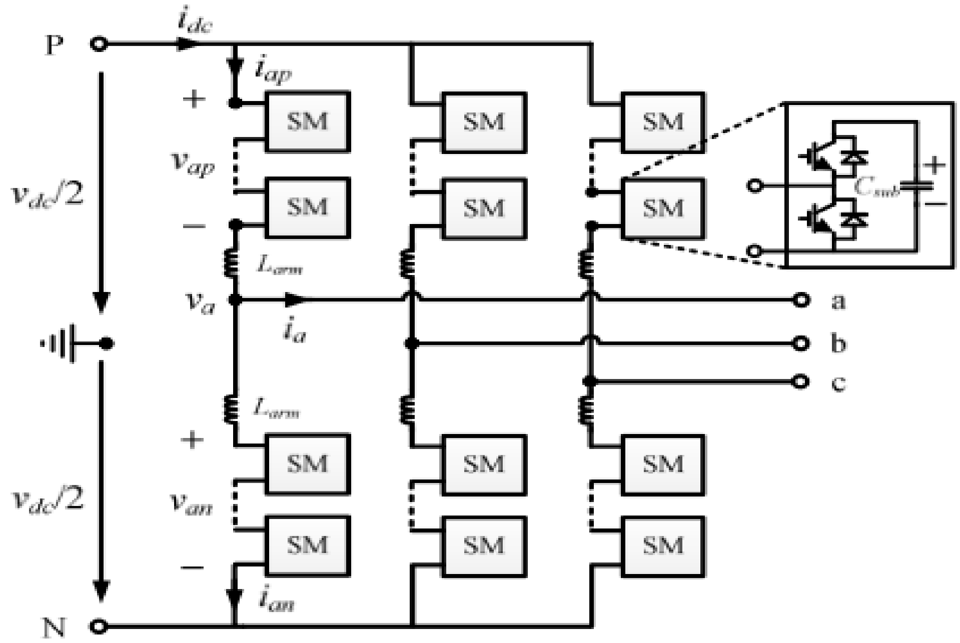


Fig1.3 Voltage and current definition in MMC

For a phase the ac side voltages and currents are defined as:

$v_a = v_{ac} \cos(\omega t + \theta)$ (1)

$i_a = i_{ac} \cos(\omega t + \theta)$ (2)

Where θ represents the phase angle between voltage and current. The arm voltages can thus be expressed as:

$$v_{an} = \frac{Vdc}{2} (1 + M \cos(\omega t)) \quad (3)$$

$v_{ap} = \frac{Vdc}{2} (1 - M \cos(\omega t))$ (4)

Where M is the modulation index defined as: $2v_{ac}/v_{dc}$. If the N SMs are always inserted in the circuit, Now capacitor voltage can be obtained as: $v_c = \frac{vdc}{N}$ (5)

4.1 SELECTION PRINCIPLE OF ARM INDUCTANCE AND SUB-MODULE CAPACITANCE

The main characteristics of MMC are the existence of arm inductors. It is in series connection with sub modules in each arm. The arm inductor uses to compensate for the voltage differences between dc side voltage and the phase-leg voltage. And the voltage differences are caused by the current circulation. The arm inductance has the major impact on a magnitude of the circulating current. Because in many applications for example HVDC transmission system, ac side for the MMC is being connected to the voltage sources. Selection criterion of the arm inductance for MMC with circulating current suppressing controller is investigating. [4] The fault current is generating as the result of discharge from sub-module capacitors during the dc side short circuit fault, as well as fed by ac side of the voltage source. Since the fault current flows through a device (Anti-paralleled diode and IGBT), if this fault current is not limited to the tolerant level the result a converter would be destroyed, so the arm inductor is a key component used to limit the fault current. [5]

4.2 REQUIREMENT OF SUB-MODULE CAPACITANCE AND ARM INDUCTANCE FOR LIMITING CIRCULATING CURRENT

The circulating current mechanism and suppressing control of circulating current explanation is presented here. By considering the equation (5) the insertion indices are obtained depending on sub module capacitor voltage average. The voltage of capacitor actually contained alternating components. The generated voltages of the arm can be given as: [5][13]

$$v_{an} = \mathrm{N}\left(\frac{1}{2} + \frac{M}{2}\cos(\omega t)\right) * v_{an-c} \quad (6)$$

$$v_{ap} = \mathrm{N}\left(\frac{1}{2} - \frac{M}{2}\cos(\omega t)\right) * v_{ap-c} \quad (7)$$

Where v_{an-c} and v_{ap-c} are the actual sub-module capacitor voltage, which is a real voltage of the arm, could be described as:

$$v_{an} = \frac{Vdc}{2}\big(1 + M\cos(\omega t)\big) + V \qquad (8)$$

$$v_{ap} = \frac{Vdc}{2}\big(1 - M\cos(\omega t)\big) + V \qquad (9)$$

Where V is the circulating voltage

Now, compared to the desired voltage of the arm in equation (8) and (9) the common modes voltages are generated. Thus the dc side voltage will not be equal to the phase-leg voltage, and the difference of the voltage (2V cir) is applied on the arm inductors, which made the circulating current. Where *ncm* component of the common mode is added to the insertion indices, and defined as $2v_{cm} / v_{dc}$

Now, compared to equation (8) and (9), and added by common mode component and differences on voltage, the arm voltage can be written as:

$$v_{an} = \frac{Vdc}{2}\left(1 + Mcos(\omega t)\right) + v_{cir} - ncm * v_{an-c} \qquad (10)$$

$$v_{ap} = \frac{Vdc}{2}\left(1 - Mcos(\omega t)\right) + v_{cir} - ncm * v_{ap-c} \qquad (11)$$

Thus, the phase-leg voltage is derived as: [14]

$$v_a\text{-}l_{eg} = v_{dc} + 2v_{cir-ncm} * (vc -_{upper} + vc -_{lower}) \qquad (12)$$

Considered to equation (12) phase-leg voltage could be controlled equation to a dc voltage by adjusting *ncm*, which show a circulating current at a frequency below or less than the bandwidth of a controller could be eliminated theoretically. [6] As known, the circulating current being dominated by the second order harmonic component, so circulating current suppressing controller could reduce the circulating current effectively.

4.3 SWITCHING FREQUENCY CIRCULATING CURRENTS

This section is intended to explain the mechanism of the switching frequency circulating current, and provides the guidance for arm inductance selection based on the circulating current. The modulation scheme analyzed in this section includes the PWM sub-module.

Fig1.4 Voltage generations of PWM sub-modules

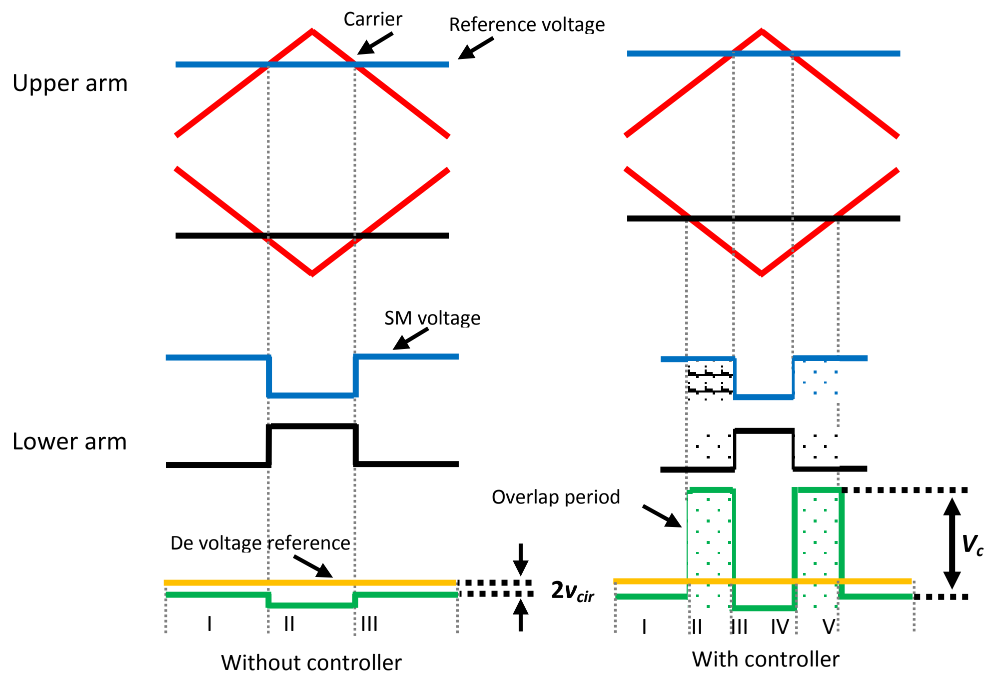


Figure 1.4 shows the pulse-width voltages generated for the PWM sub-modules.

The reference voltages are compared with the triangular carriers to decide whether the sub modules should be inserted or bypassed. The triangular carriers for the upper and lower arms are complementary. The reference voltages are actually the representation of the insertion indices. When circulating current suppressing control is not implemented, the sum of insertion indices for the upper and lower is unity, which means there are sub-modules always inserted in one phase-leg. Thus the voltages of PWM sub-modules in the upper and lower arms are complementary so the resulting phase-leg voltage has an error of $2v_{cir}$ compared to the dc voltage reference.

The phase-leg voltage difference between I, II and III represents the different sub-module capacitor voltages in the upper and lower arms. With the circulating current suppressing controller, a common mode component is added into the insertion indices. The voltages of PWM sub-modules in the upper and lower arms are no longer complementary, but have an overlap as shown in Figure 1.4 Additional sub-modules would be inserted or bypassed in the circuit based on the sign of N_{Cir} during the overlap period, which means it is no longer true that N sub-modules are always inserted in the circuit for a phase-leg.

The phase-leg voltage has a two pulses with magnitude of v_c in each switching period because of the circulating current suppressing control. Based on the equivalent circuit in Figure 1.4 the voltage difference between the phase-leg voltage and dc side voltage is applied on the arm inductors.

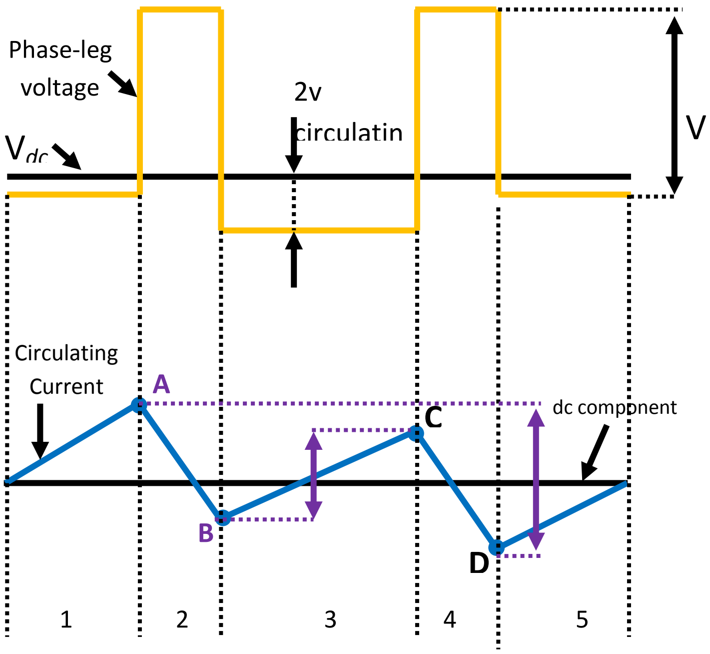


Fig1.5 Phase-leg voltage and circulating current in a switching period

Figure1.5 shows the resulting phase-leg voltage with the circulating current suppressing controller and the corresponding circulating current in one switching period. That figure is divided into 5 stages. Stages II and IV represent the overlap periods, and the phase-leg voltages in these two periods are v_c higher than the voltages in the other periods. The phase-leg voltages in stages I, III and V are nearly the same, with a small variation representing the capacitor voltages difference between the upper and lower arms. The voltage difference between VDC and the phase-leg voltages in stages I, III and V is $2v_{CIr}$, as shown in (12). If the circulating current suppressing controller is not implemented, the phase-leg voltages in stages II and IV would be the same as the other periods, and the circulating current would keep increasing or decreasing in the whole switching cycle, resulting in a second-order line frequency circulating current. But with the circulating current suppressing controller, the voltages in stages II and IV can compensate for the voltage differences in the other three periods and make the average value of the phase-leg voltage in each switching cycle equal to Vdc. The second order circulating current is thus eliminated, but the switching frequency circulating current comes out. As shown in Figure1.5 in order to calculate the switching frequency circulating current, the voltage difference between the phase-leg voltage and dc side voltage should be obtained. Based on [14]v_{CIr} can be derived as:

$$V_{CIr} = \frac{N}{8C\ Sub}\left[-\frac{3}{4\omega}M.Iac.\sin(2\omega t-\theta)+\frac{1}{3\omega}M^2\ Idc.\sin(2\omega t)\right] \quad (13)$$

Where *Idc* stands for the dc component of dc side current. It is shown in figure 1.5 above.

The value of peak current would either occur at D and A or occur at C and B determined as a result of the length of periods 1, 3, and 5. Considered the overlap periods are relatively small, and also the longest time period among1, 3, and 5 can be derived as:

$$\Delta T = \max(Dan_{real} \qquad Dap_{real}) * Ts$$

Where *Ts* is the switching period.

The value of switching frequency circulating current which is peak to peak, can be derived as:[13][14]

$$I_{PP} = \frac{VCirculating}{L\ arm}\ \Delta T \quad (14)$$

The equation (14) above shows the relationship between switching frequency circulating current and the arm inductance, so the arm inductance is possibly selected to meet a circulating current limit for a given condition of the operation. This shows that the arm inductance could be selected in order to meet circulating current limit for all different working conditions and operation in any type of MMC. From equation (13)

Assuming a maximum modulation index is 1, the maximum circulating voltage is:

$$V_{Cir\ max} = \frac{N}{8wCsub}\sqrt{\frac{9}{16}I^2ac+\frac{1}{9}I^2\ dc-\frac{1}{2}\ Iac\ Idc} \quad (15)$$

As shown above in fig1.5, the largest ΔT would be Ts. And also consider the equation (14) and (15) so maximum switching frequency circulation current is derived as:

$$I_{PP\ max} = \frac{N.Ts}{8w\ L\ arm\ Csub} \sqrt{\frac{9}{32}} I^2 ac + \frac{1}{9} I^2\ dc - \frac{1}{2}\ Iac\ Idc \qquad (16)$$

By considering the equation (16), the switching frequency circulating current is depending on the sub-module capacitance and arm inductance. And known the sub-module capacitance is really designed by its voltage ripple requirement. And the main point for all above equations is that: circulating current flowing only in arms of the MMC are usually caused by the capacitor voltage ripple and instantaneous changes between voltage level due to multi-level modulation. [5][14] Equation (14) shows that by increasing the value of arm inductance and Sub-module capacitance the maximum switching frequency circulating current would be reduced, since the Sub-module capacitance and arm inductance is opposed to the flow of it.

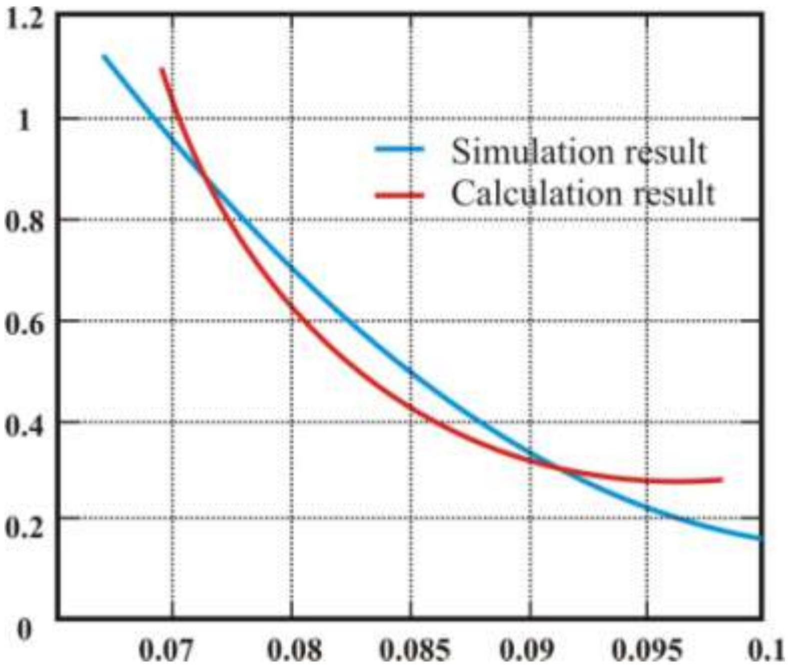
4.4 VERIFICATION OF SIMULATION

For verification of the theoretical analysis of switching frequency-circulating current, Simulation model of Three-phase MMC with the four SMs per arm is built in MATLAB. The capacity is 5MW, and rated AC grid voltage is 1.67kv, the rated AC current 1kvA and the Rated DC voltage 3.2kv, the SM capacitor voltage is 1.6kv, also AC side inductance and arm inductance is 0.45mH and 0.045mH. The sub-module capacitance is 10mF and also the Switching period (Ts) is 0.1

2.4 RESULTS

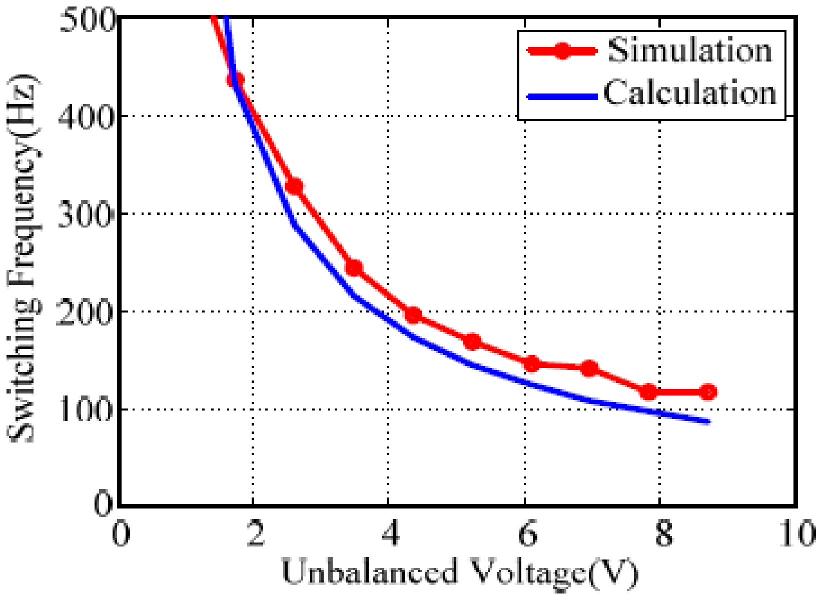
Arm inductance L (mH)

I_{pp} max (



Maximum switching frequency current versus Arm inductor

Voltage difference among sub-module capacitors increases the fluctuation of capacitor voltage, and its impact on the total voltage fluctuation is large when modular multilevel converter operates at low switching frequency conditions. The analytical relationship between the switching frequency and sub-module capacitor unbalanced voltage or maximum switching frequency circulation current is derived based on the voltage-balancing control with the modified sorting method. It is shown that the switching frequency in MMC is inversely proportional to the sub-module capacitor unbalanced voltage, which influences the sub-module capacitance selection. Simulation results verify the developed relationship between sub-module capacitor unbalanced voltage and the switching frequency. The derived relationship between maximum switching frequency circulation current or unbalanced voltage and switching frequency, on the other hand, can also provide a guide for determine the threshold voltage for the modified sorting method when the switching frequency is chosen first.



Comparison of the simulation and calculation results on the relationship between switching frequency and unbalanced voltage

CONCLUSION:

This paper has investigated the selection principle of arm inductance and also proposed that the arm inductance should be designed based for limit the switching frequency circulating current, if the circulating current suppressing controller is implemented. The derived relationship between switching frequency circulating current and arm inductance has been verified by the simulation results and calculation result of arm inductance then, Voltage difference among sub-module capacitors increases the capacitor voltage fluctuation, and its impact on the total voltage fluctuation is large when MMC operates at low switching frequency conditions. It is shown that the switching frequency in MMC is inversely proportional to the sub-module capacitor unbalanced voltage, which influences the sub-module capacitance selection.

REFERENCES

[1]. ABB. (2013). *It's time to connect with offshore wind supplement* [Online].Available: http://www.abb.com/hvdc

[2]. D. V. Hertem, M. Ghandhari, and M. Delimar, "Technical limitations towards a supergrid – a European prospective," in *Proc. IEEE International Energy Conference*, 2010.

[3]. S. Cole, K. Karoui, T. K. Vrana, O. B. Fosso, J. Curis, and C. Liu, "A European supergrid: present state and future challenges," in *Proc. 17th Power Systems Computation Conference*, 2011.

[4]. M. Callavik et al., "Roadmap to the supergrid technologies (updated report)," Friend of the Supergrid Working Group 2, 2013.

[5]. D. Jovcic, D. V. Hertem, K. Linden, J.-P. Taisne, and W. Grieshaber, "Feasibility of dc transmission networks," in *Proc. 2nd IEEE PES International Conferenceand Exhibition on Innovative Smart Grid Technologies*, 2011.

[6]. J. Candelaria, and J.-D. Park, "VSC-HVDC system protection: a review of current methods," in *Proc. IEEE Power Systems Conference and Exhibition*, 2011.

[7]. N. Flourentzou, V. Agelidis, and G. Demetriades, "VSC-based HVDC power transmission systems: an overview," *IEEE Transactions on Power Electronics,*vol. 24, no. 3, pp. 592-602, March 2009.

[8]. A. Abbas, and P. Lehn, "PWM based VSC-HVDC systems – a review," in *Proc.IEEE Power & Energy Society General Meeting*, 2009.

[9]. R. Marquart, "Modular multilevel converter: an universal concept for HVDCnetworks and extended dc-bus-applications," in *Proc. IEEE International Power Electronics Conference*, 2010.

[10]. R. Marquart, "Modular multilevel converter topologies with dc-short circuit current limitation," in *Proc. IEEE 8th International Conference on PowerElectronics – ECCE Asia*, 2011.

[11]. H. Mohammadi, and M. Bina, "A transformerless medium-voltage STATCOM topology based on extended modular multilevel converters," *IEEE Transactionson Power Electronics,* vol. 26, no. 5, pp. 1534-1545, May 2011.

[12]. M. Glinka, and R. Marquardt, "A new ac/ac multilevel converter family," *IEEE Transactions on Industrial Electronics,* vol. 52, no. 3, pp. 662-669, June 2005.

[13]. M. Hagiwara, K. Nishimura and H. Akagi, “A medium-voltage motor drive with a modular multilevel PWM inverter,” *IEEE Transactions on Power Electronics,* vol. 25, no. 7, pp. 1786-1799, July 2010.

[14]. M. Glinka, and R. Marquardt, “A new ac/ac-multilevel converter family applied to a single-phase converter,” in *Proc. IEEE 5th International Conference onPower Electronics and Drive Systems*, 2003.