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Emerging Capability on Power System Modelling: HVDC Systems

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About this report

The Institution of Engineering and Technology was commissioned by the Council of Science and Technology (CST) to research the emerging challenges for modelling electricity systems and how Britain's capabilities would need to be adapted to assess electricity system resilience as GB makes the transition to a low carbon electricity system.

This project commissioned, and received, fifteen individual papers from GB-based specialists of international standing in power system modelling. The authors of the papers worked with a wide stakeholder base of network companies, academics and others, who provided review and challenge. Professor Graham Ault CEng FIET was contracted to provide technical co-ordination and drafting. The emerging conclusions were further validated by means of an industry and academic workshop sponsored by Government Office for Science. The entire project was conducted under the direction of an independent steering committee composed of senior IET Fellows, two of whom were also CST nominees.

The report is composed of three parts:

- Part 1: Main report
- Part 2: Summary of Commissioned Papers
- Part 3: IET Special Interest Publication – Academic & Industry Papers

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EXECUTIVE SUMMARY

This brief paper introduces the background of the HVDC technologies, namely LCC HVDC and VSC HVDC, then classifications of different power system controls and power system dynamic phenomena are presented.

Then current modelling capability for HVDC technologies is discussed based on the above classifications. Noting the fact that different phenomena are studied using different simulation tools, with different level of details in power system components modelling, with different assumptions where the simulation tools are further classified into non-real-time tools and real-time tools. However, it is possible now to model and simulate all the dynamic phenomena using unified advanced Electromagnetic Transient Simulation Tools.

The models cover LCC HVDC models for Transient stability studies; LCC HVDC models for small signal stability studies; LCC HVDC model for power flow studies. In almost the same sequence, we discuss the models for VSC HVDC.

Then we review the emerging HVDC technologies and modelling challenges for HVDC modelling and research development: benchmark EMT models for HVDC; HVDC control parameters; “Multi-Terminal Test Environment (MTTE) for HVDC Systems”; high frequency small signal stability models; large scale power system simulation with HVDC grid. Finally we present our recommendations.

1. BACKGROUND

High Voltage DC (HVDC) transmission technologies have been used for long-distance bulk power delivery, system interconnections and integration of large scale renewable energy systems, in particular, offshore wind farms. There are typically two types of HVDC technologies, namely, Line Commutated Converter based HVDC (LCC HVDC) and Voltage Source Converter based HVDC (VSC HVDC). LCC HVDC technologies have been more widely used for long distance bulk power transmission where the highest DC voltage is 1100 kV and the power rating is 11GW. In comparison, VSC HVDC technology has a very promising future for long-distance bulk power delivery, system interconnections and integration of large scale renewable energy systems, in particular, offshore wind farms. The advantages of VSC HVDC include: smaller footprint; independent control of the active and reactive power; better dynamic response performance in the event of AC system faults; black-start capability; supplying power to passive loads; interconnection of very weak power grids; enabling multi-terminal configuration, etc where the power rating is up to 1 GW. More general discussions on HVDC technologies are referred to as [3]-[6], [17]. Broader topics on power electronic applications in power systems can be found in [7]-[9].

It has been recognised that with the increasing integration of large scale renewable energy, especially the offshore wind power, the multi-terminal VSC-HVDC system (MT VSC HVDC) can be used for collection of wind power from several offshore wind farms located in different areas of the sea with less investment in construction and maintenance than traditional point-to-point delivery. Consequently the interconnection of VSCs can enhance the flexibility and reliability of the power delivery. In this way, more and more attention is gained from research, industrial and business organizations. However, new challenges have emerged with the investigation of MT VSC HVDC systems. One of the key issues is how to protect the MT VSC HVDC system from the faults, especially the DC faults. Due to the structure of VSCs, the overcurrents caused by the DC faults would damage the VSCs and bring further destructive damage to the VSC HVDC.

Different VSC HVDC schemes have been developed. In the past, the familiar 2 or 3-level converter topologies have been widely used, which require a high number of semiconductor devices with blocking capability of a few kilovolts and subsequently requires sophisticated gate drive circuits to enforce adequate voltage sharing between the devices. The PWM switching means high switching losses in the semiconductor devices. In order to overcome the shortcomings, alternative VSC converter topologies namely, the Modular Multilevel Converter (MMC or M^{2}C) and the Cascaded Two-Level (CTL) converter have been proposed. The main feature of the M^{2}C approach is that with high number of levels, the size of voltage steps can be reduced, and with more voltage levels used, the harmonics become smaller and the switching frequency of individual semiconductors can be reduced, and hence the switching losses can be effectively reduced.

Furthermore, the integration of renewable energy into power grids by VSC HVDC technologies has been widely accepted and recognised as an advantageous approach. The dynamic performance and the control strategies of the complicated MT VSC HVDC with the integration of the renewable energy under normal and abnormal operating conditions deserve our exploration and study. In addition to the above LCC HVDC and VSC HVDC technologies, a hybrid HVDC system or MT hybrid HVDC grid may be built by combining LCC and VSC converters where the advantages of both technologies can be maximised. In order to design, control and operate HVDC systems, along with on site experiments, system studies using simulation platforms become necessary. In the following sections, we will present the current modelling capability for HVDC systems, and then we will discuss the emerging modelling capability for HVDC systems and identify the gaps. Finally conclusions will be drawn and recommendations will be provided. The models cover *LCC HVDC models for Detailed Electromagnetic Transient (EMT) Simulation.*

2. METHOD

As shown in Figure 1, there are different power system phenomena such as lighting strikes, line switching, sub-synchronous resonance (SSR) & sub-synchronous torsional oscillation (SSTO), transient stability, long term dynamics, etc. In the viewpoint of modelling and simulations, it may be appropriate to classify transients by the time frame and use appropriate analysis tools to investigate the phenomena involved. In Figure 1, we can also see the different time scales of control actions such as control of power electronic switching, control of HVDC and FACTS devices, protection, prime mover control of generating units, load-frequency control and operator control actions, etc.

In this brief paper, we will review the different simulation models and tools available and hence understand the existing simulation capability.

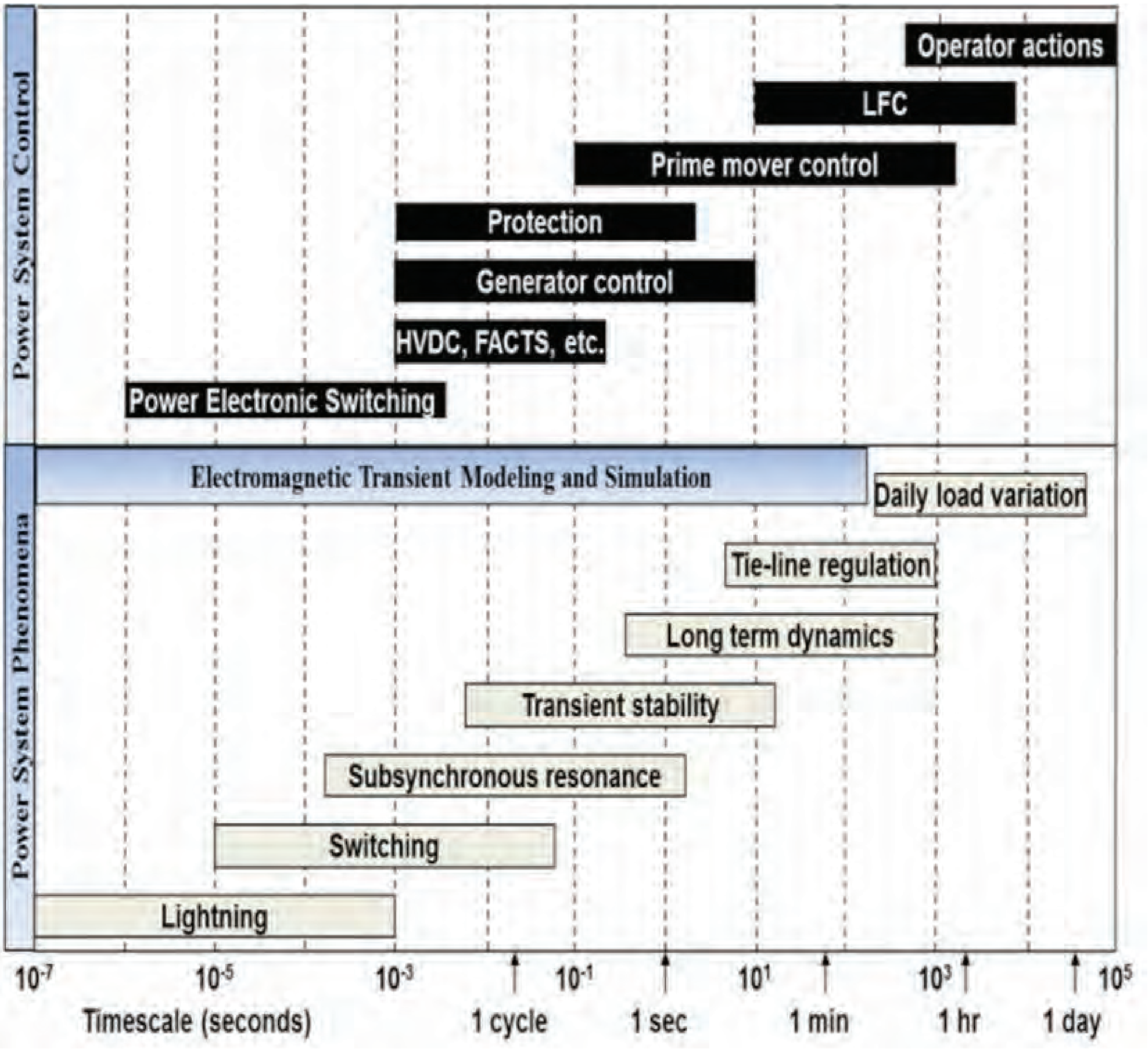


Figure 1: Time Frame of power system transient phenomena and controls.

3. CURRENT POWER SYSTEM MODELLING CAPABILITY

As shown in Figure 1, traditionally different phenomena are studied using different simulation tools, with different levels of detail in power system components modelling with different assumptions where the simulation tools are further classified into non-real-time tools and real-time tools. However, it is possible now to model and simulate all the dynamic phenomena using unified advanced Electromagnetic Transient Simulation Tools.

3.1 LCC HVDC Modelling and Simulation

3.1.1 LCC HVDC components and control architecture

LCC HVDC is a mature DC transmission technology that has been used for over 50 years and there are a large number of projects worldwide. LCC HVDC can be used in the following applications: (a) large scale long distance power transmission; (b) asynchronous AC system interconnections; (c) long submarine cable crossings; and (d) DC interconnection embedded into an AC system (for instance, the UK West DC link being constructed). There are also examples of using LCC HVDC for wind power transmission.

LCC HVDC may have a few configurations, namely Monopolar, Bipolar, and Homopolar configurations, etc [1]. A 24-pulse bipolar LCC-HVDC is shown in Figure 2 where the major components include AC filters, Converter Transformers, Converters (including both Rectifiers and Inverters), Smoothing Reactors; DC Lines; and two AC systems, denoted as System A and System B, respectively. In Figure 1, almost all the essential components are depicted except the measurement units, communication systems, protection relays and control systems.

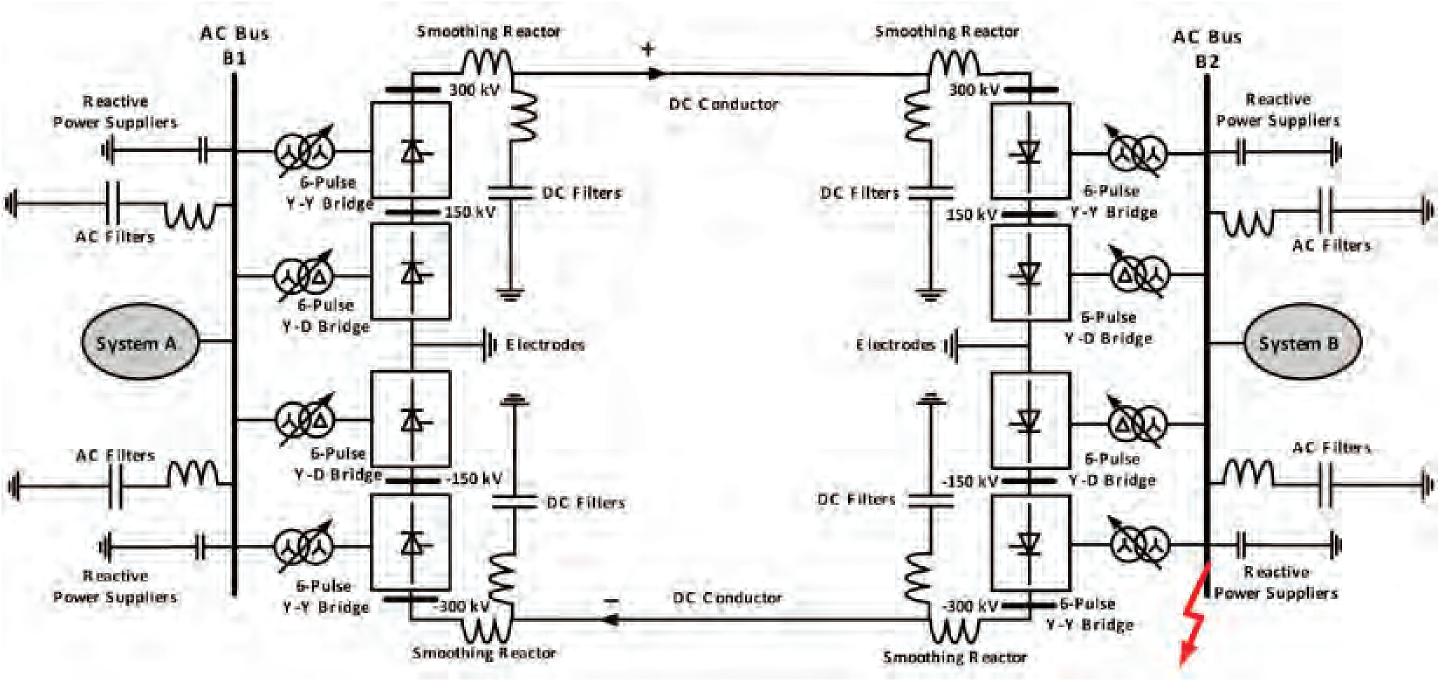


Figure 2: A single line diagram of a 24-pulse bipolar LCC-HVDC.

A LCC HVDC control system may be split into 5 hierarchy levels, from top to bottom: System Control and Dispatching; Station Control; Bipolar Control; Pole Control; and Converter Group Control [17]. The top level of the control performs the system level coordination role, which is normally located in a control/dispatching centre while all other levels of the control are carried out at the converter station. The Station Control including the control functions of power demand overrides, reactive power/AC voltage control, power modulation control and frequency control is to mainly decide the optimised active and reactive power exchange with the AC power grid. The Bipolar Control is to coordinate the power transmission between the two poles. The Pole Control is to mainly maintain the transferred power according to a given power order received from a higher control level, and provide damping control, etc. The Converter Group Control performs the key control functions at the bottom level of the control system, which determines the firing angles according to the control orders and limits.

3.1.2 LCC HVDC simulation and analysis models

Depending on the phenomena under investigation, simulation and analysis models for LCC HVDC can be classified into 4 categories:

- ***LCC HVDC models for Detailed Electromagnetic Transient (EMT) Simulation:*** In EMT models, the converter (rectifier/inverter) model, DC network model and associated control systems are described by differential equations. A detailed modelling of CIGRÉ LCC HVDC Benchmark System using PSCAD/EMTDC and SIMULINK was presented in [16]. In this model, the converters (including both rectifier and inverter) were implemented using six-pulse Graetz bridge block, including a Phase Locked Oscillator (PLO), firing & valve blocking controls, and firing angle/extinction angle measurements, as well as built-in RC snubber circuits for each thyristor. Thyristor valves were represented by ideal power electronic switches while negative turn-off and firing due to large dv/dt or di/dt were neglected. In the model, converter transformers were modelled by three-phase two winding transformers, one with grounded Wye–Wye connection and the other with grounded Wye–Delta connection where saturation characteristic and tap setting arrangement were considered. Similar transformer models are used for the inverter. The DC line was represented using an equivalent-T line model with smoothing reactors inserted on both sides. Tuned filters and reactive support were considered at both the rectifier and the inverter AC sides. The AC systems were represented by two three phase AC voltage sources.
- ***LCC HVDC models for Transient stability studies:*** There are a very large number of publications on the modelling of LCC HVDC. The models may be classified into 4 different categories: (a) the LCC HVDC is simply represented by a DC power flow equation while dynamic controls are neglected. (b) the LCC HVDC is represented by a DC power flow equation and associated control systems [12]. (c) the LCC HVDC is represented by a DC dynamic network equation while a full detailed DC control system is used [13]. The model is generic and comprehensive, which were derived based on the essential HVDC equations and transfer functions. In addition to the DC network dynamics, controls of transformer tap-changers and AC filters have also been considered. (d) the LCC HVDC is fully represented by an EMT type model where all the dynamics and associated controls can be modelled in great details, and then the model is interfaced with a phasor type AC network model [14, 15], which have overcome the limitations of AC system dynamic studies for which discontinuous and distorted interaction with DC networks are not accurately predicted. The approach is particularly useful for the study of interaction of a DC system with weak AC systems.
- ***LCC HVDC models for small signal stability studies:*** In [18], a LCC HVDC model for small signal stability program analysis implemented in TSAT was presented. A LCC HVDC model for small signal stability studies was presented in [19, 20]. A LCC HVDC model for small signal stability studies was proposed in [21] where a detailed linearised model of a point-to-point LCC-HVDC was established using a sampled data modelling approach, while the LCC-HVDC controllers and ac network were not represented in detail. In [22] small signal stability model for Multi-infeed LCC HVDC interaction studies was conducted. However, the LCC-HVDC controllers were not modelled in detail where only current and extinction angle controllers were considered.
- ***LCC HVDC model for power flow studies:*** A power flow model can be derived by setting all the differential terms dx/dt to zero where x is a state variable. In this way, all the differential equations are reduced to algebraic equations which describe voltage and current relationships, voltage and power relationships and control inputs/outputs relationships. The detailed power flow model of a LCC HVDC is referred to [2].

3.2 VSC HVDC and Components

3.2.1 VSC HVDC components and control architecture

The major technical advantages of VSC-HVDC system vs LCC HVDC include flexible power flow control, fast response to system disturbances, convenient multi-terminal DC grid configuration and black-start capability, etc. A review article is referred to [10].

A two-terminal 2-level VSC-HVDC is shown in Figure 3 where the major components include Converter Transformers, AC filters, Smoothing Reactors, Converters, DC Lines, and two AC systems, denoted as System A and System B, respectively. The controllers for VSC1 and VSC2 are shown in Figure 4. The converters use Pulse Width Modulation (PWM) technique. A decoupled current control strategy in the synchronous reference frame *d-q* and standard PI controllers are used [34].

Similar to the control architecture for LCC HVDC, the VSC HVDC control may include 5 different levels. The control level being discussed here is mainly related to Converter Control. The converter control consists of a higher level control and a lower level control [26], [25]. The higher level control at its converter terminal as shown in Figure 4 is to maintain the terminal active power flow (or DC voltage), and reactive power flow (or AC voltage) [41] at the given references. With the inclusion of DC droop control, the active power of the HVDC grid can be shared between the DC terminals, and this is very similar to the power sharing between synchronous generating units with governor droop control for AC power systems [29]. Each of the higher level controllers as shown in Figure 4 consists of two control loops, namely, the outer and inner control loops. The objective of the lower level controllers is to produce firing signals to the valves using the control signals generated by the higher level controllers. Additional control loops for frequency control, power sharing, and damping control, etc can be added into the inputs of the outer controllers.

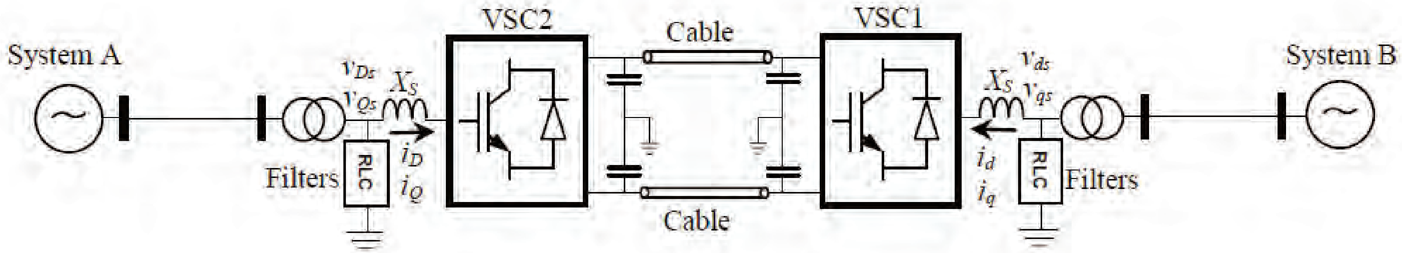
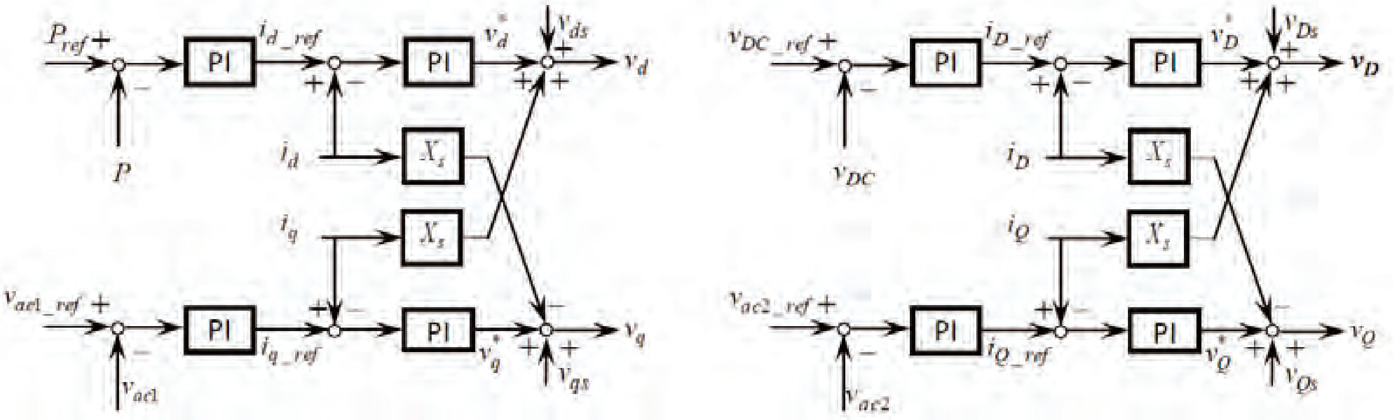


Figure 3: Single Line Diagram of a Two-Terminal VSC-HVDC.



(a) VSC1: Active power/AC voltage control

(b) VSC2: DC voltage/AC voltage control.

Figure 4: VSC HVDC Controllers.

3.2.2 VSC HVDC simulation and analysis models

Depending on the phenomena under investigation, simulation and analysis models for VSC HVDC can be classified into 4 categories:

- ***VSC HVDC models for Detailed Electromagnetic Transient (EMT) Simulation:*** In EMT models, the converter (rectifier/inverter) model, DC network model and associated control systems are described by differential equations. HVDC is a proven efficient and flexible power transmission technology for long distance bulk power transmission, system interconnections and renewable energy integration. The special features of the VSC HVDC technology enable the development of meshed DC grids. In this situation, it is necessary to study the behaviour and interactions between VSC controls and between AC and DC controls. For the purpose of EMT type simulations, both the detailed higher level controllers and lower level controllers are needed **[26], [25]**. While for stability studies, the lower level controllers may not be needed. The models proposed in **[26], [25]** have been implemented in MATLAB SimPowerSystem and validated on the real-time simulator - OPAL-RT. VSC HVDC models have been implemented in EMTP-RV. Models for VSC HVDC for EMT type simulations were also discussed in **[27]** and **[28]**. There are also relevant publications on modelling of VSC based FACTS devices such as STATCOM **[23,9]** and UPFC **[24]** where the modelling techniques are applicable to the modelling of VSC HVDC systems.
- ***VSC HVDC models for transient stability studies:*** There are a very large number of publications on the modelling of VSC HVDC for stability studies. In **[30]**, a generic VSC HVDC primary control structure suitable for stability studies has been presented where blocking function of converters and DC circuit breaker were implemented. The model was implemented and validated on DigSILENT Power Factory simulation platform. In **[32]** a generalized dynamic VSC MTDC model for power system stability studies was proposed. This model was improved in **[31]** and was implemented into EUROSTAG.

- ***VSC HVDC models for small signal stability studies:*** VSC models in terms of STATCOM for small signal stability studies were presented in [34, 35] where decoupling d-q controllers with outer and inner control loops were used. In principle, these converter and control system models can be applied to VSC HVDC without difficulty. In [24] a platform for validation of FACTS models was developed where a small signal stability model for VSC UPFC was proposed and such an approach is applicable to VSC HVDC systems. Small signal modelling and stability analysis of multi-terminal VSC-HVDC was presented in [36]. In [37], Phase-Locked-Loop (PLL) was considered in the small signal stability model. In [33] small signal stability model with a HVDC-Connected Offshore Wind Farm was presented where PLL was also considered. In [38], small-signal stability analysis of multi-terminal VSC-based DC transmission systems with synchronous machines was proposed. The modelling approach is generic, which can be extended to larger systems with an arbitrary number of converters, synchronous machines, and wind farms.
- ***VSC HVDC models for power flow studies:*** In [41], a multi-terminal voltage-sourced converter based HVDC models for power flow analysis was proposed. The model can be applied to complex DC grid, and the performance of such a model was compared with that of a multiple terminal VSC FACTS system. In addition, the model has adopted different control modes for different AC/DC terminals. In [42], droop control has been considered in the power flow studies.

3.3 Simulation tools for HVDC systems

There are a number of simulation tools and platforms available. In the following, we will discuss the modelling capability of these simulation tools. Most of these are off-line simulation packages while a few of them are real-time simulators.

3.3.1 Simulation tools

PSCAD/EMTDC, EMTP-RV and ATP are EMT type off-line simulation tools. Power system components with great details can be modelled. These tools are all based on the fixed time-step trapezoidal integration method. The main advantages of EMT-type tools include: (a) there are a large number of validated models for power system studies available. The advanced models for machine models, frequency-dependent transmission lines and transformers are provided. (b) they can be taken as a benchmark to validate other types of models and tools.

EMTP-RV offers full-featured advanced software for the simulation of electromagnetic, electromechanical and control systems transients in multiphase electric power systems, ranging in duration from microseconds to minutes. EMTP-RV provides comprehensive built-in libraries including advanced model of electrical machines, detailed models of lines and cables, advanced nonlinear models of transformers, and advanced user-defined modelling capabilities using DLLs and devices in the GUI.

DigSILENT POWER FACTORY and MATLAB SIMULINK can facilitate both EMT type and phasor type simulations. In phasor type simulations, normally AC network dynamics as well as dynamics of stator windings of synchronous machines are neglected. DigSILENT POWER FACTORY also offers eigen-value calculations for small signal stability analysis.

PSS/E includes the functionalities of short circuit calculations, optimal power flow, dynamic simulations (phasor type simulations) and eigen-value analysis using small signal stability model, etc.

PSS/NETOMAC offers advanced functions such as:

- Simulation of electromagnetic and electromechanical transient phenomena in the time domain
- Steady-state load-flow and short-circuit current calculations
- Frequency range analysis
- Eigen-value analysis
- Simulation of torsional vibration systems
- Parameter identification
- Reduction of passive / active networks, etc.

However, in comparison to PSS/E, PSS/NETOMAC is less popular. One interesting feature of PSS/NETOMAC is that for long term dynamic simulations, electromagnetic simulation can be switched to electromechanical transient simulation when electromagnetic transients decay away.

Vice versa, electromechanical transient simulation can be switched to electromagnetic transient simulation when it becomes necessary to capture the electromagnetic transients.

EUROSTAG® is a software for simulations of power system dynamic simulation and small signal stability analysis including both LCC HVDC and VSC HVDC models. The advanced dynamic simulation functions of EUROSTAG® facilitate the full range of transient, mid and long-term stability using a robust auto-adaptive step-size integration algorithm.

Power System Analysis Package (PSAPAC), developed by EPRI USA, is a collection of software tools for static and dynamic analysis of power systems, which include data preparation programs such as dynamic reduction and load synthesis programs, static analysis programs such as power flow and transmission limit programs and dynamic stability programs, such as transient stability, small signal stability and voltage stability programs.

TSAT, developed by PowerTech Labs, is a full time-domain simulation tool designed for comprehensive assessment of electro-mechanical dynamic behaviour of complex power systems. The time-domain integration approach include implicit and explicit integration methods and the package is suitable for both off-line (for instance, system planning) and on-line applications.

Most of the software packages provide user defined models.

3.3.2 Transient Network Analyser (TNA)

Basically TNA [54] can use scale-down system analogue components such as machines, transmission lines, transformers, and HVDC links to emulate the dynamic performance of real power systems. The advantages of such a TNA are: the emulated system is physically closer to the real power system under investigations; the emulated system allows a hardware in loop testing of real control systems and protection relays. However, the TNA has its obvious limitations as follows:

- Setting up a test system needs much longer time than that using other digital simulation approaches.
- Consequently re-configuration and maintenance of the systems needs a lot of human resources. In terms of modelling, accurate modelling of some components becomes impossible, for instance, travelling wave line model could not be emulated using an analogue line model.
- In order to overcome the shortcomings of TNA, Digital/Analog Hybrid Simulator is preferred [11].

3.3.3 Real-time digital simulators

A real-time digital simulator is considered to be the best alternative to an analogue TNA that can solve the system, in which equations are solved in real time using advanced digital processing and parallel processing technology [43]. Real-time digital transient simulators now become very popular for model validation, hardware in loop testing of controllers and protection relays. Real-time digital simulators need to solve the system differential equations within the time-step selected for simulation. The simulation time step-size for EMT type simulators should be around 50 µs or smaller.

Typical HYPERSIM [44], RT-LAB [45], and RTDS [46] are considered to be industrial grade real-time digital simulators. HYPERSIM can simulate networks in non real-time mode using available parallel CPUs for much faster simulation than the performance of a single CPU using supercomputer. The HYPERSIM and RT-LAB both use a generic computer for the real-time simulation. The benefits of using a generic computer rather than a dedicated hardware are twofold: (1) it can be used for other software applications; and (2) it can be easily upgraded with faster processor and therefore keep the simulator at the forefront of the technology. Now RT-LAB uses low-cost, easily obtainable multi-core processors. While the hardware architecture of RTDS is based on parallel processing techniques and employs many dedicated high-speed digital signal processors. RTDS has detailed power system component models together with flexible analogue and digital I/O enable detailed testing of power systems and external devices connected to such systems.

RT-LAB real-time simulation software relies on SIMULINK to establish power system models, SIMULINK library has a lot of power system modules that can be used. With the continuous development of power industry, RT-LAB software needs to establish its own associated power module library, and to enable customers to have more choices. The HYPERSIM and RT-LAB real-time simulation model takes too long to compile. For a relatively small model, the speed of compile and download is negligible, but for a larger model, if you want to modify a small part of the system, you will need to recompile the entire system model.

4. EVALUATION OF HVDC MODELLING CAPABILITY AND GAPS

4.1 EMT models of MMC VSC HVDC grid

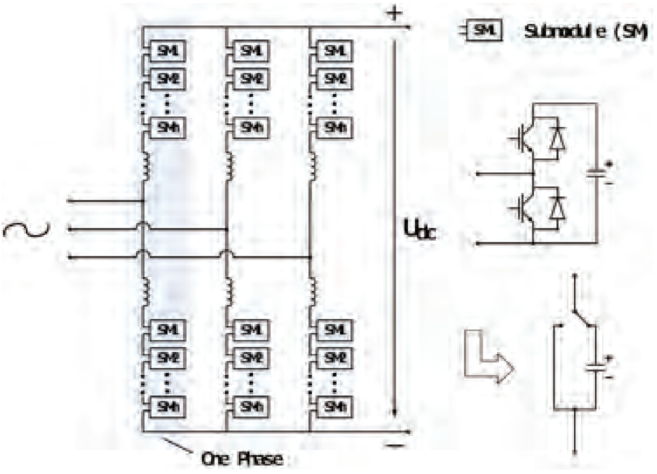


Figure 5: Topology of M^{2}C.

The topology of M2C is conceptually shown in Figure 5. The current M2C can have a power capacity of up to 1GW. The M2C now can be implemented in at least three different topologies such as half bridge, full bridge and hybrid configurations [48]. The half bridge M2C may not have the ability to suppress DC fault currents. In contrast, the full bridge M2C can suppress DC fault currents effectively. Based on the concept of MMC, Siemens commissioned the first M2C HVDC project – the “Trans Bay Cable” project, which provides a dedicated connection between the East Bay and San Francisco has been operational from March 2010. The system has a power rating of 400 MVA, a DC-link voltage of ±200 kV, and a stack of 200 cascaded sub-modules per leg [49]. With these features, the MMC VSC HVDC system is ideally suitable for the implementation of multi-terminal (MT) DC grids.

However, as a new technology, there are very few projects that employ the MMCs, the study of the dynamic performance of the MMC HVDC system can only be based on simulations, and most of them employ PSCAD/EMTDC simulations. However, the large number of switching elements in the MMC introduces a challenge for modelling the converter, thus simplified models would be desirable.

Different models can be used according to the type of study with required accuracy. The models being used may be classified into the following models [50]:

- ***Model 1*** - Detailed IGBT-Based Model: This is the most sophisticated model.
- ***Model 2*** - Equivalent Circuit-Based Model: In this model the SM power switches are replaced by ON/OFF resistors, which lead to an arm circuit reduction for eliminating internal electrical nodes [52]. But it should be mentioned that the blocked state condition and other implementation details have not been considered.
- ***Model 3*** - Simplified Arm Circuit Equivalent [50]: In this model, we assume (1) each MMC arm is averaged using the switching function concept. (2) capacitor voltages of each arm are balanced. (3) the average values of capacitor voltages are equal. (4) voltage differences between capacitors are neglected.
- ***Model 4*** – Average Dynamic Model of MMC: In this model, the IGBTs and their diodes are not explicitly represented and the MMC behaviour is modelled using controlled voltage and current sources [51].

The comparisons of these models were based on a two-terminal MMC HVDC system [50]. More detailed comparisons on meshed HVDC grid are needed to fully understand the limitations of those simplified models and general guidelines will need to show how to use those simplified models properly.

As MMC HVDC Grid is an emerging technology, benchmark simulations using Model 1 will be needed to examine the adequacy of those simplified models. Both RTDS and Opal-Lab are able to use Model 1 to do the very detailed benchmark simulations, which allow fully featured control and protection functionalities to be considered at IGBT level. In terms of HVDC Grid modelling, technical guidelines and pre-standardization work for first HVDC grids are needed to consider detailed DC grid components such as DC circuit breakers, DC/DC converters, DC power flow controllers, etc [53].

In addition, the interoperability of a multiple terminal MMC HVDC grid will need to be considered in the modelling of the DC grid in the situation of multi-vendor multiple terminal DC grid.

4.2 High frequency small signal stability models

Normally for power system small signal stability analysis, network dynamics can be neglected if the frequency of interest is between 0.1 - 2 Hz. However, if the frequency of interest is higher than 5Hz, network dynamics cannot be neglected. A modular approach was proposed to consider network dynamics in High frequency small signal stability models [39].

If small signal stability analysis in a power system is mainly concerned with electromechanical oscillations, it is adequate to model the transmission system using a constant admittance matrix, in other words, network dynamics are neglected. It has been recognised that for torsional oscillations and HVDC interactions, the frequency of interest is much higher and in this situation, the constant admittance representation is not sufficient any longer. If the approach proposed in [39] is used, for large networks, the dynamic representation of the entire transmission network leads to large computation burden due to the large system matrix.

Therefore, in order to improve the computational efficiency, a hybrid model was proposed in [40] to allow the parts of the transmission network in the vicinity of HVDC converters or any other dynamic devices to be modelled with their dynamics while the remaining parts to be modelled as constant admittances.

4.3 Large scale power system simulation with HVDC grid

Despite the advances in computing technologies, large scale EMT type simulation is still a big challenge. One possibility is to use hybrid simulation combining electromagnetic transients (EMT) simulation and transient stability (TSA) simulation to model large networks [47]. However, for practical application of such an approach, there are interfacing issues that need to be investigated further.

4.3.1 Benchmark MMC HVDC grid test system systems and system parameters

It is desirable to set up multiple terminal MMC HVDC grid test systems as a benchmark to understand the basic characteristics of DC grid, validate control and protection algorithms, develop new control strategies, etc.

Satisfactory operating performance of MMC HVDC Grid relies on the well designed control systems and associated parameters. As far as modelling is concerned, detailed model of MMC HVDC Grid and associated control parameters are extremely important. However, due to issues of confidentiality, manufacturers may not be able to provide requested detailed model parameters. This will in turn lead to the difficult to understand the operating characteristics of the HVDC grid and affect the system performance being maximised. Suitable protocols should be established to ensure that all the essential DC Grid model and control parameters will be provided to system operators.

The facility "Multi-Terminal Test Environment (MTTE) for HVDC Systems" led by SSE in collaboration with National Grid and Scottish Power will house: a real-time simulator system (which simulates HVDC schemes), IT infrastructure and accommodation for replica HVDC control panels. In collaboration with suppliers, it is likely that the facility will be helpful to facilitate multi-vendor HVDC schemes and de-risk control interactions and hence maximise the benefits of utilisation of multiple terminal HVDC technologies.

5. CONCLUSIONS AND RECOMMENDATIONS

1. **Benchmark EMT models for HVDC:** It is highly recommended that benchmark models for HVDC systems including the emerging MMC HVDC Grid should be developed. The models being used in different simulation tools should be harmonised. The models for HVDC with different levels of details should be compared and then general guidelines should be given on how to use these models. In addition, the interoperability of a multiple terminal MMC HVDC grid will need to be considered in the modelling of the DC grid in the situation of multi-vendor multiple terminal DC grid. It is desirable to set up multiple terminal MMC HVDC grid test systems as a benchmark to understand the basic characteristics of DC grid, validate control and protection algorithms, develop new control strategies, etc.
2. **Standardised simulation scenarios:** There is a lack of standards and consistent simulation scenarios that can be conducted at different stages such as equipment design, network design, and system operational planning where different levels of risks from failure of a single component to complete shut-down of the HVDC system.
3. **HVDC control parameters:** Satisfactory operating performance of MMC HVDC Grid relies on the well designed control systems and associated parameters. As far as modelling is concerned, a detailed model of MMC HVDC Grid and associated control parameters are extremely important. However, due to issues of confidentiality, manufacturers may not be able to provide requested detailed model parameters. This will in turn lead to the difficulty in understanding the operating characteristics of the HVDC grid and affect the system performance being maximised.

Suitable protocols should be established to ensure that all the essential DC Grid model and control parameters will be provided to system operators.

4. **"Multi-Terminal Test Environment (MTTE) for HVDC Systems":** The facility "Multi-Terminal Test Environment (MTTE) for HVDC Systems" led by SSE in collaboration with National Grid and Scottish Power will house: a real-time simulator system (which simulates HVDC schemes), IT infrastructure and accommodation for replica HVDC control panels. In collaboration with suppliers, it is likely that the facility will help to facilitate multi-vendor HVDC schemes and de-risk control interactions and hence maximise the benefits of utilisation of multiple terminal HVDC technologies.
5. **High frequency small signal stability models:** Normally for power system small signal stability analysis, network dynamics can be neglected if the frequency of interest is between 0.1 - 2 Hz. However, if the frequency of interest is higher than 5Hz, network dynamics cannot be neglected.
6. **Large scale power system simulation with HVDC grid:** In terms of the development of HVDC technologies, there is a big gap in terms of R&D in large scale power system simulation. With the advances in computing and electronic technologies, new large scale simulation technologies will need to be developed.

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