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Modeling Techniques for MMC Employed on VSC-HVDC Schemes

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Abstract—Modular multilevel converters (MMC) are presently the converter topology of choice for voltage-source converter high-voltage direct-current (VSC-HVDC) transmission schemes due to their very high efficiency. These converters are complex, yet fast and detailed electromagnetic transients simulation modelsare necessary for the research and development of these transmission schemes. Excellent work has been done in this area, though little objective omparison of the models proposed has yet been undertaken. This paper compares for the first time, the three leading techniques for producing detailed MMC VSC-HVDC models in terms of their accuracy and simulation speed for several typical simulation cases. In addition, an improved model is proposed which further improves the computational efficiency of one method. This paper concludes by presenting evidence-based recommendations for which detailed models are most suitable for which particular studies.

Index Terms—Accelerated model, electromagnetic-transient (EMT) simulation, HVDC transmission, modular multilevel converter (MMC), voltage-source converter (VSC).

I. INTRODUCTION

The demand for voltage-source converter (VSC) highvoltage direct-current (HVDC) transmission schemes has grown significantly in recent years. This growth is primarily due to the improvements in the voltage and power ratings of insulated-gate bipolar transistors (IGBTs) and a number of new VSC-HVDC applications, such as the connection of large offshore windfarms. Since its inception in 1997 and until 2010, all VSC-HVDC schemes employed two- or three-level VSCs. In 2010, the Trans Bay Cable Project became the first VSC-HVDC scheme to use modular multilevel converter (MMC) technology.

The MMC has numerous benefits in comparison to two- or three-level VSCs; chief among these is reduced converter losses. Today, the three largest HVDC manufacturers offer a VSC-HVDC solution which is based on multilevel converter technology. Modeling MMCs in electromagnetic transient simulation (EMT) programs presents a significant challenge in comparison to modeling a two- or three-level VSC. The stack of series connected IGBT's in each arm of a two- or three-level VSC is switched at the same time. This simultaneous switching action enables the stack of IGBTs to be modeled as a single IGBT for many studies. The MMC topology, however, does not contain stacks of series-connected IGBT's which have identical firing signals and, therefore, comparable simplification in the model cannot be made. The converter employed on the Trans Bay Cable Project is an MMC with approximately 201 levels. A traditional detailed model (TDM) of this converter would require more than 2400 IGBTs with anti parallel diodes and more than 1200 capacitors to be built and electrically connected in the simulation package's graphical user interface, resulting in a large admittance matrix.

The admittance matrix must be inverted each switching cycle, for which MMCs can have hundreds of times per fundamental cycle which is extremely computationally intensive. This makes modeling MMCs for HVDC schemes using traditional modeling techniques impracticable. In the DEM was shown to significantly reduce the simulation time in comparison with a TDM without compromising accuracy. A drawback of the DEM is that the individual converter components are invisible to the user. This makes the model unsuitable for studies which require access to the individual converter components and it makes it difficult to reconfigure the converter sub module for different topologies. This model was found to offer greater computational efficiency than a TDM without compromising accuracy and it gives the user access to the individual converter components.however, a full and objective comparison could not be completed because the models were built by different researchers on different computers. The objective of this paper is to perform a much needed independent comparison of the TDM, DEM, and AM models which will enable the reader to make a more informed decision when selecting which type of detailed MMC model to use and to have a greater degree of confidence in the MMC models' performance. In this paper, the TDM, DEM, and AM models are built in the same software on the same computer and compared in terms of their accuracy and simulation speed. This enables a fair comparison between the DEM and the AM and it provides the first independent verification for the AM against the TDM, and the DEM against the TDM in PSCAD. Having completed this verification, this paper also highlights potential limitations of the AM and proposes an enhanced accelerated model (EAM) with improved simulation speed.

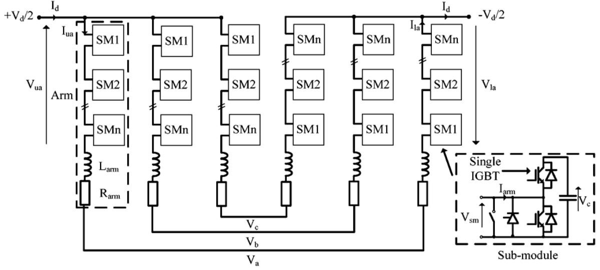


Fig 1: Three-phase MMC.

The basic structure of an MMC is shown in Fig. 1. Each leg of the converter consists of two converter arms which contain a number of submodules, SMs, and a reactor , connected in series. The SM contains a two-level half-bridge converter with two IGBT's and a parallel capacitor. The SM is also equipped with a bypass switch to remove the SM from the circuit in the event that an IGBT fails and a thyristor to protect the lower diode from over current in the case of a dc-side fault. The bypass switch and thyristor are, however, typically omitted from steady-state and transient studies. The SM terminal voltage is effectively equal to the SM capacitor voltage when the upper IGBT is switched-on and the lower IGBT is switched-off; the capacitor will charge or discharge depending upon the arm current direction. With the upper IGBT switched off, and the lower IGBT switched on, the SM capacitor is bypassed and, hence, is effectively 0 V.Each arm in the converter, therefore, acts like a controllable voltage source with the smallest voltage change being equal to the SM capacitor voltage. With reference to Fig. 1, the following equation for the phase a converter voltage can be derived.

II. DETAILED MMC MODELING TECHNIQUES

This section describes three detailed modelling techniques which represent the converter's IGBTs and diodes using a simple two-state resistance.

A. Traditional Detailed Model

In a traditional detailed MMC model, each SM's IGBTs, diodes, and capacitors are built in the simulation package graphical user interface, and electrical connections are made between the SMs in each arm as shown in Fig. 1. This is the standard way of building a detailed MMC model and, hence, is why this type of model is referred to as the traditional detailed model (TDM). This method of modeling is intuitive and gives the user access to the individual components in each SM; however, for MMCs with a large number of SMs, this method is very computationally inefficient.

B. Detailed Equivalent Model

The DEM uses the method of nested fast and simultaneous solution (NFSS) [5]. The NFSS approach partitions the network into small sub networks, and solves the admittance matrix for each network separately [2]. Although this increases the number of steps to the solution, the size of admittance matrices is smaller, which can lead to reduced simulation time. A summary of the DEM is presented in the Appendix; however, further information can be found in [2]. The DEM employed in this comparison was obtained directly from PSCAD.

C. Accelerated Model

The accelerated model (AM) was proposed by Xu *et al.* in [4]. In many respects, the AM is a hybrid between the TDM and the DEM. The user is able to access the SM components, as they can with the TDM, but the converter arm is modeled as a controllable voltage source, which is similar to the DEM. An overview of the AM is presented here; the reader is referred to [4] for further information. In the AM, the series-connected SMs are removed from each converter I_{arm}, separated and driven by a current source with a value equal to the arm current . A controllable voltage source is installed in place of the SMs as shown in Fig. 2, where the value of the controllable voltage source is given by

$$V_{arm}=\sum_{i=1}^{n} V_{smi}$$

The AM reduces the size of the main network admittance matrix by solving the admittance matrix for each SM separately. The AM has two key advantages in comparison to the DEM. The first is that the AM allows the user access to SM components. The second is that because the AM is implemented using standard PSCAD components, the internal structure of the SM can be easily modified; for example, changing from a half-bridge SM to a full-bridge SM.

III. SIMULATION MODELS

A detailed MMC model for a typical VSC-HVDC scheme, employing the traditional detailed model (TDM) converter arm representation, has been developed. This model is used as the TDM simulation model base case. The simulation models for the DEM and for the accelerated model (AM) are identical to the TDM, except that the TDM converter arms are replaced with the converter arms required for the DEM and AM, respectively. This approach ensures that fair comparisons between the different modeling techniques can be made.

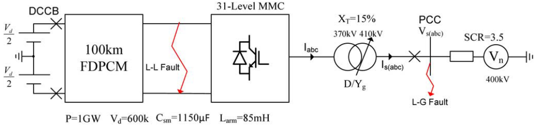


Fig. 2. Basic simulation model structure.

A. Model Structure

This model is similar in scope to [2] and [4] but representsa subsection of the network rather than just the converter used in [4]. This gives a more realistic timing comparison since one would not normally just be simulating the converter in typical power system studies. The basic structure of the simulation model and the key parameters are shown in Fig. 3. Developing a TDM for an MMC with hundreds of SMs, such as a commercial installation, would result in lengthy simulation times. A 31-level MMC was selected for this model since it produces acceptable harmonic performance (at the PCC) [6] with a nearest level controller (NLC) without unnecessarily increasing the simulation time and yet still providing a sufficient converter complexity to provide a fair test. The key factor which determines the required number of SMs in commercial HVDC installations is the dc voltage and the maximum permissible voltage stress per IGBT, rather than the harmonic content of the output waveform. Therefore, more levels would be used in commercial installations. The selection of the SM capacitance value is a tradeoff between the capacitance ripple voltage and the size of the capacitor. The SM capacitance was calculated to give a ripple voltage of 10%.

The arm reactors have two main functions. The first function is to suppress the circulating currents between the legs of the converter, which exist because the dc voltages generated by each converter leg are not exactly equal. The second function of the arm reactor is to limit the fault current rate of rise to within acceptable levels. According to [7], the Siemens HVDC Plus MMC arm reactors limit the fault current to tens of amperes per microsecond even for the most critical fault conditions. The arm reactor for this model was dimensioned to ensure that the fault current rate of rise does not exceed 20 A s for a short circuit between the dc terminals of the converter, and to limit the circulating current to approximately 0.15 p.u. The dc system is modeled as a dc voltage source connected in series with a frequency-dependent phase cable model (FDPCM) which represents two 300-kV 100-km XLPE cables. The ac network is modeled as a voltage source connected in series with a resistor and an inductor, to give a relatively strong short-circuit ratio (SCR) of 3.5. The converter transformer employs a delta/star winding with a tap changer.

B. MMC VSC-HVDC Control Systems

A simplified diagram for the three-phase 31-level MMC control system is shown in Fig. 4.

1) *Current Controller:* The impedance between the internal voltage control variables and the ac system voltage*1) Current Controller:* The impedance between the internal voltage control variables and the ac 2. System Voltage

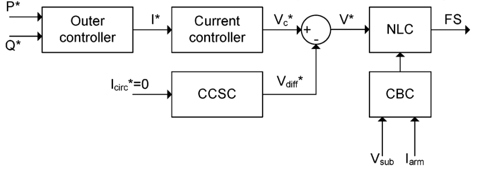


Fig. 3. Simplified MMC control system.

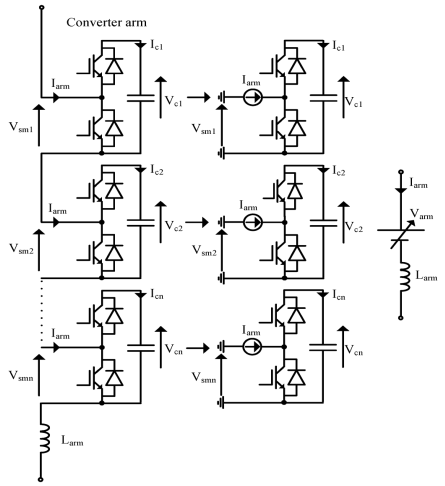


Fig. 4. Implementation steps for the accelerated model.

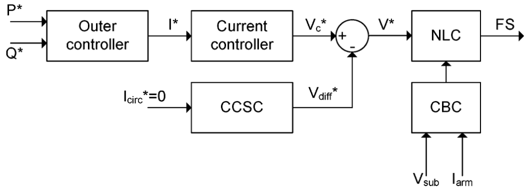


Fig. 4. Simplified MMC control system.

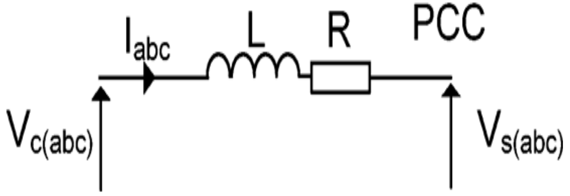


Fig. 5. MMC phase a connection to an ac system.

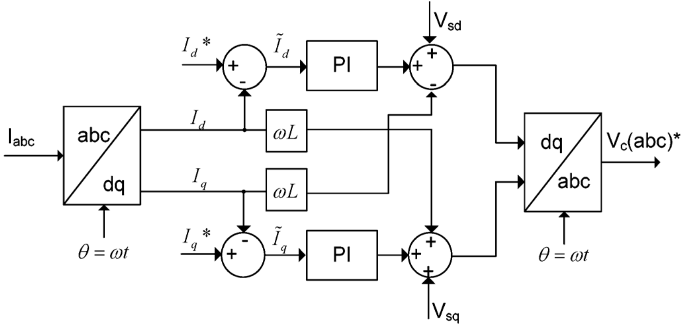


Fig. 6. Implementation of the DQ currentcontroller

IV. RESULTS

In this section, the three models are compared in terms of their accuracy and Dc Line Fault.

A. Accuracy

The models' accuracy is assessed for steady-state and transient events through conducting a range of typical studies. Their accuracy is evaluated graphically and numerically by calculating the mean absolute error (MAE) of the waveforms produced by the DEM and AM with respect to the TDM. The MAE is normalized to the mean value of the TDM waveform. *1) Steady-State:* The steady-state waveforms produced by the models for the converter operating as an inverter at 1000 MW are shown in Fig. 8. The waveforms are virtually identical and this is confirmed by the very small (1%) normalized MAE values given in Table I. The models were re-simulated for the converter operating as an inverter at 500 MW and 100 MW, and their normalized MAE values are given in Tables II and III, respectively. The results generally show that the accuracy of the models decreases as the operating point decreases. This is especially the case for the phase current and arm current. At lower operating points, the magnitude of the arm and phase currents are smaller and the switching noise is more noticeable. It appears to be the case that the effect of this switching noise on the dominant signal and the model's inability to replicate it is impacting the normalized MAE values. The average THD of the phase A output voltages for the three models, when operating at 1000 MW in steady state, was found to be between 1.35% and 1.36%.

2) DC-Side Line-to-Line Fault:

A dc line-to-line fault is applied at 4.5 s to the MMC terminals as shown in Fig. 3. The dc circuit breakers (DCCBs) are opened 2 ms after the fault is applied so that the dc voltage sources do not continue to contribute to the fault current. The MMC converter is blocked at 4.502 s, and the ac-side circuit breakers (CBs) are opened at 4.56 s. In this paper, the converter is considered to be blocked when both IGBTs are switched off. The waveforms produced by the models are shown in Fig. 9 and their normalized MAE values are given in Table IV. The waveforms produced by the DEM and the AM are virtually identical (1%) and very similar (2.5%) to the TDM, respectively. An error in the AM model's to bottom: (a) dc current, (b) phase A output voltage, (c) phase A upper arm current, and (d) phase A upper arm mean capacitor voltage

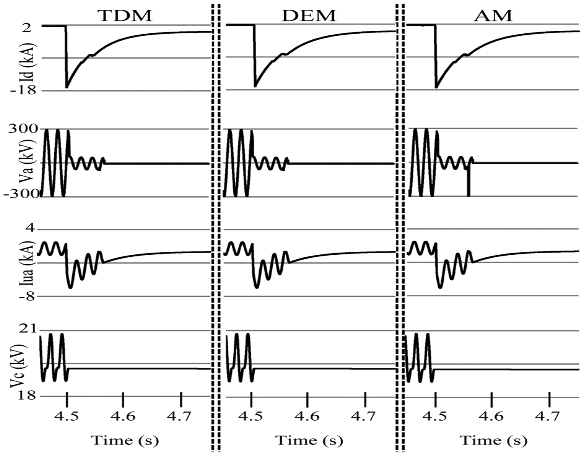


Fig. 7. DC line current for a dc line-to-line fault applied at 4.5 s. From top

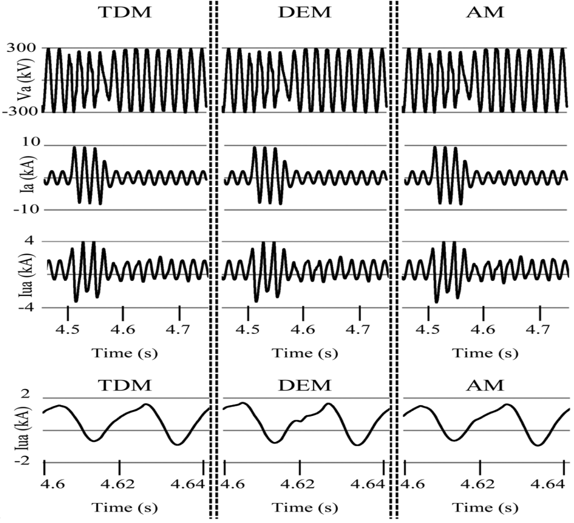


Fig. 8. Line-to-ground fault for the phase applied at 4.5 s. (a) Phase A output voltage. (b) Phase A output current. (c) Phase A upper arm current. (d) Phase A arm current, zoomed.

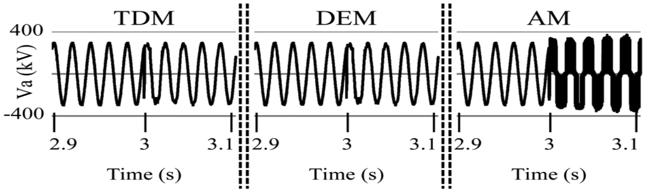


Fig. 9. Phase A output voltage.

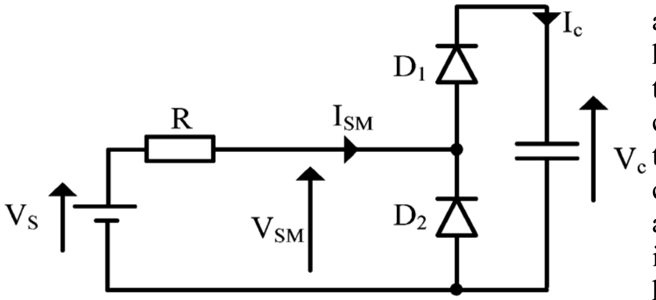
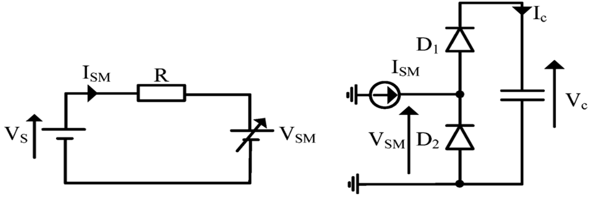


Fig. 10. Example SM test circuit



Primary Secondary

Fig. 11. Implementation of the SM test circuit based on AM principles.

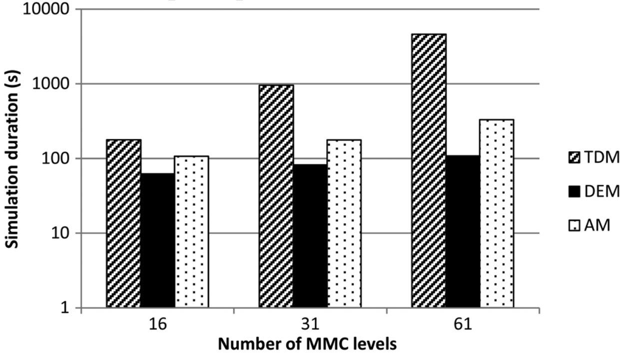


Fig. 12. Simulation times of the three models for different MMC levels.

V. CONCLUSION

This paper has presented the first independent comparison of two previously developed MMC modelling techniques (AM and DEM). It is has also presented the first independent verification of the AM, and the first independent verification of the DEM in PSCAD. An MMC-HVDC test system was developed and the AM model and DEM modelling techniques were compared against the TDM modeling technique in terms of accuracy and simulation speed. The accuracy of the AM and DEM models was evaluated graphically and numerically for steady-state and transient studies. The unique findings contained within this paper have shown that the AM and DEM modeling techniques offer a good level of accuracy but that the DEM is generally more accurate than the AM. The AM and DEM models have been shown to simulate significantly faster than the TDM, and the DEM is more computationally efficient than the AM. However, the AM model does provide access to SM components (which is not possible with the DEM) and so may be considered when this is an important factor. The AM model was found to have limited performance for certain conditions when the converter is blocked. This finding highlights the importance of this comparative study since it has highlighted previously unreported shortcomings of discussed modeling techniques. It was also shown that by modifying the original AM by producing a subnetwork for a number of SMs rather than for a single SM, the simulation run time could be improved.

These results have been used to propose a set of modeling recommendations (Section VI) which summarize the findings of this study and offer technical guidance on state of the art of detailed MMC modelling.

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