Comparison of Detailed 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 models are necessary for the research and development of these transmission schemes. Excellent work has been done in this area, though little objective comparison 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) high-voltage 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 [1]. 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.

Modelling 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 antiparallel 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.

To address this problem, an efficient model was proposed by Udana and Gole in [2], which is referred to as the detailed equivalent model (DEM) in this paper. In [2], 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 submodule for different topologies. Only one other publication has compared the DEM with the TDM, which was performed in EMTP-RV [3].

A new model, referred to as the accelerated model (AM) was proposed by Xu et al. in [4]. 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. In [4], an attempt was made to compare the AM simulation time with the DEM simulation time data from [2]; 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.

II. MMC VSC-HVDC

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 \( I_{\text{arm}} \), 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 overcurrent 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 \( V_{\text{sm}} \) is effectively equal to the SM capacitor voltage \( V_c \) 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, \( V_{\text{sm}} \) 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:

\[
V_a = \frac{V_d}{2} - V_{\text{ua}} - L_{\text{arm}} \frac{dI_{\text{ua}}}{dt} - R_{\text{arm}} I_{\text{ua}} \tag{1}
\]

\[
V_a = V_{\text{ua}} - \frac{V_d}{2} + I_{\text{arm}} \frac{dI_{\text{la}}}{dt} + R_{\text{arm}} I_{\text{la}}. \tag{2}
\]

The converter arm currents consist of three main components as given by (3) and (4). The circulating current \( I_{\text{circ}} \) is due to the unequal dc voltages generated by the three converter legs. Substituting (3) and (4) into (1) and (2), then summing the resulting equations gives

\[
I_{\text{ua}} = \frac{I_d}{3} + I_a + I_{\text{circ}}, \tag{3}
\]

\[
I_{\text{la}} = \frac{I_d}{3} - \frac{I_a}{2} + I_{\text{circ}}. \tag{4}
\]

\[
V_a = \frac{V_{\text{la}} - V_{\text{ua}}}{2} - R_{\text{arm}} \frac{dI_{\text{ua}}}{2} - \frac{R_{\text{arm}}}{2} I_a, \tag{5}
\]

Equation (5) shows that the converter phase voltages are effectively controlled by varying the upper and lower arm voltages. Each converter arm contains a number of SMs: \( n \). The SM capacitor voltage can be described by (6), assuming the SM capacitance is sufficiently large enough to neglect ripple voltage and that the capacitor voltages are well balanced

\[
V_c = \frac{V_d}{n}. \tag{6}
\]

The voltage produced by a converter arm is equal to the number of SMs in the arm which are turned on, multiplied by the submodule capacitor voltage as given by (7) and (8). Through appropriate control of the SMs, the output voltage magnitude and phase can be controlled independently. The number of voltage levels that an MMC can produce at its output is equal to the number of SMs in a single arm plus one

\[
V_{\text{ua}} = n_{\text{ua}} V_c \tag{7}
\]

\[
V_{\text{la}} = n_{\text{la}} V_c. \tag{8}
\]

III. 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 subnetworks, 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 arm, separated and driven by a current source with a value equal to the arm current $I_{arm}$. 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

$$V_{arm} = \sum_{i=1}^{n} V_{arm,i}.$$  \hfill (9)

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.

### IV. 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.

#### 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 $V_{(a,b,c)}$ and the ac system voltage...
V_{s(abc)} is shown in Fig. 5. Equation (10) describes the relationship between the internal voltage control variable and the ac system voltage for the three phases

\[
V_{e(abc)} = L \frac{dI_{abc}}{dt} + RI_{abc}
\]  

where

\[
L = \frac{I_{arm}}{2} + L_T \quad R = \frac{R_{arm}}{2} + R_T.
\]  

Equation (10) in the dq synchronous reference frame gives (12), where \( p = \frac{d}{dt} \)

\[
\begin{bmatrix} V_d \\ V_q \end{bmatrix} = R \begin{bmatrix} I_d \\ I_q \end{bmatrix} + L_p \begin{bmatrix} I_d \\ I_q \end{bmatrix} + \omega L \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix}.
\]  

The current controller employed in this model is a fast feedback dq decoupled controller, which produces a voltage reference for the MMC based upon the current setpoint from the outer controllers. The implementation of the controller is shown in Fig. 6.

2) Outer Controllers: In the magnitude invariant dq synchronous reference frame with the q-axis aligned with \( V_a \), the real and reactive power flow at the point of common coupling can be described by (13) and (14), respectively. Feedforward controllers are used to set the \( I_d \) and \( I_q \) values to control the real and reactive power, respectively

\[
P = \frac{3}{2} V_s I_d
\]  

\[
Q = -\frac{3}{2} V_s I_q.
\]  

3) Circulating Current Suppressing Controller: The circulating current is a negative-sequence (a-c-b) current at double the fundamental frequency [8]. This current is found to increase the rms value of the arm current leading to increased converter losses [8]. The circulating current suppressing controller (CCSC) is able to suppress the circulating current by controlling the voltage across the arm impedance. The development of this controller is based on work carried out in [8]. Using phase a, as an example, the dc voltage can be described by (15). Substituting (3) and (4) into (15) and then rearranging gives

\[
V_d = V_{ua} + I_{afc}(R + Lp) + I_{afc}(R + Lp) + V_{fa}
\]  

\[
V_{eff-a} = I_{diff-a}(R_{arm} + I_{arm}p)
\]  

where

\[
V_{eff-a} = \frac{V_d}{2} - \frac{V_{ua} + V_{fa}}{2}
\]  

\[
I_{diff-a} = \frac{I_d}{3} + I_{circ-a}.
\]  

In matrix form, (16) for the three phases can be written as (19). Applying the abc/dq transform to (19) gives (20). The zero-sequence quantities do not affect the \( d \)-axis and \( q \)-axis values and, hence, the use of \( I_{circ} \) in

\[
\begin{bmatrix} V_{diff-a} \\ V_{diff-c} \\ V_{diff-b} \end{bmatrix} = R \begin{bmatrix} I_{diff-a} \\ I_{diff-c} \\ I_{diff-b} \end{bmatrix} + L_p \begin{bmatrix} I_{diff-a} \\ I_{diff-c} \\ I_{diff-b} \end{bmatrix}
\]  

\[
\begin{bmatrix} V_{diff-a} \\ V_{diff-c} \\ V_{diff-q} \end{bmatrix} = -H_{arm} \begin{bmatrix} I_{circ-a} \\ I_{circ-c} \\ I_{circ-q} \end{bmatrix} + I_{arm} p \begin{bmatrix} I_{circ-a} \\ I_{circ-c} \\ I_{circ-q} \end{bmatrix} + \begin{bmatrix} 0 \\ -\omega L_{arm} \\ 0 \end{bmatrix} \begin{bmatrix} I_{circ-a} \\ I_{circ-c} \\ I_{circ-q} \end{bmatrix}.
\]  

A dq decoupled circulating current controller is employed with the \( I_{circ-dq} \) reference values set to zero as shown in Fig. 7.

4) Capacitor Balancing Controller: The capacitor balancing controller (CBC) ensures that the energy variation in each converter arm is shared equally between the submodules within that arm. The CBC method proposed in [9] has formed the basis of many of capacitor balancing controllers for VSC–HVDC
5) Nearest Level Controller: A number of modulation methods have been proposed for MMCs [9], [11], [12]. The nearest level controller (NLC) method produces waveforms with an acceptable amount of harmonic content when a suitable number of MMC levels are employed. It is the least computationally complex method of the aforementioned techniques and, thus, is used for the model in this paper.

V. RESULTS

In this section, the three models are compared in terms of their accuracy and simulation speed.

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
The circulating current is a key component of the arm current as described in (3). Comparing the accuracy of the arm current therefore effectively compares the models’ ability to simulate the circulating currents. The CCSC suppresses the circulating currents to very low values in steady-state operation, which is shown in Fig. 10(c) by the low levels of distortion in the arm current waveforms before the ac fault and several cycles after it are cleared (>4.7 s).

4) AM Simulation Limitation: The AM implemented in this paper was found to be unable to fully manage the simulation case when the converter is blocked as shown in Fig. 9. To further demonstrate this issue, the converter is blocked at 3 s when operating as an inverter at 1000 MW, and the Phase A output voltage for the three models is shown in Fig. 11. Clearly, the converter voltage for phase A for the AM is different. This is an inherent issue with the implementation of the AM and can be illustrated further at the SM level. A circuit diagram for a blocked SM connected to a voltage through a resistor is

**TABLE IV**

<table>
<thead>
<tr>
<th>Signal</th>
<th>DEM Error (%)</th>
<th>AM Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Id</td>
<td>0.41</td>
<td>2.29</td>
</tr>
<tr>
<td>Va</td>
<td>0.22</td>
<td>1.12</td>
</tr>
<tr>
<td>lua</td>
<td>0.51</td>
<td>1.83</td>
</tr>
<tr>
<td>Vc</td>
<td>0.07</td>
<td>0.07</td>
</tr>
</tbody>
</table>

**TABLE V**

<table>
<thead>
<tr>
<th>Signal</th>
<th>DEM Error (%)</th>
<th>AM Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Va</td>
<td>0.96</td>
<td>1.76</td>
</tr>
<tr>
<td>Ia</td>
<td>0.51</td>
<td>1.37</td>
</tr>
<tr>
<td>Iau</td>
<td>3.01</td>
<td>4.34</td>
</tr>
<tr>
<td>Iau zoom</td>
<td>11.72</td>
<td>5.14</td>
</tr>
</tbody>
</table>

phase voltage is shown in Fig. 9 at the instances when the arm current goes through zero. This issue occurs because the AM is not able to correctly determine the ON/OFF status of the SM diodes in a single time step when the converter is blocked. This issue is discussed further in Section V-A-4.

3) AC Line-to-Ground Fault: A line-to-ground fault is applied to phase A at the point of common coupling (PCC) for 60 ms at 4.5 s as shown in Fig. 3. The waveforms produced by the models are shown in Fig. 10, and their normalized MAE values are given in Table V.

With the exception of the Phase A upper arm current, the waveforms produced by the DEM and the AM are virtually identical (<1%) and very similar (<2.5%) to the TDM, respectively. From all of the simulations conducted, the greatest difference between the three models was found to be in the Phase A upper arm current a few cycles after the fault is cleared when the MMC becomes overmodulated as highlighted in Fig. 10(d). This difference lasts for a few cycles, and there is no significant difference in the peak current values for the three models.
shown in Fig. 12. A model of this circuit based on the principles of the AM is shown in Fig. 13.

The SM current $I_{SM}$ is measured in the primary circuit and is used as the current source reference in the secondary circuit, and the SM voltage is measured in the secondary circuit and is used as the voltage-source reference in the primary circuit. Each network is therefore solved at the present time step based on information from the other network at the previous time step.

Upon model initialization, $V_{SM} = 0$ V and, therefore, the SM current $I_{SM}$ flows in the positive direction causing the upper diode $D_1$ to conduct and the SM capacitor to charge. Once the SM capacitor is fully charged, if the voltage-source value is reduced, the upper SM diode should become reversed biased. Assuming that the SM diodes are ideal, the SM capacitor voltage should remain constant and $0$. However, this is not the case with the model implemented based on the AM principles. The arm current in the primary circuit becomes negative because the value of $I_{SM}$ is equal to $I_{SM}$ which is higher than $I_{SM}$. At the next time step, the negative arm current value causes the lower diode in the secondary circuit to conduct and, hence, $V_{SM} = 0$. At the next time step, the arm current becomes equal to $V_{c}/I_{c}$, causing the SM capacitor to charge. This behavior continues for the remaining simulation time. This limitation is understood to have been addressed by Xu et al. and is therefore not discussed further in this paper.

### Table VI

<table>
<thead>
<tr>
<th>MMC Levels</th>
<th>Indices</th>
<th>TDM</th>
<th>DEM</th>
<th>AM</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>Time (s)</td>
<td>178</td>
<td>62</td>
<td>107</td>
</tr>
<tr>
<td>31</td>
<td>Time (s)</td>
<td>949</td>
<td>82</td>
<td>176</td>
</tr>
<tr>
<td>61</td>
<td>Time (s)</td>
<td>4570</td>
<td>107</td>
<td>329</td>
</tr>
</tbody>
</table>

The data show that the DEM is the fastest, and that TDM is the slowest. It also shows that the simulation time for the TDM increases at a much faster rate than the DEM and AM models as the number of converter levels increases.

It is worth noting that the results in [2] and [4] do appear, in general, to show that their respective models simulate faster in comparison to the TDM than the results presented in Table VI. The models simulated in this report are, however, different from the models employed in [2] and [4] in terms of complexity which may explain the difference.

#### 1) Enhanced AM Model

The AM has the advantage that it is much faster than the TDM without noticeably sacrificing accuracy for the majority of case studies. It does, however, need to be used with care when the converter is blocked. In comparison with the DEM, the AM has the advantage of allowing access to the SM components, but it is slower. This paper proposes an enhancement to the AM to improve its speed.

The procedure outlined in [4], to produce the AM divides the series-connected SMs in each arm into individual circuits, driven by a current source whose value is equal to the arm current, as explained in Section III-C. This approach effectively creates a subsystem for each SM and solves the admittance matrix for each SM separately. Although this increases the

### B. Simulation Speed

A 5-s simulation was performed for a 16-, 31-, and 61-level MMC using the three modeling techniques with a 20-μs time step. The simulations were conducted on a Microsoft windows 7 operating system with a 2.5-GHz Intel core i7-2860 processor and 8 GB of RAM, running on PSCAD X4. The simulation times are given in Table VI and compared in Fig. 14.
number of steps to the solution, the size of admittance matrices is smaller, which can lead to reduced simulation time [2], [4], [5] as shown in Table VI.

The simulation speed is affected by the number of steps to the solution and the size of the admittance matrices. Hence, it can be more efficient to group a number of SMs together in order to reduce the number of steps to the solution at the expense of larger admittance matrices.

A 5-s simulation was performed for a 31-level MMC with groups of 1 (AM), 5 (AM5), 10, and 30 SMs. The results given in Table VII show that it is more efficient to create a subnetwork for 5, 10, or 30 SMs rather than produce a subnetwork for each SM. This is an important result since splitting a simulation model into a smaller number of subnetworks tends to be less time consuming for the user, can improve simulation speed, and reduce the risk of application instability.

The ac fault test scenario (Section V-A-3) was performed using an AM30 model to assess any change in the model’s accuracy. The arm current waveforms for a TDM, AM, and AM30 are compared in Fig. 15 and the normalized MAE values for the AM and AM30 model with respect to the TDM are given in Table VIII. The results show that there is very little change.

### VI. ANALYSIS AND RECOMMENDATIONS

The three detailed EMT models compared in this paper represent the converter’s IGBTs and diodes using a simple two-state resistance and are therefore not suitable for studies which require a detailed representation of the power-electronics devices, such as the assessment of switching losses. The type of model compared in this paper is typically employed for control and protection studies where the converter dynamics are important.

Although the three models compared in this paper represent the power-electronics devices in the same way their implementation is different, this has an effect on the accuracy of their results. A key difference between the TDM and DEM used in this paper is that the DEM does not use interpolation and the key difference between the TDM and AM is that the solution of the AMs is dependent upon information from different subnetworks at the previous timestep. These are the two most significant reasons why there is a small difference between the results produced by each model, particularly under transient conditions. The results in Table VIII have shown that even when two models are based on the same modeling technique, but implemented slightly differently, the simulation results are not identical. Using the TDM as the benchmark, the DEM was generally found to be more accurate than the AM, and the AM was also found to produce numerical errors when the converter is blocked and the arm current changes direction.

The different implementation methods for the three models have a significant impact on their simulation speed. The results in this paper have shown that the DEM is the fastest and the TDM is the slowest. The simulation times for the TDM increase significantly more than the DEM and the AM as the number of converter levels increase and, hence, the DEM and AM modeling techniques have great value when modeling MMCs with a relatively large number of levels. The results in this paper have shown that a model of a 61-level MMC based on DEM and AM techniques is 43 and 14 times faster than the TDM, respectively.

In the DEM, the SM components are not visible to the user and, therefore, this model is not suitable for studies which require direct access to the SM components. The TDM and AM do allow the user access to the SM components and can therefore be easily modified for the required study.

It is for these reasons that the DEM is considered to be the most suitable model for all studies which do not require access to the SM components. The AM should be considered for studies which require access to the SM components and where simulation speed is an important factor; however, great care should be taken if the study requires the converter to be blocked. The user is also advised to create a subnetwork for a number of SMs rather than for each SM since this may reduce implementation time, simulation time, and the possibility of application instability. The TDM is recommended for studies which require access to the SM components and for the converter to be blocked. The TDM is also recommended when simulation speed is not an important factor.

### VII. 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 modelling 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 modelling recommendations (Section VI) which summarize the findings of this study and offer technical guidance on state of the art of detailed MMC modelling.

APPENDIX

MMC MODEL DETAILS

A. Detailed Equivalent Model

A summary of the DEM is presented here; however, further information can be found in [2].

1) Nested Fast and Simultaneous Solution: The NFSS approach is best explained with the aid of an example [2]. The equivalent admittance matrix for a network which is split into two subsystems is given by

$$
\begin{bmatrix}
Y_{11} & Y_{12} \\
Y_{21} & Y_{22}
\end{bmatrix}
\begin{bmatrix}
V_1 \\
V_2
\end{bmatrix}
=
\begin{bmatrix}
J_1 \\
J_2
\end{bmatrix}
$$

(21)

where

- $Y_{11}, Y_{22}$ are the admittance matrices for subsystem 1 and subsystem 2, respectively;
- $Y_{12}, Y_{21}$ are the admittance matrices for the interconnections;
- $V_1, V_2$ are the unknown node voltage vectors;
- $J_1, J_2$ are the source current vectors.

The number of nodes in subsystem 1 and subsystem 2 are $N_1$ and $N_2$, respectively. The direct solution of (21) for the unknown vector voltages requires an admittance matrix of size $(N_1 + N_2) \times (N_1 + N_2)$ to be inverted.

Rearranging the second row of (21) for $V_2$ gives (22). Substituting (22) into the first row of (21) produces (23) which can be rearranged for $V_1$, as given by

$$
V_2 = -Y_{22}^{-1}Y_{21}V_1 + Y_{22}^{-1}J_2
$$

(22)

$$
J_1 = Y_{11}V_1 + Y_{12} [Y_{22}^{-1}J_2 - Y_{22}^{-1}Y_{21}V_1]
$$

(23)

$$
V_1 = (Y_{11} - Y_{12}Y_{22}^{-1}Y_{21})^{-1} (J_1 - Y_{12}Y_{22}^{-1}J_2).
$$

(24)

Once all unknown voltages are calculated, all currents can then be calculated. This approach requires the inversion of two matrices $Y_{22}$ of size $(N_2 \times N_2)$ and $(Y_{11} - Y_{12}Y_{22}^{-1}Y_{21})$ of size $(N_1 \times N_1)$, instead of a single matrix of size $(N_1 + N_2) \times (N_1 + N_2)$. This example partitioned the original network into two subsystems; however, the network can be split into many subsystems. In the DEM, each converter arm is modelled as its own subsystem.

The size of the admittance matrices for each converter arm is related to the number of SMs; hence, for MMCs with a high number of levels, the size of the admittance matrices to be inverted are still relatively large. To further improve the simulation speed, the DEM reduces each converter arm to a Norton equivalent circuit.

2) Norton Equivalent Circuit for the Converter Arm: This modelling method is based on converting a multinode network into an exact, but computationally simpler, equivalent electrical network using Thevenin’s theorem. The IGBTs and antiparallel diodes employed in each SM form a bidirectional switch and can therefore be represented as a resistor, with two values $R_{on}$ and $R_{off}$. The resistor value is dependent upon the firing signal to the IGBT and the arm current direction $I_{arm}$. The converter is considered to be blocked when both IGBT’s are switched off and, hence, the values of $R_1$ and $R_2$ are determined by the arm current direction. The SM capacitor can be represented as an equivalent voltage source $V_{eq}$, connected in series with a resistor $R_C$, as shown in Fig. 16.

The $V_{eq}$ and $I_c$ values are determined from the following analysis:

$$
I_c(t) = C \frac{dV_c(t)}{dt}. 
$$

(25)

Solving (25) for $V_c(t)$ using the trapezoidal integration method gives

$$
V_c(t) = R_cI_c(t) + V_{eq}(t - \Delta t)
$$

(26)

where

$$
R_c = \frac{\Delta t}{2C}
$$

(27)

$$
V_{eq}(t - \Delta t) = I_c(t - \Delta t) \frac{\Delta t}{2C} + V_c(t - \Delta t).
$$

(28)

The voltage at the terminals of the SM is given by (29)

$$
V_{sm}(t) = I_{arm}(t)R_{smeq} + V_{smeq}(t - \Delta t)
$$

(29)

where

$$
R_{smeq} = R_C \left(1 - \frac{R_2}{R_1 + R_2 + R_C}\right) 
$$

(30)
The development of the DEM has a clear advantage over the TDM in terms of simulation speed; however, there are some limitations. The user is not able to access the SM components, which means that the model is not suitable for studies which require internal converter access. Also reconfiguring the component for other SM topologies is not straightforward since it needs to be recoded for that specific topology, which can be complex and time consuming. Half-bridge and full-bridge MMC equivalent arm components are currently available to PSCAD users.

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**REFERENCES**


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