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Performance and Analysis of Modular Multilevel Converter

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***Abstract:* -** The Modular Multilevel Converter (MMC) represents an emerging topology with a scalable technology making high voltage and power capability possible. The MMC is built up by identical, but individually controllable sub modules. The Modular Multilevel Converter (MMC) is a new topology for multilevel converters with potential for medium voltage and high voltage applications. Equivalent Circuit models and dynamic models for the MMC that provide a faithful representation of system behavior are quite complex given the large number of energy states and control variables. They are not particularly useful in studying the terminal behavior of the converter and for the development of an intuitive control approach to regulate power transfer. A control scheme with a new sub module capacitor voltage balancing method is also proposed in this paper. Modular multilevel converters, based on cascading of half bridge converter cells, can combine low switching frequency with low harmonic interference. They can be designed for high operating voltages without direct series connection of semiconductor element.

***Keywords:* -** *Modular Multilevel Converter (MMC), Voltage Source Converter (VSC), Harmonic Analysis, Terminal model, high voltage direct current.*

I. INTRODUCTION

The introduction of the paper should explain the nature of the problem, previous work, purpose, and the contribution of the paper. The contents of each section may be provided to understand easily about the paper. With new renewable energy production, HVDC is more applicable than ever. More stochastic energy production calls for solutions that can transport power from areas with high generation to areas with lower generation. Offshore wind farms far from the coast require HVDC transmission to the shore and compact and reliable converter technology with large power capability. Connecting the converter to a DC grid should be feasible and the converter should be able to handle fault situations. To gain compactness, the need for filters should be minimized. The emerging topology, the Modular Multilevel Converter (MMC) might address these aims. The newest generation of voltage source converters (VSCs) is the main driver for the latest evolutionary step in the EMT software community due to their use of a very high number of power electronic devices. This technology, known as modular multilevel converters (MMCs) or cascaded two-level converters (CTLCs), generates voltages with very low harmonic content and presents loss levels much closer to those of “classic” thyristor line-commutated converters [1] [2] [3]. A MMC consists of multiple cascaded sub-modules (SM), the internal structure of which can be a half-bridge, a full bridge, or a clamp-double SM [8]. This work is dedicated to mathematical model which can be useful in the analysis and design of structures and control strategies of MMCs This paper studies the modular multilevel STATCOM using full-bridge SM. Due to its topology, MMC offers some advantages and unique features:

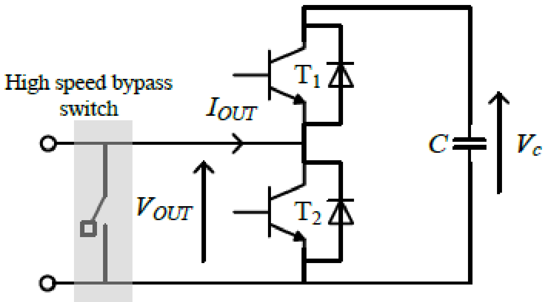
1. Its AC voltage and current have low harmonics. A passive filter becomes unnecessary.
2. MMC arm currents are continuous, and there is no longer a single bulky capacitor in a DC link.
3. The PWM carrier frequency is low, and consequently the losses are reduced.
4. Short-circuit of one sub-modules (SM) capacitor has little effect on others, and the system has fast recovery.
5. The modular structure provides redundancy to temporarily tolerate breakdown of some SM.

In MMC, there is a strong harmonic content in the arm current, although this is not reflected in the load current. This essentially controls the dynamic behavior of the converter. It is necessary to understand and predict the harmonic content of the arm current because transient behavior of this system depends on the current harmonics. In addition, to evaluate the abnormal operation of the converter; such as the failure of a module's control system or failure of the module itself, it is necessary to derive a well-defined model based on frequency domain methods.. However, in the available literature, no analytical frequency domain description of the MMC could be found that focused on harmonic interaction of the converter.

In general, power converters are nonlinear and time varying devices. It is well known that a small-signal model in the frequency domain can be used to predict the dynamic performance and stability of an MMC. Such a model is generally advantageous because it requires less computational time compared with time-domain simulation. It also provides more insight and understanding of the interaction between the AC and DC sides caused by the converter. To some extent, the harmonic distortion difficulties experienced with the previously used two-and three-level topologies are replaced by harmonic fluctuation challenges in the cell capacitors which require attention with regard to the dimensioning and control of the system.

An analytical study is made in Ref. [6] of the impact of capacitor voltage ripple, under simplified assumptions with regard to the control and modulation of the converter. To date however, there has been no comprehensive frequency-domain model of this topology and the analysis has generally relied on extensive simulation studies. In this paper a steady-state harmonic model is presented which can explain the relationship between the operating point variables, the pulse pattern used in the cells, and the harmonics of the cell capacitor voltages and the circulating currents. A power rating of 1 GW and above now becomes possible. Although the MMC topology has been presented in earlier literature [9],[10], the discussion on control methods is sparse. This paper discusses control approaches and investigates their performance using electromagnetic transients (EMT) simulation. The paper also investigates the control and performance of a HVDC transmission scheme feeding to a weak ac system.

1.1 Structure of Modular Multilevel Converter

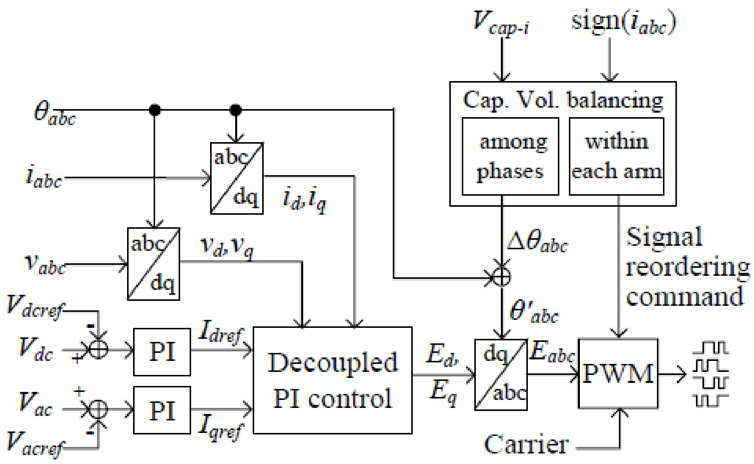


"Fig."1 Basic MMC Converter

The SM terminal voltage is determined by the states of the four switches. For a SM, there are three operating modes, namely PWM mode, natural rectifying mode, and forbidden mode. In the PWM mode, four IGBT, T1 to T4 receive PWM gating signals. The pair of T1 and T2 has complementary signals, as well as the pair of T3 and T4. The SM terminal voltage is either equal to its capacitor voltage, or the negative of capacitor voltage, or zero. When there is at least one pair of IGBT being blocked, the SM is in the natural rectifying mode. The terminal voltage is determined by the current direction which forces certain anti parallel diodes to conduct. When there is no current, the SM has high impedance and the terminal voltage is determined by the external circuit. Two IGBT in one pair cannot have ON signals at same time. This mode will short circuit the capacitor and damage the device and therefore is forbidden.

1.2 Control Schemes

To some extent, the harmonic distortion difficulties experienced with the previously used two-and three-level topologies are replaced by harmonic fluctuation challenges in the cell capacitors which require attention with regard to the dimensioning and control of the system. An analytical study is made in Ref. [6] of the impact of capacitor voltage ripple, under simplified assumptions with regard to the control and modulation of the converter. To date however, there has been no comprehensive frequency-domain model of this topology and the analysis has generally relied on extensive simulation studies. In this paper a steady-state harmonic model is presented which can explain the relationship between the operating point variables, the pulse pattern used in the cells, and the harmonics of the cell capacitor voltages and the circulating currents.



"Fig."2 Control Schemes

Several recent publications provide analytical models suitable for studying the behavior of MMC. One MMC averaged equivalent circuit that assumes all the sub modules to be identical is illustrated in Fig. 2, where the internal converter arm currents *iBij* and arm-level capacitor voltages *vSij* of the *i*th row and *j*th column may be described via (1)–(3) using an averaged duty ratio *dBij* [9], [12]. Rows and columns in this context refer to the arm position a sub module in the circuit schematic of the MMC. Each arm possesses *n* sub modules and *x* denotes the sub module number within the arm. Further nomenclature detail of the variables is illustrated in Fig. 2, and more details may be found in [9], [15], and the nomenclature.

The dynamic model that represents the coupling between the various quantities are expressed in (1)–(3), where *v*NSB is defined as the bridge neutral voltage, which is nominally zero under balanced operating conditions. While this equivalent circuit model provides a faithful representation of system behavior, it still is not particularly useful in studying the terminal behavior of the converter, because it consists of 12 coupled differential equations, even if all the sub modules are identical to each other. This section further reduces the complexity of the MMC analytical model to an equivalent boost–buck converter circuit. The transformation is performed in a step-by-step process beginning with the model defined in Fig. 2 and manipulation of (1)–(3).

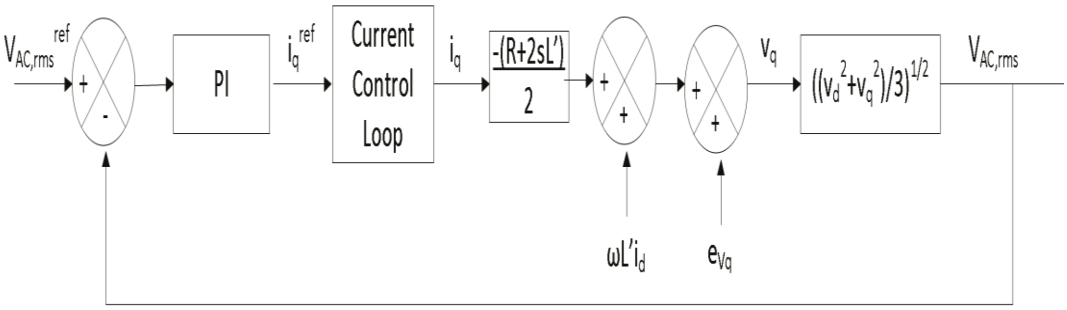
II. PARAMETER REPRESENTATION

2.1 Dual capacitance selection

In the voltage source converters the energy is stored in DC-link capacitors. The maximum energy stored in capacitors *E*Cmax is determined by the rated converter power *S*n and the energy-power ratio. This ratio varies depending on the converter application and typically is *EP* = 10 J/kVA to 50 J/kVA Lower values mean a reduction of the converter cost but higher voltage ripples in the DC-link circuit. In this paper it is assumed that the same energy-power ratio is applicable to the modular multilevel converter. At the beginning of the AC-DC converter design stage two main converter parameters are set. It is the rated converter power *S*n and rms value of the line-to-line voltage *V*acll, rms at the ac side of the converter or the voltage *V*dc at the dc side of the converter. Assuming that in the MMC there are no redundant Sub modules, the relation between ac side and dc side voltages.

2.2 Power conversion within the cell strings

In the previous section it was assumed that the cell strings of the phase legs can be treated as voltage sources. Due to the presence of low-frequency voltage and current harmonics in the cell capacitors this assumption is only applicable with few qualifications. To gain a better understanding of the behavior of the cells and cell strings when the cell capacitor ripple cannot be neglected a frequency-domain model is derived in this section. Throughout the section as well as the next section, only one phase leg is considered since the treatment of all phase legs is identical. For this reason the index *i*, related to the phase leg number is dropped.



"Fig."3 Closed loop conversion

2.3 Arm inductance selection

The role of the arm inductors *L*arm in the MMC is to suppress any high frequency components of the arm currents caused by differences in upper and lower arm voltages. These differences can exist for example, due to different switching times of converter switches. From Table I it can be seen that different arm inductances *L*arm have been chosen in different references. The exact value of the arm inductance depends on the sub module capacitor voltage *V*dc/*n*, the modulation technique, the switching frequency and an additional controller optionally used for suppressing the circulating current.

In this paper only direct modulation is considered as a modulation technique and the circulating current is not suppressed by any other control methods. It means that the circulating current has to be suppressed only by proper selection of the arm inductance *L*arm. This can be done by avoiding resonances (11) that occur in the circulating current for the previously given arm capacitance *C*arm, thus shows a cell, numbered *n*, with the relevant electrical quantities indicated. The signal *s{u,l}n* is the switching function which assumes the value 0 when the valve in parallel to the cell terminal conducts and the value 1 when the valve in series with the capacitor conducts. Firstly, the equations relating the cell capacitor voltage and current to the voltage and current at the cell terminal.

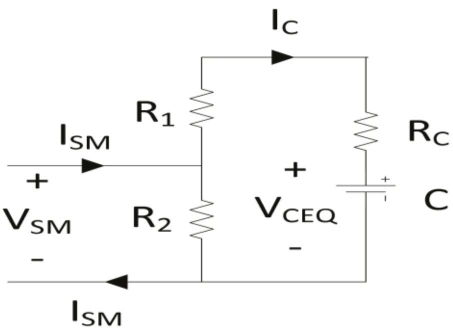
Every phase-leg is composed of two arms where each arm has a number of n sub modules. In turn, in every sub module there is a DC capacitor charged with the voltage Vdc . Note that during any moment, half the modules are connected and half the modules are bypassed. This is necessary since the sum of all connected modules in a phase-leg must be Vdc.

$$V_{SM}(t) = I_{SM}(t)\frac{R_2(R_1+R_C)}{R_2+R_1+R_C} + V_{CEQ}(t-\Delta T)\frac{R_2}{R_2+R_1+R_C} \tag{1}$$

$$R_{SMEQ}(t) = \frac{R_2(R_1+R_C)}{R_2+R_1+R_C}$$

$$V_{SMEQ}(t-\Delta T) = V_{CEQ}(t-\Delta T)\frac{R_2}{R_2+R_1+R_C} \tag{2}$$

III. FREQUENCY –MODULAR MODELING METHOD



"Fig."4 Voltage source converter

With VSCs, both active power flow and reactive power flow can be controlled, independently, and accordingly no reactive compensation is needed. A VSC station is therefore more compact than a LCC station as the harmonic filters are smaller and no switch yards and capacitor banks are needed. Other advantages with the VSC is that the converter can be connected to weak systems and even to networks lacking generation, and as no phase shift is needed, the VSC can use ordinary transformers.

A disadvantage is that the VSC has larger losses than LCC, typically 1.7 % per converter. Using LCC, the current direction is fixed and power reversal is done by changing the voltage polarity. With VSCs power reversal is done by changing of the current direction. This makes the VSC technology more suitable for a DC grid application. Cross-linked polyethylene (XLPE) cables can be used with VSCs, but cannot handle the stress from a polarity change. XLPE cables are advantageous as they are less costly, lighter, and smaller in diameter than traditional mass impregnated cables.

The power reversal with VSCs can be done gradually because the full range of active power is available, even zero active power can be combined with a positive or negative reactive power. Because both active and reactive power can obtain positive and negative values, the converter is said operate in all four quadrants of the PQ plane. LCCs normally have a minimum active power output 5% below rated power. This makes VSC more favorable for power transmission with varying power e.g. power generated from a wind farm. But an advantage with LCC HVDC is that DC pole to pole short circuit faults can be cleared in the converter station. This is not the case with classical VSC HVDC where in most cases the fault currents must be suppressed by opening the AC breaker feeding the converter.

$$V_{MV}(t) = \sum_{i=1}^{N} V_{SM_i}(t) = I_{MV}(t) \sum_{i=1}^{N} R_{SMEQ_i}(t) + \sum_{i=1}^{N} V_{SMEQ_i}(t - \Delta T) = I_{MV} R_{EQ} + V_{EQ}(t - \Delta T) \quad (3)$$

$$i_U + i_L = i_v$$

$$i_U = I_{s1} + i_{diff}$$

$$i_L = I_{s2} - i_{diff} \quad (4)$$

IV. SIMULATION RESULTS

In this section, a point to point MMC based HVDC transmission system; feeding to a weak ac network has been simulated. The dc link is connected to the two ac systems. The sending end ac system has a short circuit ratio (SCR) of 2.5, and is relatively strong. The receiving end system is weak, with an SCR of 1.0. The simulated system is schematically shown in Fig. 10. In the simulation, MMC1 acts as the rectifier and MMC2 acts as the inverter. The dc system is rated at 400MW, ±200kV. Each MMC has 100 sub-modules in a multi-valve; hence the sub-modules were rated at 4.0kV.

Parameters used for MMC

Parameter name	Symbol	Value
Voltage at the converter dc side	V_{dc}	5.0 kV
Output current amplitude	I_V	100 A
Fundamental frequency	f_m	50 Hz
Modulation index	m_a	1.0
Output phase shift angle	φ	0 deg
Arm capacitance	C_{arm}	0.02, ..., 2 mF
Arm inductance	L_{arm}	0.05, ..., 5 mH
Arm resistance	R_{arm}	0.1 Ω

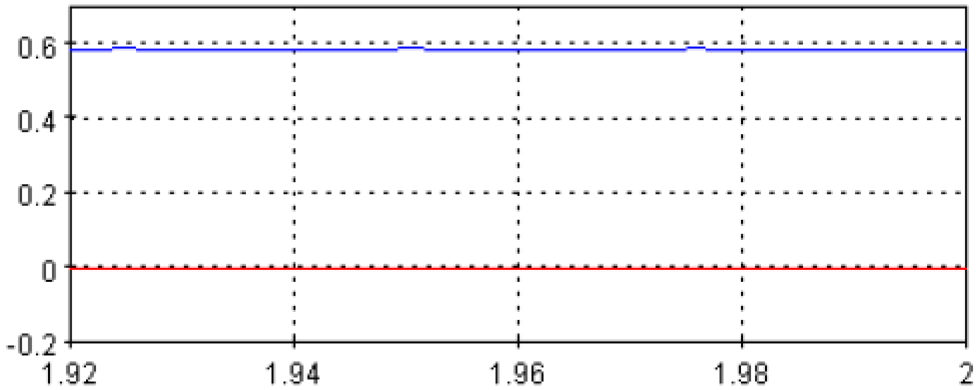
As there is a total of 2400 switches in the two converters, it is practically impossible to model the converters using the traditional approach using individual switches in EMT programs. Therefore, computationally fast model discussed in section IV, was used for modeling the system [8]. HVDC System controls. The direct control strategy [7] was selected for the higher level controllers of the system. The controllers output the desired phase shift angle δ and the magnitude M of the reference signal (Vref). The reference for measuring the angle is the ac converter bus-bar (Bus 1 for MMC1 and Bus 2 for MMC2). The angle of this bus voltage is tracked by a phase locked loop (PLL) which provides the synchronizing reference. The details of the individual rectifier and inverter side controllers are given below.

4.1 Rectifier Side Controller

The MMC1, rectifier is responsible for regulating the dc side voltage and ac side Bus1 voltage. Proportional-integral controllers derive magnitude, M1, and phase, δ1, of the reference waveform to regulate the ac bus-bar voltage and the dc bus voltage respectively. Using these, three phase reference waveforms are generated and sent to the firing control system.

4.2 Inverter Side Controller

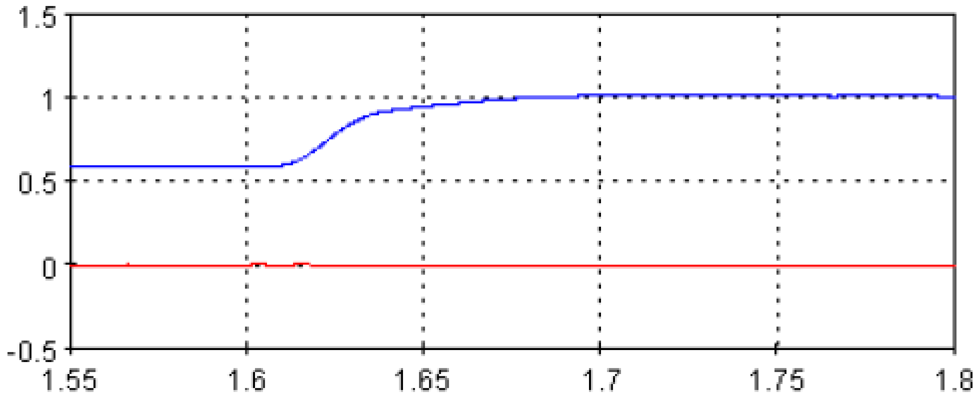
At the inverter, a similar control strategy is used, with the difference that the magnitude, M2, and phase, δ2, of the reference waveform are the outputs of proportional-integral controllers that regulate ac bus voltage and real power. The above HVDC transmission system where a power order change from full power (400 MW) to half power (200 MW) is applied at 0.4 s. The real and reactive power at the receiving end with the inverter side rms ac voltage and three phase bus voltage waveforms shown respectively. From the simulation, it can be seen that when the load is reduced, the voltage is immediately controlled to the rated value of 115kV and no significant overvoltage is seen, even though the inverter side ac system is weak. The control of voltage is obtained by rapid control of the reactive power to follow the real power change, as shown in the trace of reactive power. The change in power to (to 90% of final setting) is seen to be achieved in approximately 60 ms. The converter output ac voltage waveforms are shown during this transient and are indeed sinusoidal even though no ac filters are used.



"Fig."5 Voltage Representation

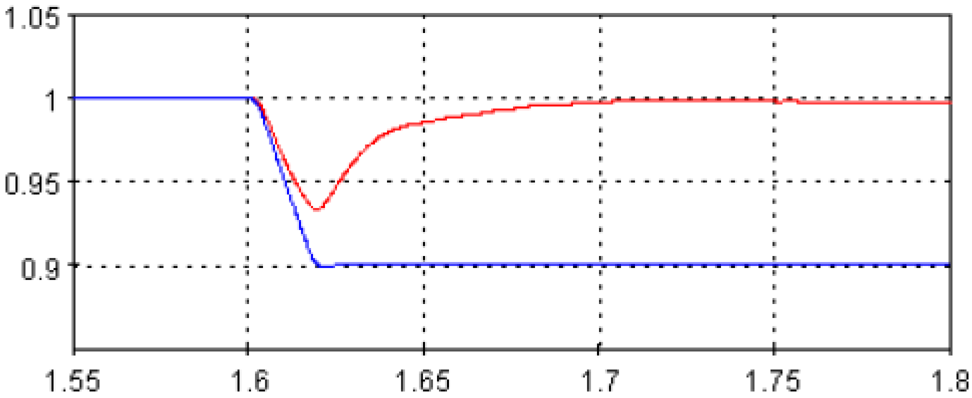
From the similarity of these two equations, it can be seen that the active power controller and the reactive power controller will have the same structure and parameters. The reactive power control loop will contain the q axis current control loop. This loop has the same closed loop transfer function as the d axis current control loop. Due to these similarities only the active power control loop is shown here (Fig. 7). It consists of a PI controller, the d axis current control loop, and a gain given by equation (34). Tuning of the PI controller must be done to ensure a sufficiently large phase margin combined with a high crossover frequency. Plotting 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 higher than the time delay in the converter *Ta*.

The nonlinearity of the switching function in the cells provides a few challenges for the derivation of a frequency domain model. According to Eq. (3) the capacitor current, and hence the capacitor voltage ripple, will contain modulation products of the switching function and the phase branch currents. On the other hand, Eq. (4) shows that the capacitor voltage ripple will influence the voltage at the cell terminals, and hence also the phase-branch currents, according to the discussion in the previous section. Thus, the branch currents influence the capacitor voltages which in turn affect the cell output voltages that together contribute to the phase-branch currents etc. For this reason, it is not trivial to obtain a closed analytical solution to the harmonic problem in the general case. A possible approach is to iterate between calculations of the capacitor harmonics on the one hand, and the phase-branch currents on the other hand until a solution is found. Such an algorithm is outlined in Figure 5, and Described in detail below. Starting from an estimate of the phase-branch current, the harmonic components of the current injected into cell capacitor *n* can be obtained as shown



"Fig."6 Current Representation

The Current Control Loops. Fig. 6 shows the d axis current control loop. It consists of a PI controller, a time delay representing the converter and a block representing the electrical system given by equation (3). From the symmetry of equations (1) and (2) it can be seen that the q axis current control loop will have the same structure and parameters and this loop is therefore not shown here. The PI controller in the control loop can be tuned using modulus optimum [18]. Using modulus optimum, the PI controller's zero should cancel the largest time constant in the system transfer function. In this case that will be the time delay in the block representing the electrical system



"Fig."7 Magnitude Displacement

As regards the average cell capacitor voltage, a few alternatives are possible, depending on the control of the considered converter. If, on the one hand, a control algorithm is implemented to maintain the average voltage at a certain set point, this value is used since this would be the steady-state value. If, on the other hand, the converter is connected to a dc bus bar with constant pole-ground voltage *Udc*, the cell capacitor voltage will adapt to the bus bar voltage and this corresponding capacitor-voltage dc. For the steady-state operation of the MMC converter it is vital to maintain energy balance between the dc and ac sides. In the previous chapter it was mentioned that the frequency-domain model does not give any direct guidance as to the dc components of the cell capacitor voltages and the converter dc-side current, both of which are related to the energy balance of the system. In this section the considerations necessary for choosing these variables in each iteration are discussed.

V. CONCLUSION

A benefit of the method is that it allows for a clear separation of steady-state and dynamic Effects which is not always possible by time-domain simulation. A weakness of the studied method is that no dynamic phenomena can be modeled, so that it is less useful as a tool for designing and evaluating closed-loop control systems, for instance. In this paper, the methodology was employed to solve the problem where the converter is connected to fixed ac and dc circuits and a fixed pulse pattern applied for the cells. However, also other problems may be solved by the studied model, which will be the topic of coming work. Furthermore, the methodology has been applied to the MMC converter with half bridges. However it could with modifications also be applied to other similar cell-based topologies, such as converters employing full bridges, where similar cell capacitor ripple effects are present For the simulation model, a The equivalent was introduced to obtain a voltage value for each multivalve at every instant. This model must be combined with a capacitor voltage balancing algorithm. The equivalent is important as it reduces the computational efforts a lot, and hence makes realistic simulations possible. Regarding 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 DC voltage or active power and either AC voltage magnitude or reactive power. The presented control loops 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.

REFERENCES

Journal Papers:

[1] M Ozaki, Y. Adachi, Y. Iwahori, and N. Ishii, Application of fuzzy theory to writer recognition of Chinese characters, *International Journal of Modelling and Simulation, 18(2),* 1998, 112-116. (8)

[2] S. S. Gjerde and T. M. Undeland, “The best suitable multilevel converters for offshore wind power generators without transformers,” in *Proc. Int. Power Electron. Conf.*, 2010, pp. 2398–2404.

[3] S. Allebrod, R. Hamerski, and R. Marquardt, “New transformerless, scalable modular multilevel converters for HVDC-transmission,” in *Proc. IEEE Power Electron. Spec. Conf.*, 2008, pp. 174–179.

[4] J. K. Reed and G. Venkataramanan, “Fault tolerant MVDC-HVAC power converter for wind farm applications,” presented at the CIGRE HVDC Colloq., San Francisco, CA, USA, 2012.

[5] A. L. P. de Oliveira, C. E. Tiburcio, M. N. Lemes, and D. Retzmann, “Prospects of voltage-sourced converters (VSC) applications in DC transmission systems,” in *Proc. Transmiss. Distrib. Conf. Expo.: Latin Am.*, 2010, pp. 491–495.

[6] U. N. Gnanarathna, S. K. Chaudhary, A. M. Gole, and R. Teodorescu, “Modular multi-level converter based HVDC system for grid connection of offshore wind power plant,” in *Proc. IET Int. Conf. AC DC Power Transmiss.*, 2010, pp. 1–5.

[7] G. P. Adam, O. Anaya-Lara, and G. Burt, “Multi-terminal DC transmission system based on modular multilevel converter,” in *Proc. 44th Int.Universities Power Eng. Conf.*, 2009, pp. 1–5.

[8] D. Soto-Sanchez and T. C. Green, “Control of a modular multilevel converter-based HVDC transmission system,” in *Proc. 14th Eur. Conf. Power Electron. Appl.*, 2011, pp. 1–10.

[9] D. C. Ludois, J. K. Reed, and G.Venkataramanan, “Hierarchical control of bridge-of-bridge multilevel power converters,” *IEEE Trans. Ind. Electron.*, vol. 57, no. 8, pp. 2679–2690, Aug. 2010.

[10] J. Reed, G. Venkataramanan, and F. Martinez, “Complex phasor modeling and control of modular multilevel inverters,” in *Proc. IEEE Energy Convers. Congr. Expo*, 2011, pp. 4013–4020.

[11] S. Rohner, J. Weber, and S. Bernet, “Continuous model of modular multilevel converter with experimental verification,” in *Proc. IEEE Energy Convers. Congr. Expo.*, 2011, pp. 4021–4028.

[12] K. Ilves, A. Antonopoulos, S. Norrga, and H.-P. Nee, “Steady-state analysis of interaction between harmonic components of arm and line quantities of modular multilevel converters,” *IEEE Trans. Power Electron.*, vol. 27, no. 1, pp. 57–68, Jan. 2012.