Dynamic Average Converter Model for MVDC Link Harmonic Analysis

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Abstract—**Medium-voltage direct-current (MVDC) technology has been widely considered as a key enabler to generate, convert and dispense electrical power with enhanced connectivity, security and quality. However, with the significant deployment of power electronics converters with high-switching frequency in MVDC systems, accurate analysis of system dynamic behavior such as harmonic distortions have become a computationally intensive task. To address these challenge average models of converters have been proposed to facilitate faster computation. However, these models only capture the steady-state characteristics of the system. To this end, in this paper, three types of time-domain based converter models: detailed, average and switching average models are presented for harmonic studies. The suitability of the modelling fidelity in reducing substantial simulation time has been validated with a practical converter topology used for the first MVDC link in Europe. Simulation based on the switching average model is shown to provide all relevant information as obtained from the detailed switching model while consuming considerably less computation time than the latter.**

Index Terms— **Average model, distribution netwroks, harmonic distortion, medium voltage DC, voltage source converters.**

I. INTRODUCTION

The increased environmental concerns combined with a higher customer demand have put enormous pressure on the existing medium-voltage alternating-current (MVAC) networks. Besides, the current MVAC assets are running at full capacity requiring reinforcements to accommodate the growing distributed energy resources (DERs) [1]-[7]. However, any form of restructuring is restricted by voltage and thermal stability limits [2].

To this end, flexible and accurate power flow control and increasing DER hosting capability offered by medium-voltage direct-current (MVDC) has become a valuable alternative solution for the intractable challenges in the distribution networks [1]-[3]. Inserting new MVDC links and/or converting existing MVAC lines to MVDC operation have been considered as an emerging approach to uprate the transmission capability [5]-[7]. At present, voltage source converter (VSC) based MVDC technology is widely used in traction applications, shipboard power systems and is identified as a feasible option for offshore wind power collection systems and micro-grid applications [11]-[13]. Besides these, an MVDC system for the conversion of an existing AC line to DC operation has been considered to enhance the utilization of existing assets [4]-[6]. For instance, the “ANGLE DC” project which is the first MVDC link in Europe. The project aims to convert an existing 33 kV MVAC line which connects Isle of Anglesey and North Wales in the UK to ± 27 kV MVDC link [2], [17]-[19].

With the increasing number of power converters connected, the distribution networks could potentially suffer from harmonic instability issues [8]-[16]. The harmful effects of these devices, in general, are not severe, however, the impact of aggregate harmonic distortions generated by the DERs and non-linear loads on the future grid operation has been an increasing concern among utilities [8].

Distribution level harmonic studies were usually performed using simplified converter models due to the lack of data from the manufacturers [12]. However, a detailed electromagnetic transient (EMT) converter model, where the topology and control systems of the device under test is masked, is typically provided by the developer for transient studies [9]-[13]. The so called ‘black-box model’, can be used to analyze harmonic interactions, however, requires long simulation time to cope with the power electronic device switching transition which demands very small-time steps [12]. To this end, the two main approaches used for harmonic interaction studies with VSC technology are frequency-domain and time-domain modelling [11]-[14].

In the frequency-domain model, a matrix is created with VSC’s represented as current injection and grid impedance at each harmonic order [11], [14]. The key advantage is the small computational time, afforded by the simplified representation of VSCs [14]. However, the accuracy of harmonic estimation could be compromised as it depends on the resolution of the analysis technique used. Moreover, for large systems with multiple converters, the process of developing matrices is a

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time-consuming exercise and needs to rebuild each time for changing operating conditions.

On the other hand, time-domain models provide an instinctive way of representing each component in the network using a user-friendly interface [9]-[12]. Moreover, they allow a detailed representation of VSC's, cables and overhead lines (OHL's), which significantly impacts the harmonic studies compared to the frequency-domain models [12], [19]. However, the detailed representation deteriorates the computational speed especially when multiple VSC's are connected.

To address this modelling dilemma, several simplifications of detailed converter models have been proposed in the literature [20]-[22]. In [20]-[21], an average value model using controlled voltage and current sources has been presented for wind and HVDC systems. A more detailed converter model with switching function is introduced in [20]. Most of the studies in this direction focused on saving computational speed and less attention has been made onto harmonic analysis. Moreover, the converter representation is more idealistic rather than considering a practical scenario which typically uses cascaded/multiple converter configurations.

To this end, in this paper, a comparison of different converter models for the proposed ANGLE DC link is presented. Dynamic simulation based on three models: detailed model (DM), average model (AM) and switching average model (SAM) have been used to test the accuracy under harmonic performance and computational speed using the cascaded converter configuration of the ANGLE-DC link.

II. THE ANGLE DC PROJECT OVERVIEW

The 33 kV MV network operated by the Scottish Power Energy Networks (SPEN) is the system under investigation. The distribution network is upgraded with an MVDC link between the island of Anglesey and North Wales, UK [17]-[19]. The increased growth of DERs in the Anglesey area combined with additional demand growth in the mainland causes voltage and thermal stability issues at several parts of the network [18]. To address these challenges, the 33kV double-circuit ac line between Llanfair PG substation, on Anglesey Island, and Bangor substation on the mainland in North Wales, is selected as the location for the MVDC demonstration project--The ANGLE DC [2],[18]. It aims to convert the existing 33 kV double-circuit ac line to ± 27 kV dc operation as depicted in Fig. 1.

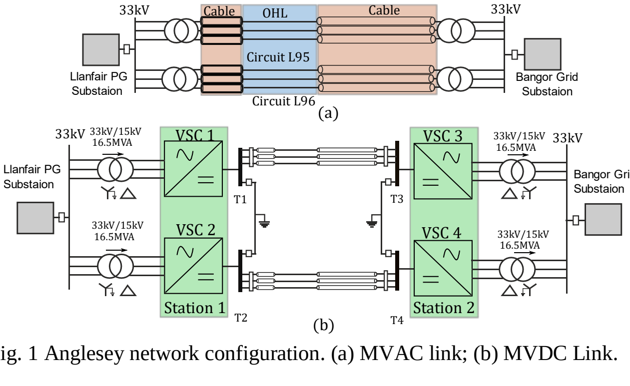


Fig. 1 Anglesey network configuration. (a) MVAC link; (b) MVDC Link.

Power flow control and ancillary services to the Anglesey and mainland network will be achieved through converter stations installed at each end of the circuit [17]-[18]. The total length of the existing ac line is approximately 3 km with a combination of underground cable and OHL sections [17]-[19].

A. *Converter Configuration*

Power electronic converters topology plays a significant role in the harmonic contribution and modelling complexity. The proposed ANGLE DC link uses three-level neutral point clamped (3L-NPC) topology in cascaded structure to form a symmetrical monopole configuration [18]. The structure of inverter topology is shown in Fig. 2 and is connected to the 33 kV ac network through two 33/2.1 kV transformers [18]-[19]. Each transformer is rated at 17 MVA, 3-phase, Y-(Δ x 6), having six low voltage windings of 2.85 MVA. Six independent 3L-NPC cells connected in two groups (see Fig.2(b)), interconnected at the ac terminal forms the 18 level converter topology per pole [18]-[19].

For one converter station (Llanfair PG or Bangor Grid) a total of 12 cells, each rated at 2.75 MVA capacity at 4.5 kV dc voltage (V_{dc}) is used to generate ± 54 kV at the dc side. A grounding is provided at the midpoint of the two six-cell modules through a 10-ohm resistor [18]. To smoothen the dc current, each pole of the converter station is equipped with a 6 mH air-cored dc line reactor [19]. A sinusoidal pulse width modulation (SPWM) is employed with a switching frequency of 750 Hz to achieve a total of 36 level of voltage at one converter station [19].

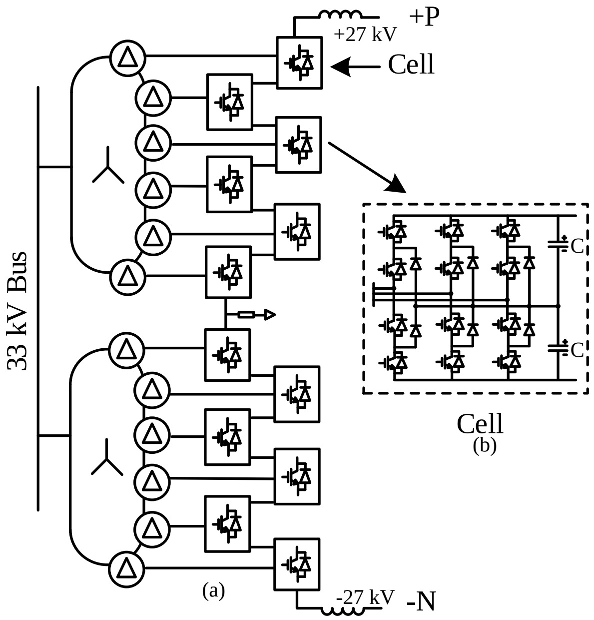
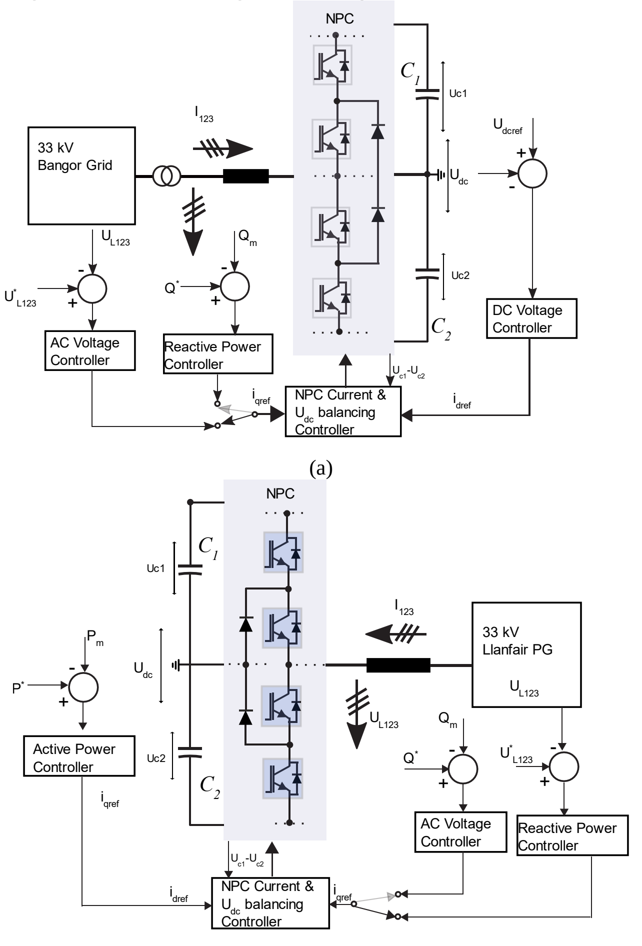


Fig. 2 Cascaded NPC Structure. (a) Inverter topology; (b) Cell topology.

B. *Control System of the MVDC Link*

The MVDC link with its flexible control capability facilitated by the VSC technology is capable of independently control power flow and ac voltage at each end [17]-[19]. These control objectives are achieved by operating the Llanfair PG substation converter station in inverter mode, *i.e.* DC voltage and reactive power/AC voltage control mode (Vdc-Q). The rectifier operation is achieved through active power and reactive power/AC voltage control mode (P-Q) of the converter station connected to Bangor Grid substation. The two control schemes are shown in Fig. 3, use measurements from the transformer low-voltage ac-side of each VSC as input to the local controller [17].

The grid connection is achieved through the two three-phase transformers at each end of the MVDC link. A decoupled current control strategy is employed at the converter level to generate the reference voltage pulses. To maintain a dc voltage balance between the two capacitors in three-level configuration, a dc voltage balancing controller is used [17].



(a)

(b)

Fig. 3 MVDC Link Control System. (a) Inverter Control; (b) Rectifier Control.

C. DC Link Sections

The existing 33 kV MV ac line between Bangor and Llanfair PG consists of a combination of double-circuit underground cables and OHL in short sections. The total length of the whole section is approximately 3 km, with 2.3 km of cable and 0.4 km of OHL sections which constitute the two circuit sections L95 and L96 [18]-[19].

Fig. 4 illustrates the schematic diagram of the two ac circuits forming the dc link. The multiple mixed line sections were made of several cable designs (1-core, 3-core, copper and aluminium). Many of the cable sections were originally installed in the 1960's, however, several overhauls were performed on them with more modern designs [19].

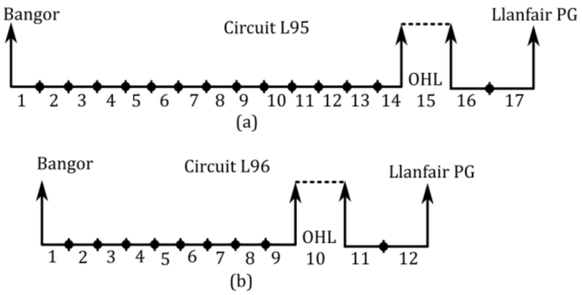


Fig. 4 DC Link Circuit Sections.

III. CONVERTER MODELLING APPROCHES

Traditional converter models used for harmonic studies employ detailed representation of switches which demands extensive computational resources and requires significant simulation time [12]. This problem is aggravated when multi-level topologies or cascaded converter configuration is used. To address these issues different converter models were proposed and are tested with dynamic simulations[11]-[12], [20]-[21]. Among the widely used converter models, the AM and SAM are employed here for the ANGLE DC 3L-NPC converter topology and are compared against the DM for accuracy and computational efficacy.

A. Average Model

The average model uses controlled voltage sources on the ac side and a current source on the dc side interfaced through the VSC controllers as shown in Fig. 5(a). They do not include a PWM scheme and the simulation step is free from carrier frequency [20]. Moreover, the averaged electrical quantities only contain fundamental component thereby the harmonic contents in voltage and current waveforms are not represented [12]. Therefore, this model is not suitable for detailed EMT analysis, such as harmonic and protection studies. The reference voltages on the ac side are the output voltages obtained from the inner current control system (see Fig. 3), where the amplitude and phase are controlled independently. The ac side of the VSC in the phase (or *abc*) reference frame is composed of three controlled voltage sources [20]:

$$U_n(t) = \frac{1}{2}U_{dc}(t)\, m_n(t), \qquad n = a,b,c \tag{1}$$

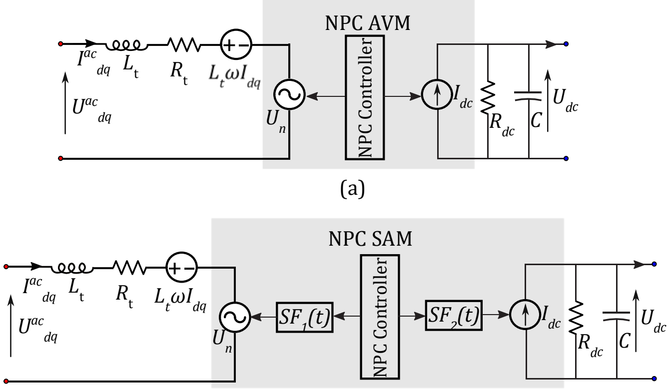
where m_n is the modulation index generated from the *dq-abc* transformation of the reference signal from the control system. The dc side current is derived from the power balance equation given by

$$U_a I_a + U_b I_b + U_c I_c = U_{dc} I_{dc}\,. \tag{2}$$

where I_{abc} is the ac side current in the *abc* reference frame which is transformed into *dq* reference frame and fed to the control systems and used to derive the dc current as in (3).

In *dq* reference frame the dc side average current function can be written as

$$I_{dc} = \frac{3}{2U_{dc}}(U_d I_d + U_q I_q) \; . \tag{3}$$



(a)

(b)

Fig. 5. Average Converter Models. (a) AM; (b) SAM.

B. *Switching Average Model*

The switching average model encompasses switching function equations of the converter model under study to realistically represent the performance of real switches [20]. Like AM, the SAM uses controlled voltage sources on the ac side and a controlled current source on the dc side. The ac and dc sides are interfaced through the controllers and two switching functions are used to generate the harmonic content as shown in Fig. 5(b) [20]. These models approximate the high-frequency harmonic nature of the converter voltages and current thus making them suitable for harmonic and power quality studies. They provide an accurate representation with less computational burden compared to DMs [20]. However, SAM needs more simulation time compared to AM with the PWM technique used for switching emulation.

The mathematical derivation of the ac voltage functions employed for the switching function modelling of 3L-NPC is

$$V_n = \frac{1}{2} S_{fn} V_{dc}, \qquad n = a, b, c \tag{4}$$

$$S_{fn} = S_{fu1} \cdot S_{fu2} - S_{fl1} \cdot S_{fl2} \tag{5}$$

where S_{fn} is the switching function of phase n, S_{fu1} and S_{fu2}, S_{fl1} and S_{fl1} represent the states of two upper valves and lower legs (S_{fu1} = [1; 3; 5]; S_{fu2} = [2; 4; 6]; S_{fl1} = [2; 4; 6]; S_{fl2} = [1; 3; 5]) respectively. The changes in switching function, S_{fn} is limited to ±1. The dc current can then be expressed as

$$I_{dc} = \sum I_n \left(S_{fu1} \; S_{fu2} \right) . \tag{6}$$

IV. CASE STUDY

A detailed harmonic analysis of the ANGLE DC link with different average converter models connected in cascaded configuration is performed and compared against the detailed model for accuracy and computational speed. The test parameters used for the case study is presented in Table I. The DM, AM and SAM of the converters are built in PSCAD/EMTDC with a detailed frequency dependent cable and OHL sections used to build the dc-link configuration [19].

Table I. Simulation parameter set

Parameter	Value
Nominal DC voltage	± 27 kV
Rated Capacity	33 MVA
Rated Active Power	30 MW
Rated Reactive Power	20 MVAr
AC voltage (rms)	33 kV
Carrier Frequency	750 Hz
DC link capacitor (C_1 and C_2)	4600 µF
Grid transformer impedance for 17 MVA	0.2 p.u.

A. *MVDC Converter with Switching Average Model*

The resultant waveform of AM approach is generic and can be applied to any converter topology. This is evidenced in Fig. 6 that in AM, the phase voltage at one of the 3L-NPC cell terminal generates a pure sinusoidal waveform. However, the DM and AM clearly show the three voltage levels for the 3L-NPC. The SAM voltage closely follows the DM as illustrated in Fig. 6, showing good accuracy of the switching function-based model in emulating the IGBT valves behaviour. The discrepancy in the switching pulses pattern is due to the delay and transition introduced by the IGBT switches in DM compared to SAM, where controlled voltage and current sources are used for generating the pulses and varies depending on the local value of the reference waveform.

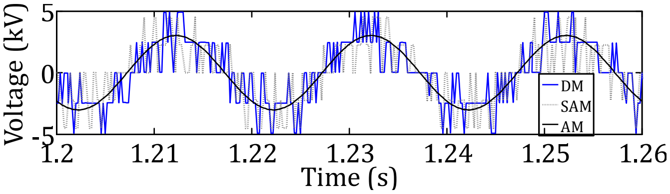


Fig. 6. Phase-a voltage (V_{an}) at the 3L-NPC cell terminal for three converter models.

B. *Harmonic Analysis*

Fig. 7 compares the voltage profiles at the point of common coupling (PCC) for an MVDC inverter station with cascaded 3L-NPC configuration, using three different modeling techniques. For the case study, the 33kV network at either end of the MVDC link is represented using sinusoidal voltage source at the fundamental frequency. The PCC voltage waveforms in Fig. 9 for all three cases closely follow each other and the SAM, in particular, follows the detailed model even for small oscillations.

Even though the time-domain signals in Fig. 7 closely follow each other, any valuable insight into harmonic content is not observed. To highlight this, the PCC voltage frequency spectrum for the three modeling techniques is compared in Fig. 8. The AM spectrum features only the fundamental component as evidenced by the one bar for this modeling technique in the graph. However, the SAM shows a good accuracy in identifying harmonic components compared to the DM. This exercise demonstrates the suitability of SAM modelling approach for harmonic or high frequency interaction studies. For the study performed here the frequency spectrum range is limited to 2500 Hz because above this frequency, no significant harmonic components are observed.

The spectra included in Fig. 8 shows the presence of harmonic components in the region around 700-800 Hz, which are related to the switching frequency (750 Hz), but with very small magnitude compared to the fundamental. A zoomed-in version of the graph shows that this frequency is also identified using the SAM converter modelling, showing good agreement with DM.

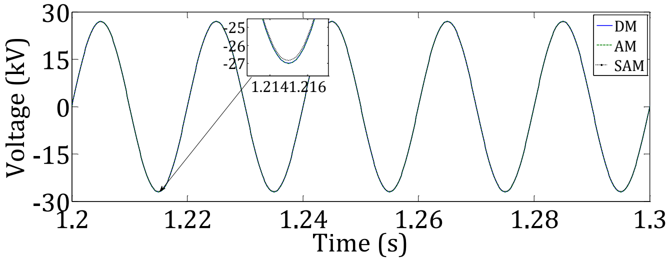


Fig. 7. Voltage at the PCC.

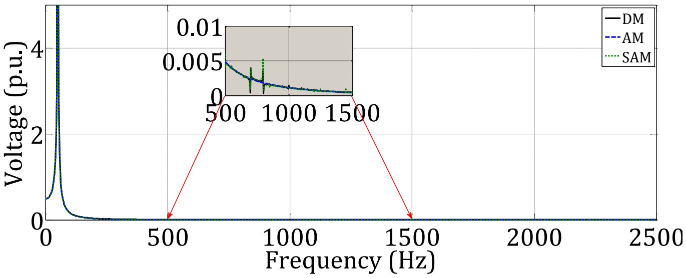


Fig. 8 Frequency spectrum of voltage at the PCC for the three cases shown in Fig. 7.

To get a further insight into the harmonic distortion generated by the MVDC system using different converter models, the current waveforms at the inverter station is plotted in Fig. 9. A more visible pre-existing harmonic distortion is evidenced in the current compared to the voltage. The current waveform in the SAM closely represents the DM even in the presence of oscillations, showing good accuracy in the modeling approach. The AM only features the fundamental current, as shown in Fig 9 and evidenced through the spectrum results depicted in Fig. 10. The presence of harmonic content in the currents at and around the switching frequency is also evident in the spectrum results for both SAM and DM.

A similar pattern can be observed from the current plots at the rectifier station shown in Figs. 11 and 12. The current waveform and its spectrum results at both ends of the MVDC link show good accuracy. The results indicate that, even though the amplitude of the oscillations is quite small, an accurate model for harmonic studies needs to be able to duplicate these phenomena.

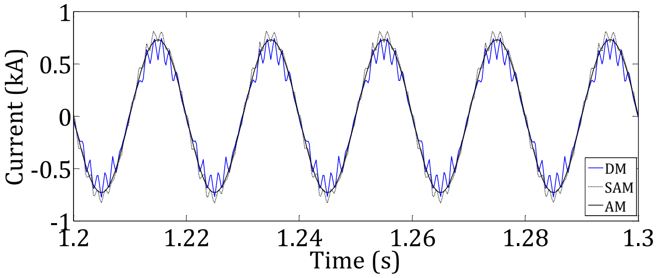


Fig. 9. Currents at the PCC for the cascaded 3L-NPC inverter station with three models compared.

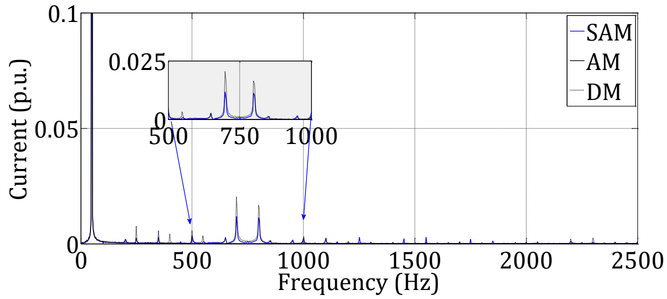


Fig. 10. Frequency spectrum of the currents at the PCC for the three cases shown in Fig. 9.

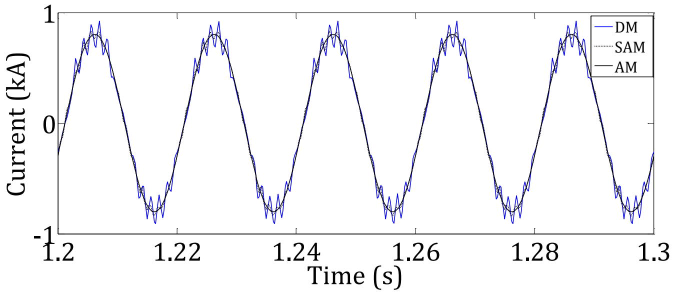


Fig. 11. Currents at the PCC for the cascaded 3L-NPC rectifier station with three models compared.

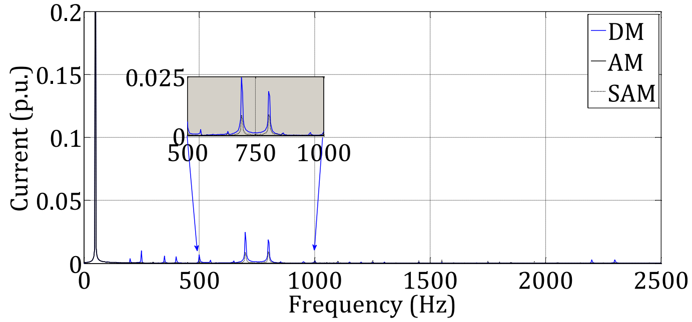


Fig. 12. Frequency spectrum of current at the PCC for the three cases shown in Fig. 11.

C. *Computational Time*

The accuracy of the SAM in emulating the DM is tested and shows good agreement. However, the next essential requirement for effective harmonic studies involving converters is the computation time for simulation methods. Together with accuracy, an improved computational performance is envisaged using SAM compared to the DM. To evaluate this, simulations of the MVDC link have been carried out on a PC with 2.6 GHz core-i7 processor and 16 GB ram. Table II summarises the computation time of each modeling technique implemented for harmonic analysis. AM and SAM are compared against the DM. Among the studied modelling techniques, the AM features the smallest computation time, afforded by the simplified representation of switches. The, SAM on the other hand, offers a significant improvement in the simulation time for the same time step compared to DM while still allowing great accuracy as shown in Figs. 7-12.

TABLE II
COMPUTATIONAL TIME REQUIREMENTS FOR 2S SIMULATION

Modelling Type	**Detailed Model**	**Average Model**	**Switching Average Model**
Computational Time	840 min	2.5 min	4.6 min
Simulation Step	20 μs		
Simulation Plot Step	200 μs		
Simulation Platform	PSCAD/EMTDC Version 4.6 On a 2.6 GHz core i7 4960 pc with 16 GB RAM		

V. CONCLUSION

A detailed model is required to represent all the dynamics and transient performance of a grid connected converter. However, the computational burden introduced by the switches and multilevel converter topologies has limited the opportunity of detailed time-domain simulations for transient analysis such as harmonics and power quality studies. Besides, an accurate representation of converter systems with low computational burden will be required for large network studies.

To this end, simplified converter models are presented in this paper to facilitate harmonic studies in an MVDC link with cascaded converter topology. The test system used is the proposed ANGLE DC demonstration project in the UK, which is the first MVDC link project employs ac lines for dc operation. Three 3L-NPC converter models (DM, AM, SAM) were presented and implemented for harmonic studies with detailed dc link configuration. Comparison amongst the AM, DM and SAM models show that: the AM is fast, accurate and can be used for any converter topology but limited only for fundamental frequency operation and are therefore not suitable for harmonic studies. On the other hand, the SAM model is accurate in replicating harmonic distortion, while significantly reducing the simulation time compared to DM.

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