Modular Multilevel Converter-based HVDC System: A Review

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Abstract – *The modular multilevel convertor (MMC) represents a rising topology with a scalable technology creating high voltage and power capability possible. The MMC is constructed up by identical, but on an individual basis controllable sub-modules. Therefore the convertor will act as a controllable voltage supply, with a large number of accessible discrete voltage steps. The MMC consists of a large number of simple voltage sourced converter (VSC) sub modules that may be easily assembled into a converter for high-voltage and high power. This paper shows that the MMC converter has a fast response and low harmonic content in comparison with a two-level VSC option. This paper gives the modeling approach used, including a solution to the modeling challenge imposed by the very large number of switching devices in the MMC. A general overview of modeling techniques of the MMC along with their performance for HVDC applications is provided.*

Key Words: Modular Multilevel Converter (MMC), HVDC transmission, Voltage Source Converter (VSC), Converter Control, Mathematical modelling.

1. INTRODUCTION

With new renewable energy production, in the last 40 years, HVDC has played a key role in transmission systems with a series of economic and technical considerations. More stochastic energy production concerns solutions which will transport power from areas with high generation to areas with lower generation. Connecting the converter to a DC grid should be feasible and also the converter should be able to handle fault situations. To gain compactness, the need for filters should be minimized. The rising topology, the modular multilevel converter (MMC) would possibly address these aims.

2. HVDC CONVERTER TECHNOLOGIES

2.1 Load Commutated Converters

The thyristors based Load Commutated Converters (LCCs) were introduced in 1970s. LCC is still the converter which can build with highest power rating and hence is the best solution for the transmission of the bulk amount of power. Another advantage of LCC is the low losses, generally 0.7 % per converter [1]. The biggest disadvantage is that both the rectifier and inverter absorbs continuously changing amount of reactive power from the grid, and hence accordingly to it adjustable reactive compensation is required [2]. Also the LCC requires an AC voltage source at each terminal which will to succeed with commutation. To minimize the harmonic content generally the standard LCC design is made with two 6-pulse bridges in series on the DC side and parallel on the AC side. The two bridges are phase shifted by 30 degrees on the AC side, using transformers [3].

2.2 Load Commutated Converters

The ABB concept HVDC Light in 1997 introduced Classical Voltage Source Converter (VSC) utilizing Insulated Gate Bipolar Transistors (IGBTs) [4]. The Classical VSC for HVDC applications is based on two or three-level converters [4]. With this concept adjusting the voltage magnitude at AC terminals is not possible, but the voltage can be either ±V with two-level or ±V or zero voltage with three-level VSC [2]. Pulse width Modulation (PWM) is employed to approximate the desired voltage waveform. The difference between an implemented and desired waveform is an unwanted distortion which has to be filtered [2]. Because of the limited voltage blocking capability of IGBT, they have to be connected in series in two-level and three-level VSCs [4]. Series connected IGBTs must be switched absolutely simultaneously, in order to limit the voltage across each semi-conductor. This requires the sophisticated gate drive circuits to enforce voltage sharing under all conditions [5].

2.3 Modular Multilevel Converters

Siemens first HVDC PLUS system was commissioned, a multilevel VSC technology called MMC in 2010 [2]. At the same time, ABB updated their HVDC Light product by using approximately same technology [4]. MMCs are built up by number of identical but at the same time individually controllable sub-modules.

The sub-modules in the MMC can either be two-level half-bridge converters, each of capable to producing +V or zero voltage, or two-level full-bridge converters, producing ±V or zero voltage [5]. This means that the converter is acts as a controllable voltage source with a high number of discrete voltage steps. The multilevel converter topology prevents the formation of any high harmonic content [4].

The MMC is a scalable technology. The voltage level determines the number of sub-modules which will requires, and the technology can be used for high voltage transmission [9]. The configuration is without series connection of semiconductor switches, and hence the problems with simultaneous switching are irrelevant. Losses are lower as that of two-level and three-level VSCs, about 1 % per converter [4]. The lower losses are obtained by lowering the switching frequency in each sub-module and low voltage across each switch [9]. However, as the sub-modules are switched at different points in time, the effective switching frequency of the converter is high, giving a low harmonic distortion [4].

A MMC with two-level half-bridge sub-modules requires twice the number of IGBTs as that of two-level VSC of the same rating. For a MMC with two-level full-bridge sub-modules, the needs IGBTs twice as high as with half-bridge sub-modules [5]. The MMC does not have DC link capacitance, but one capacitor in each sub-module is required and these capacitors require both large voltage capacity and large capacitance. The results of several semiconductor switches and capacitors with high ratings could be a significant and bulky circuit, giving a converter that is less compact than the classical VSC, but still more compact than the LCC [5].

During a DC pole to pole fault, the MMC with two-level half-bridges doesn't block fault currents. With two-level full-bridge sub-modules the MMC is capable of suppressing the fault current and therefore no AC breaker opening is required [5]. It will be discussed whether or not this advantage is giant enough to defend the increased number of semiconductors. As each vendors delivering MMC solutions uses two-level half-bridges [2, 4], only this solution will be described in the following.

An advantage with MMCs compared to classical VSC is that the dv/dt on the AC side is reduced because the voltage steps at the terminals are smaller. This enables the employment of transformers with lower insulation requirement [10]. Compared to LCC, MMC uses ordinary transformers, no phase shift is required. Installations of LCC HVDC in 2011 shows that LCC HVDC can be built with 7200 MW and ±800 kV, while MMC projects are planned with 1000 MW and ±320 kV [11, 12].

3. THE OPERATING PRINCIPLE OF THE MMC

In three phase MMC, each of the phase unit is consist of two multi-valves, and each multivalve is consist of N sub-modules connected in series as shown in Fig. 1 [9]. With a DC voltage of ±320 kV 38 numbers of sub-modules are usually required [4]. The half-bridge sub-module consists of two valves (T1 and T2) and a capacitor as shown in Fig. 2. The valves are consisting of an IGBT and a freewheeling diode in anti-parallel manner. In normal operation, only one of the valves is switched on at a given instant of time. Depending on the direction of current the capacitor can charge or discharge [9].

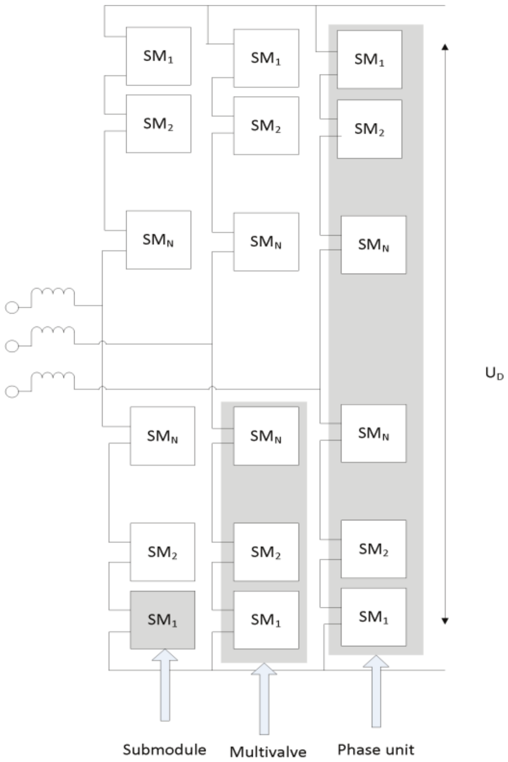

Fig -1: The MMC Structure

When just one IBGT is switched on, either that IGBT or the freewheeling diode in the same valve will conduct, depending on the current direction.

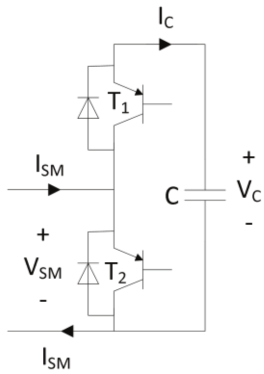

Fig -2: The Sub-module Circuit

Three possible switching states can be defined [4]:

• In the ON or inserted state T1 is on, and T2 is off. The sub-module output voltage (VSM) is equals to the capacitor voltage (VC) and the capacitor charges, if the multivalve current is positive otherwise discharges.

• In the OFF or bypassed state T2 is on, and T1 is off, VSM is zero and VC is constant, i.e. the capacitor will not charge nor discharge.

• Within the blocked state, both valves are off, and the current can only conduct through the freewheeling diodes. The capacitor can charge if the current is positive, but ideally it cannot discharge

The block voltage in each phase unit is double the DC voltage. This can be explained from the situation once all the sub-modules within the upper multivalve are bypassed, giving a phase voltage equal to the DC voltage. The lower multivalve should be able to block the voltage across itself, i.e. the DC voltage. The result is that each switch must be able to block the DC voltage, UD, which is given as Vblock=Ud/N. The capacitors within the lower multivalve also will share the DC voltage and should be dimensioned within the same method as the IGBTs. Considering a similar case and a negative ism relative to Fig. 2, each IGBT in the upper valve must be able to block the voltage across the capacitor in the same sub-module. This is one of the reasons why capacitor voltage balancing is important. Both the upper and also the lower multi-valves should have half the DC link voltage as average value so as to get a phase output with zero DC offset. The multi-valves might take any amplitude between zero and also the DC voltage. The sum of inserted sub-modules in a phase is constant, thus inserting a sub-module on one multivalve is done at the same time as bypassing one in the other multivalve of the same phase.

4. CONTROL OF THE MMC

By controlling the firing angles the control of the LCC is done. In a DC link, one of the converter controls the DC current while other one controls the DC voltage. The Tap changing transformer can be used to obtain the desired combination of voltage and current [7]. With VSCs it is possible to control both the magnitude of voltage as well the delay angle, the first influencing the active power and the latter influencing the reactive power [7]. The voltage magnitude is manipulated with the modulation index. The control of the VSC is generally done in a dq frame of reference with one active power and one reactive power control loop. The active power control loop can either controls active power or DC voltage, while the reactive power loop can control the reactive power or the magnitude of AC voltage [7]. The possibilities of the MMC control system is usually equal to that of the two-level and three-level VSCs, Both can generally implemented in a dq frame of reference controlling two out of the four parameters mentioned above. However, the mathematical modelling is quite different; the blocks representing the converter system will differ. In addition, the MMC will require a capacitor voltage controller, keeping the capacitor voltages as equal and as close to the reference value as possible.

The dq frame of reference controllers use a cascaded structure with a fast inner current loop and an outer loop controlling active power and reactive power or the AC voltage magnitude.

4.1 The Current Control Loops

The d axis current control loop is shown in fig.3. It consists of a PI controller where time delay represents the converter and a block represents the electrical system. The PI controller in the control loop is tuned using modulus optimum [18]. Using modulus optimum, the zero of PI controller's should cancel the largest time constant in the system transfer function. In this case the time delay in the block representing the electrical system.

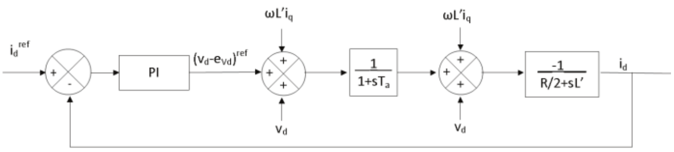

Fig -3: The D Axis Current Control Loop

The open current loop transfer function is obtained by multiplying all the blocks transfer functions:

$$H_{c,OL} = k_c \frac{1+T_{ic}s}{T_{ic}s} \frac{1}{1+T_a s} \frac{-1}{\frac{R}{2}+L's} \quad (1)$$

Where, kc is the gain in the PI controller, Tic is the integral time constant, Ta is the converter time delay, and R and L' are the electrical system parameters.

Using modulus optimum [18] the parameters of the PI controller are determined as kc = L' and Tic $= \frac{2L'}{R}$.

4.2 The Active and Reactive Power Control Loops

The active power and reactive power controllers use the dq frame of reference expressions which are obtained when the grid voltage vector is defined to be aligned with the d-axis. With this alignment vq = 0 and the active and reactive power are given as follows [19]:

$$P = vdid \quad (2)$$

$$Q = vdiq \quad (3)$$

From the similarity of these two equations, it seems that the active power and the reactive power controller will have the same structure and parameters. The reactive power control loop contains the q-axis current control loop. This loop has the same closed loop transfer function as that of d-axis current control loop. Due to these similarities only the active power control loop is shown fig. 4. It consists of a PI controller, the d axis current control loop, and a gain given by equation (2). Tuning of the PI controller should be done to ensure sufficiently large phase margin combined with high crossover frequency. Plot of the transfer function shows that the gain must be kept under a certain value and that the integral time constant, TiP, must be kept a number of times greater than that of the time delay in the converter Ta.

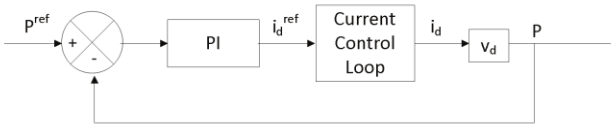

Fig -4: The Active Power Control Loop

4.3 The AC Voltage Magnitude Control Loop

The AC voltage magnitude controller uses the relation between rms values and dq quantities as given below:

$$Vrms = \sqrt{\frac{vd^2 + vq^2}{3}} \quad (4)$$

The controller in Fig. 4 consist of a PI controller, the q axis current control loop and a function representing the relationship between dq quantities and phase quantities given by equation (4). With any parameters in the PI controller, the control loop is stable.

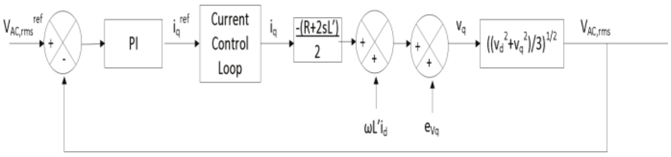

Fig -4: The AC Voltage Magnitude Control Loop

5. CONCLUSION

The computational modelling of a MMC has been presented. These enable both analytical evaluations and simulations, and hence are important tools when the MMC is introduced in the power system. Due to the MMC topology complexity, simulation models turn out to be somewhat different from the classical VSC models. For the simulation model, a Thevenin's equivalent was introduced to obtain a voltage value for each multivalve at every instant. This model should be combined with a capacitor voltage balancing algorithm. The Thevenin's equivalent is important as it reduces the computational efforts, and hence makes realistic simulations possible. With Regard to control, the MMC has the same advantages as two-level and three-level VSCs, d-axis and q-axis control can be done independently. This can be used to control either active power or DC voltage and AC voltage magnitude or reactive power. The control loops which are presented uses cascaded structure with a fast inner current loop and an outer loop controlling active power and reactive power or magnitude of AC voltage. As the equations resulted in similar id and iq control loops, the structure and parameters of the active power and reactive power control loops also became quite similar. By using modulus optimum the tuning of the PI controllers in the current loops can be done. PI controllers in the outer control loops must be tuned in order to achieve a reasonable crossover frequency combined with suitable phase and gain margins. In the future, simulations should be carried out to spot the appropriateness of the controllers.

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