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# High frequent modelling of a modular multilevel converter using passive components

W. Z. El-Khatib, J. Holboell, T. W. Rasmussen

**Abstract—** Prevalence of High Voltage direct current (HVDC) based on Voltage source converters (VSC) has made it necessary to investigate the behavior of the converter under various fault conditions. In this paper we will deal with the transient characteristics of a modular multilevel converter (MMC). This means that a high frequency model of the converter has to be designed, which gives a better overview of the impact of high frequency transients etc. The functionality of the model is demonstrated by application to grid connections of off-shore wind power plants.

Grid connection of an offshore wind power plant using HVDC fundamentally changes the electrical environment for the power plant. Detailed knowledge and understanding of the characteristics and behavior of all relevant power system components under all conditions, including under transients, are required in order to develop reliable offshore wind power plant employing HVDC. In the present study, a back to back HVDC transmission system is designed in PSCAD/EMTDC. Simulations and results showing the importance of high frequent modeling are presented.

**Keywords:** *Modular multilevel converter, High frequency modeling, High voltage direct current (HVDC) transmission, Electromagnetic transients (EMT) simulation,*

## I. INTRODUCTION

THE Establishment of offshore wind farms at large distances from shore means that connection between farm and the onshore grid connection point by means of traditional AC-transmission lines becomes proportionally more infeasible as longer the distance is. This is due to the physical limitation of AC- cables, such as high resistive losses in the cables resistances caused by the capacitive current and inductances causing problems with voltage stability. HVDC-based transmission technologies therefore are getting attractive as an alternative wind power transmission system. Furthermore, HVDC-technology is used to interconnect areas which are non-synchronous, and hence HVDC-technology is expected to form the backbone of the future super grids.

On that background, also the transient behavior of HVDC-systems is getting increasingly relevant. For transient investigations in all kinds of power systems, usually high

frequent models are necessary and for HVDC, this includes the converters, and, in particular regarding future systems, the more flexible voltage source converters (VSC) are in focus. Due to the VSC's ability to connect large offshore wind power plants to the onshore grid, and furthermore its ability of connecting asynchronous networks, while keeping the stability of the power system, it offers the opportunity for an increased integration of a larger share of renewable energy in the power system.

In the present paper will be presented a VSC-model based on passive components, suitable for numerical simulations in time domain.

Even though VSC is a well-known topology, only few modeling approaches seem to be available, especially regarding transients and the related high frequency range. A possible reason for this might be the large number semiconductor switches in a modular multilevel converter (MMC). Simulating such complex components with a considerable number of nodes in electromagnetic transient simulation programs such as PSCAD will have a negative effect on the calculation with simulation times being remarkably increased, often up to non-acceptable levels. In the present work are presented methods to simulate the converter without using any kind of semiconductors in order to reduce the simulation time. The model consists only of passive components representing the sub modules in different states. For each state, new values are calculated for the converter. In order to cover the transient and high frequent range, all parasitic components, in particular of capacitive character had to be added to the model. All contributions are taken into account forming a mathematically and dynamically equivalent, which models the entire converter. That accurate and well defined model allows for a considerable reduction of the simulation time.

Time domain simulations of a back to back VSC demonstrate the capabilities of the model.

## II. MODULAR MULTILEVEL CONVERTER

The main component of the modular multilevel converter is the submodule. The submodule consists of 2 IGBTs each with a diode located in anti-parallel and a submodule capacitor as seen in the figure 1. The submodule can attain two different states, being either turned on or turned off.

### A. State 1 – turned on

The definition of the submodule being turned on means that the IGBT called IGBT1 in the figure 1 below is conducting, which means that the current is being conducted through the submodule capacitor. Therefore the voltage across the IGBT called IGBT2, which is turned off, will be the same as the

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voltage across the submodule capacitor.

### B. State 2 – turned off

When the submodule is turned off, IGBT2 is conducting, and IGBT1 has stopped conducting, therefore the current will be bypassing the submodule capacitor and the submodule will be seen as a short circuit. As a result of this, the voltage across the IGBT2, will be 0.

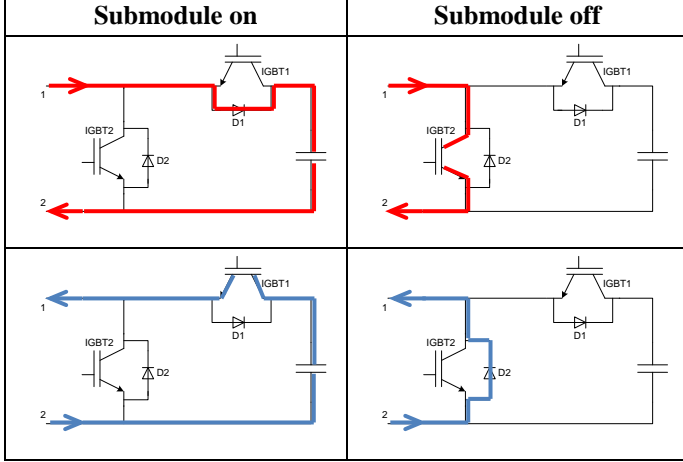


Figure 1: The different operating states of the MMC submodule

In a converter applying the MMC-topology, the number of steps of the output voltage is related to the number of series connected submodules and their state, if they are turned on or off. Each phase arm of the MMC consists of a stack which together forms a valve. There are two valves for each phase (e.g. upper and lower). The submodule capacitors are nominally charged to a desired voltage. This means that the output voltage is dependent on the number submodules turned on in each arm. Since the capacitor voltages of each submodule will add up to the net output voltage, this voltage can be determined from the two expressions seen below.

The output voltage of the converter, based upon the number of submodules turned on in the lower arm is [2]:

$$u_{lower} = u_0 + \frac{u_{dc}}{2}$$

The output voltage of the converter, based upon the number of submodules turned on in upper arm is [2]:

$$u_{upper} = -u_0 + \frac{u_{dc}}{2}$$

Where  $u_{lower}$ , the combined voltage of the submodules, is turned on in the lower arm and  $u_{upper}$  is the combined voltage of the submodules turned on in the upper arm.

Figure 2 below gives a graphical explanation of the operation of the MMC under two different situations. In the figure on the right, all submodules in the upper arm are turned on; hence the output voltage will be equal to the voltage of the negative pole of the HVDC-system [3]. Similarly, the figure on the left

shows the opposite situation, in which all of the submodules in the lower arm are turned on, and hence the output voltage will be equal to the voltage of the positive pole [3]. From the expressions above it is also clear, that when all the submodules in either the upper or lower arm are turned on, these submodules will actually be carrying the entire DC-voltage. This is due to the bipolar nature of the HVDC-system.

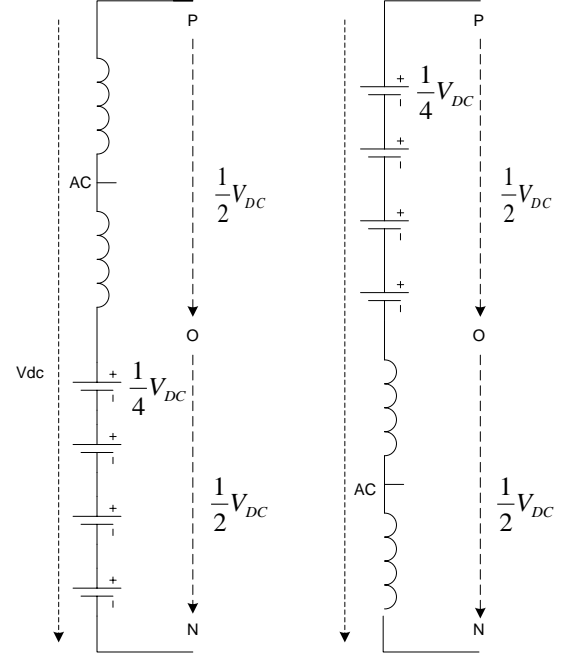


Figure 2: Operation of MMC single-phase diagram, on the right all lower submodule on and all upper submodule of. To the left the opposite case.

The three phase legs of the converter impress the same DC voltage  $V_{dc}$ . And due to the fact that the converter is actually symmetrical, all three phase legs have the same impedance with respect to the dc terminals since they have the same number total of submodule in each leg. Knowing this, we recognize that the dc terminal current  $I_{dc}$  is split up among the three phase legs equally. In addition, each phase terminal current  $i_a$ ,  $i_b$  and  $i_c$  will also split up equally due to the fact that the converter is symmetrical.

### III. COMPONENT MODELING

In case the IGBT is turned off, no current is flowing through it, which means that the IGBT will constitute a capacitance only [4]. However as there inevitably will be some inductance in the IGBT, this will have to be modeled as well by insertion of the inductor.

In case the IGBT is turned on, there will be some conductive losses, and these losses will represent the dynamic resistance of the IGBT [5]. Furthermore the inductance of the IGBT will have influence in high frequencies. Also, as can be seen the figure 4, a capacitor has been placed in parallel, which is applied in order represent the capacitance of the IGBT. When the IGBT is turned on, a small forward voltage exists across the IGBT due to the dynamic resistance of the IGBT, and when examining the voltage characteristics of the IGBT-capacitance, as seen in the figure 7 below, it is clear that

the capacitance of the IGBT is significant at low voltages.

### A. Submodule Capacitor

The submodule capacitor cannot simply be modeled as an ideal capacitor, as this component besides the capacitance also includes some inductance known as the Equivalent Series Inductance [ESL], which is mainly caused by the leads and internal connections used to connect the plates or foil to the outside environment. It is obvious that the ESL will first start to matter at high frequencies, in particular at the resonance frequency formed together with the capacitor. The resistance known as the Equivalent Series Resistance [ESR] covers the physical series resistance in the capacitor (e.g. the ohmic resistance of the leads and plates or foils). Including all parasitic components, the model of the submodule capacitor looks as seen in the figure 3 [6].

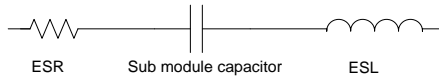


Figure 3: Equivalent circuit of the submodule capacitor [6]

### B. Submodule

In figure 4 the circuit diagram as implemented in PSCAD is shown for the situation in which the submodule is turned on. Here we have also added the protective thyristor as a capacitor for a more uniform picture of the submodule.

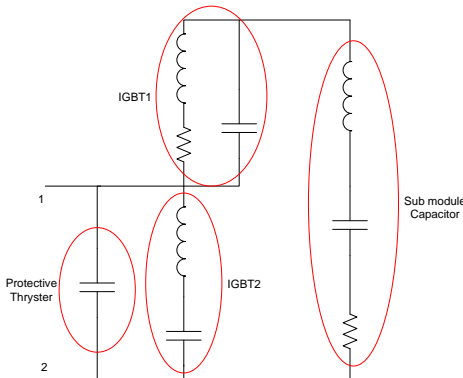


Figure 4: Submodule being turned on implemented in PSCAD

In figure 5 the circuit diagram is shown for the situation in which the submodule turned off

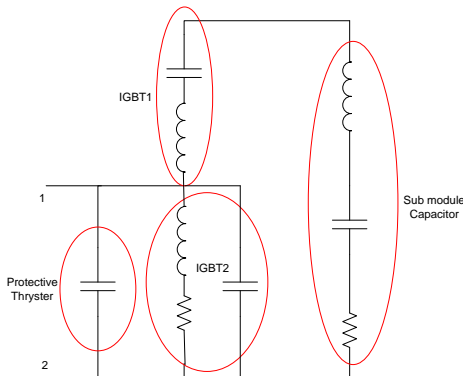


Figure 5: Submodule being turned off implemented in PSCAD

### C. Stray Capacitance

In the datasheet of the IGBT a number of capacitances are listed. Figure 6 shows 3 different capacitances in an IGBT, with a capacitance between each terminal of the IGBT. Since it doesn't contribute to our work to represent the individually, these 3 capacitances have been combined into a single capacitance.

However when doing so, it is necessary to point out that the gate-collector capacitance and the gate-emitter capacitance are placed in series. Also, the specific datasheet for the IGBT-module applied in this case shows that the gate-emitter capacitance is significantly larger, roughly 30 times larger, than the gate-collector capacitance, depending of course upon the magnitude of the collector-emitter voltage. It is obvious, based on simple circuit analysis that the combined capacitance of the 2 capacitances will be dominated by the gate-collector capacitance. This means that the gate-emitter capacitance can be omitted in this study due to its insignificance and only the gate-collector capacitance and the collector-emitter capacitance are taken into consideration.

These capacitances are not constants, in fact as figure 7 below shows; there is a highly non-linear relationship between the capacitances and the collector-emitter voltage applied to the IGBT. Besides the capacitances of the IGBT, there will inevitably also be some capacitance across the diode, when not conducting. However, the value of the diode capacitance has not been specifically stated in the specific datasheet of the IGBT-module. Therefore it is assumed that the measurements of the capacitances were carried out, with the entire module assembled, including the capacitance of the diode.

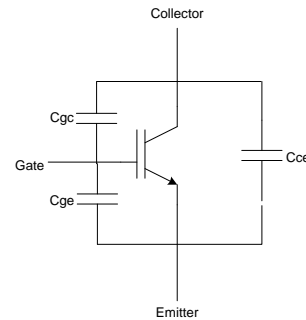


Figure 6: Capacitances of an IGBT [7]

The non-linear relation between the capacitances of the IGBT as a function of collector emitter voltage is shown in figure 7 [7].

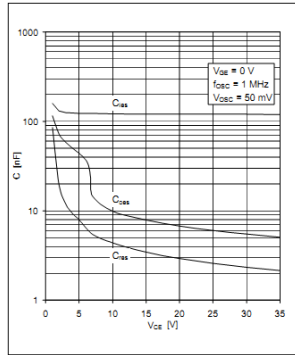


Figure 7: The non-linear capacitance-voltage characteristic of an IGBT [8]

#### D. Transformer

In the standard transformer model in PSCAD which is being applied in this case, it is not possible directly to include the various capacitances of the transformer.

The capacitances contribute to the high-frequency behavior of power transformers as characterized by several resonance points due to inductive and capacitive effects from the windings, tank, and core. This behavior should be included in any overvoltage study where the high frequency characteristics of the transformer is of significance, e.g., transferred over voltages and resonant over voltages [9]. The capacitive nature of the transformer at high frequencies is important for both transient voltage and transient current transfer, which will be strongly dependent on parasitic capacitances and less on the inductances.

A simple but effective way of modeling the transformer including capacitances is to add them externally, as seen below the values shown are given for a typical 430MVA Y/ $\Delta$  transformer [10]. In a VSC-HVDC transmission system, the zero-sequence components are usually excluded from the converter by a Y/ $\Delta$ -connected three-phase transformer, with the  $\Delta$ -connection on the converter side. However the zero-

sequence components are unavoidable in an event of asymmetrical faults on the converter side of the transformer. This doesn't give a complete picture of the high frequent behavior of the transformer, but includes the most important capacitances having influence under fault conditions and is considered as a sufficient approximation in connection with focus of the present work.

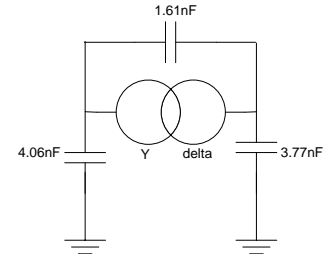


Figure 8: Implementation of transformer capacitances

#### IV. SIMULATIONS AND RESULTS

A schematic view of the back to back HVDC connection is shown in figure 9. The HVDC transmission system is as mentioned based on VSCs using our high frequent submodules, hereby enabling bi-directional power flow between the WPP and shore [11]. The shore-based grid will be represented by a Thevenin voltage source, operating at a line-to-line voltage level of 400kV. Overhead lines (OHL) are placed between the onshore converter and the voltage source. In order to have a proper representation of the shore-based grid, the grid impedance also has to be represented. In this case we have chosen to use the substation of Bjæverskov in east Denmark as point of connection. Magnitude and angle of the short-circuit impedance at Bjæverskov was found here [12].

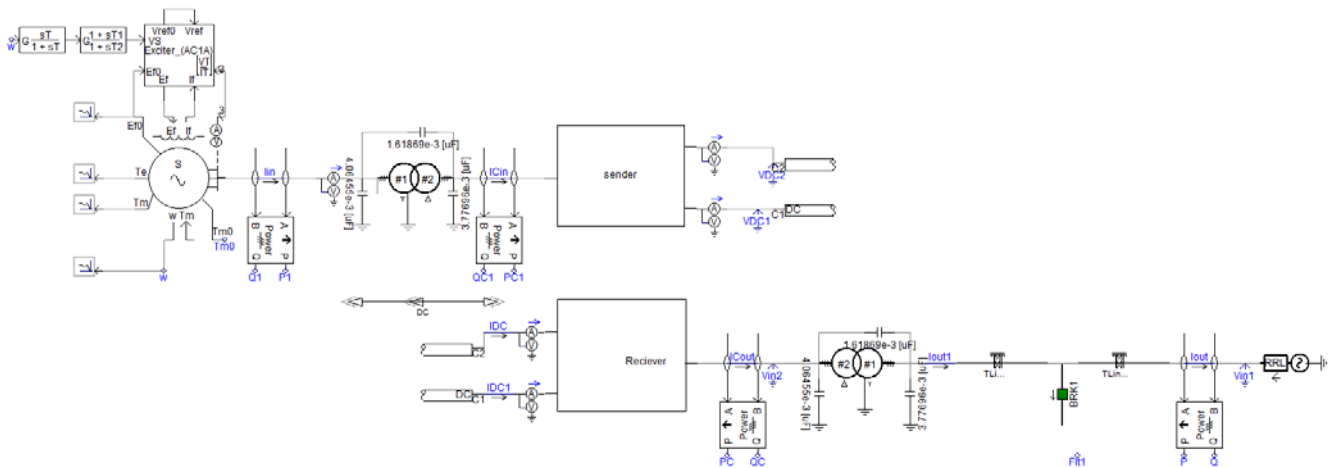


Figure 9: The figure shows the entire back to back HVDC transmission model in PSCAD. On the upper left we have the wind power plant connected to offshore transformer then to the rectifier. The rectifier is connected to the onshore inverter through 70 km of DC cable. The onshore transformer is then connected to 20 km OVH that have been split up in two not equal parts. 14 km away from the onshore transformer station we have line-ground fault.

In table 1 the main parameters describing the system under consideration are presented.

Table 1: System parameters

Line to line Voltage	400 kV
Frequency	50 Hz
Transmission rating	1000MVA
DC Cable length	70 Km
Resistance of cable	14.9 mΩ/Km
Capacitance of cable	0.2 μF/Km
Reactance of cable	0.11 Ω/Km
Nominal DC voltage	250 kV
Sub modules per valve	200
Onshore OHL length	20 Km

TOVs (Transient Overvoltage's) in electrical transmission and distribution networks result from the unavoidable effects of lightning strikes and network switching operations. A TOV can be defined as the response of an electrical network to a sudden change in network conditions, either intended or accidental, (e.g. a switching operation or a fault) or network stimuli (e.g. a lightning strike). A transient is a natural part of the process by which the power system moves from one steady state condition to another the time for it to do so is the transient time [9]. Its duration is in the range of microseconds to milliseconds. A switching overvoltage or as they sometimes are switching transients is generated due to the interaction between the inherent elements (inductance, capacitance and resistance) associated with an electric power system. When current flows through an inductance, it produces magnetic flux. Any effort to change the magnetic flux (i.e. the current) will be opposed by the inductance, which is manifested by the generation of a counter EMF in the inductance in such a direction as to keep the magnetic flux (and the current) in the inductance constant. Therefore when the current is interrupted in any way a voltage is developed by the system inductance to oppose the current change. Though faster the interruption is though higher the developed overvoltage becomes.

In this test case, we are assuming a line to ground fault at the OHL, 14 km away from the onshore converter. The fault will start at 60 ms and continue until the current switches polarity or the fault has been cleared. To investigate the importance of including the high frequent component characteristics of the components, the fault is invoked in the system with different values of these characteristics.

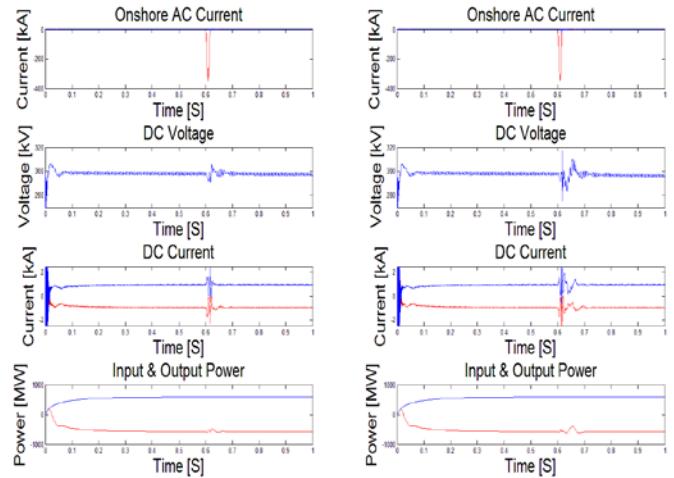


Figure 10: On the left *MMC response to dc link short circuit fault* a) AC phase voltage b) AC phase current c) DC link voltage for one pole d) DC current e) Active power transfer, on the right *MMC response to dc link short circuit fault with increased transformer series capacitance*.

In figure 10 can be seen the effect of varying the series capacitance between the low and high voltages sides. As expected, when increasing capacitance, the imposed fault will have an even larger impact on the rest of the system. Changing the capacitance also has influence on the transformer resonance frequencies and the increased the crossover during the transient thereby increases the oscillations on the low voltage side. The voltage increase on the low voltage side will have two effects. Firstly, the current flowing through the converter will be influenced by these oscillations, causing further dissemination of the fault due to the enlarged impact. Secondly, the additional oscillations on the low voltage side imply that we get these oscillations in the control system. In a sense the fault will be modestly amplified through the control system, since it to some extent will try regulating for the disturbances. Looking at figure 10 it can be noticed that the fault on the onshore high voltage side appears identical for both cases but on the low voltage side it's not only that the magnitude has increased but the duration of the fault due to the effect on the control. This will cause the voltage on the high voltage side to be unstable until the control stabilizes again.

From figure 11 can be see that by increasing the IGBT parasitic capacitance, we get a noticeable change in the DC current. Due to the decrease of the impedance (e.g. the increase of capacitor size) and by having the same voltage oscillations this will naturally give higher currents. Figure 11 shows that in the second run, the spikes reach 4 kA compared with 2.5 kA in the first run. A part of this will be damped in the DC cable but some of it will be carried to the wind park converter. This phenomenon could become worse with even longer faults, or if no filtering is done before the control system. More work will be done for more detailed investigations on these phenomena.

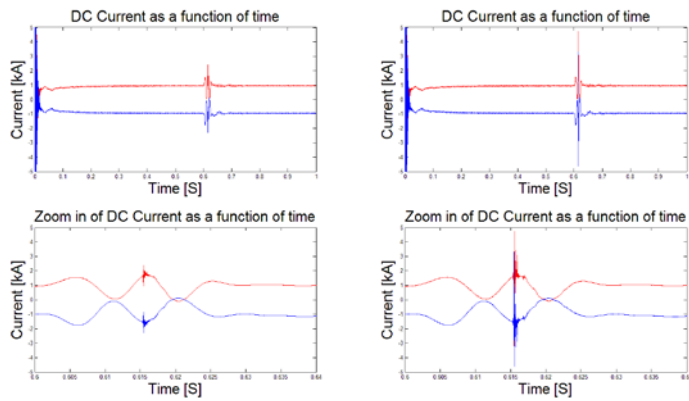


Figure 11: On the left MMC response to dc link short circuit fault a) DC current b) zoom in on the DC current. On the right MMC response to dc link short circuit fault with increased converter parasitic capacitance

## V. CONCLUSION

A new approach for modeling modular multilevel converters with a very large number of switching devices was introduced. A high frequent equivalent model for the converter that still maintains the individual identity of every submodule was developed. A simple high frequent transformer model was designed and included in the HVDC transmission system. The numerical simulations have shown that the system is operating correctly under steady-state and transient operating conditions. Regarding the investigated high frequent behavior, it is shown that the impact of transient situations strongly depends on the high frequent properties of the included components. .

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