Strathclyde Engagement with the National HVDC Centre: Phase I Converter and GB Network Modelling

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Project background

The use of HVDC transmission systems facilitates UK's increased exploitation of renewable energy resources, e.g. offshore wind power, provides efficient highways for transmitting large active power between generation and load centres, and supports the overreaching vision of European transnational power grids. As a result, GB electricity network is expected to undergo significant changes in the coming decades with rapid growth in the amount of power generated from power electronics interfaced renewable power plants and HVDC power transmission. The adoptions of HVDC systems to facilitate the development of offshore renewable energy and increased network connectivity, and to ensure efficient and safe operation of the GB power network, a number of control, operation and protection challenges need to be addressed at converter stations and AC and DC networks at large.

Detailed system modelling and simulation are usually required to assess system performance and identify potential issues for new HVDC connection during planning, design, commissioning and system operation. Real-time control hardware-in-the-loop simulation that uses converter control replicas interfaced with models running at real-time is the most effective way to reproduce near real system operation conditions for testing, performance evaluation and validation. Due to the complex structure of HVDC converters and existing control dynamics that spread over wide time-scale, the frequencies of interest for networks with significant converter penetration span a wide range, which demands much more detailed and accurate converter and system models when compared to those for traditional power system studies.

To study the performance and dynamic response of a real system, vendor-specific models from manufacturers are required. However, such models are usually provided as "black-box" models with predefined inputs and outputs, and with no access to the internal converter structure and system control by the users. The restricted access to key internal converter and control system variables that describe system dynamics may hinder understanding of potential issues that may arise at converter and system levels from continued evolution of the power network. Therefore, to aid future network development, and identify potential problems and solutions with large renewable generation and HVDC connection, it is essential that accurate and high fidelity converter models are available for system studies.

Recent modular and hybrid multilevel voltage source converters for HVDC applications have adopted the concept of modular power electronics building blocks that employ thousands of semiconductor switching devices and capacitors, with each building block or submodule contains few switching devices and capacitors. Such an approach has enabled scalability of a single converter to significantly higher voltages and rated powers such as 640kV and 1000 MW. However, the exponential increase in the numbers of submodule makes their modelling and understanding of their dynamics increasingly challenging.

Project Objectives

The main objectives of the project are to develop detailed and accurate offline and real-time RTDS models of modular multilevel converters (MMC) and DC grids. Such models deliver a useful platform for a variety of offline and real-time studies to be carried out with reasonable accuracy and reduced computation time suitable for real-time implementation. The models also provide building blocks for the UK National HVDC Centre and wider community to further develop generic and detailed power system models for a wide range of studies beyond that possible with manufacturers' confidential "black-box" models (due to their restricted access).

A. Development of offline and real-time sub-module level MMC models

Detailed submodule (SM) level half-bridge (HB), full-bridge (FB) and hybrid MMC models with an adjustable number of SMs per arm and generic and customized control functions are developed and validated against benchmark models from PSCAD and RSCAD software libraries. The developed MMC models can facilitate testing of MMC control and protection solutions in offline and real-time, offer the users the means to investigate further potential performance improvement and use as a strong basis for explorations of multi-vendor schemes. The benefit of these developed user-defined converter models comes from their unrestricted access to all converter and control system variables, which will allow the users to improve further and modify to achieve any control objectives at device and system levels.

B. Development of offline and real-time DC grid models in PSCAD and RTDS environments

Multi-vendor and multi-terminal DC grid with different converter topologies poses significant challenges in terms of system operation, coordination and protection. This work develops offline and real-time three-terminal DC grid models are closely resembling the Caithness-Morey-Shetland HVDC system to investigate DC grid power flow control during steady state and AC faults. The models provide platforms for further investigation into DC grid operations with different DC voltage control and power dispatch strategies, the interaction of AC and DC grids including voltage and/or frequency stability, system protection, integration of renewables etc.

Methodology

MMC in HVDC applications typically contains hundreds of submodules (cells) per arm and modelling a detailed MMC with such large numbers of SMs is very challenging. Modelling each SM using detailed switching model is not practical due to the extremely slow simulation speed. In recent years, a number of modelling methods that aim to address the aforementioned modelling challenges have emerged, namely, switching function model, averaged model and an extension of Dommel pre-solved integration method (also known as Thevenin or Norton Equivalent).

Although Thevenin equivalent method is widely known and used in established simulation tools such as PSCAD, many have recognized the computational superiority of the switching function models over the Thevenin equivalent, and as a result switching function based models have started to displace the Thevenin equivalent in many offline and real-time platforms. Information wise, both switching function and Thevenin equivalent models account for detailed dynamics of modular and hybrid multilevel converters from SMs' levels, and therefore, they are capable of reproducing detailed behaviours of converters as detailed switching model during both normal and abnormal conditions such as AC and DC faults. However, retention of detailed behaviours at SM levels plus incorporation of capacitor voltage balancing methods have significant impacts on simulation speeds and memory requirements, and in the determination of the minimum simulation time-step needed in order to observe high-frequency dynamics in AC and DC sides. As a result, the switching function and Thevenin equivalent modelling methods are well-suited for detailed design and protection simulation studies of power systems that contain a fewer number of full-scale modular and hybrid HVDC converters, where submodule level dynamics and stresses are of interest.

If the internal dynamics within MMC converters are not of interest, the averaged models that account for average dynamics of the converter arms are well suited, and especially, for system level dynamic studies of large power systems that contain a large number of HVDC converters and synchronous machines. In such studies the averaged MMC models offer significant computation advantages such much faster simulation speeds and low memory requirement.

For validating the developed user-defined MMC models, model validations are carried out by comparing the steady-state and dynamic responses, as well as responses during large transients, e.g. symmetrical and asymmetrical AC fault, pole-to-pole and pole-to-ground DC faults, among the developed models and those provided by PSCAD and RSCAD under identical operating conditions and control systems.

Model Development

The project has developed a number of high fidelity PSCAD (off-line) and RTDS (real-time) models for half-bridge (HB) MMC, full-bridge (FB) MMC, and hybrid MMC which comprise mixed HB and FB SMs using different modelling techniques. Typical converter controls are incorporated into the converter models including: active power, reactive power, AC voltage, DC voltage control, circulating current and horizontal and vertical capacitor voltage balancing (also known as phase and arm energy balancing) controllers, and DC fault current control for FB- and hybrid MMCs.

A. PSCAD MMC models

HB-MMC: Averaged, Thevenin equivalent and switching function models

FB-MMC: Averaged and switching function models

Hybrid MMC: Average model

B. RTDS MMC models

HB-MMC: Averaged and switching function models

FB-MMC: Averaged and switching function models

Hybrid MMC: Averaged model

Models for a three-terminal HVDC network resembling the future Caithness-Morey-Shetland HVDC system have also been developed to investigate the suitability of the developed user-defined models and controllers for DC grid simulation studies, with two of the converter terminals connected to AC grids and third terminal (Shetland) connected to a wind farm.

C. DC Grid models

PSCAD and RTDS 3-terminal DC grid models using averaged HB MMCs

Project Findings

Based on the extensive simulation studies performed in this project, it has been concluded that the developed user-defined averaged, switching function and Thevenin equivalent MMC models with generic controllers are well-suited for a wide range of electromagnetic transient studies, and in particular:

- The three MMC models produce practically identical results during a wide range of steady-state and transient system operation including AC and DC faults. The developed converter models provide unrestricted access to all converter and control system variables allowing the users to improve further and modify to achieve any control objective at device and system levels.
- The averaged model has the highest computation efficiency and for the tested simulation cases, its simulation speed is 2.5 times and 6.5 times of those of switching function and Thevenin equivalent models respectively.
- As Thevenin and switching function models are capable of reproducing the inter-submodule and inter-arm dynamics with sufficient accuracy, they can be used for detailed sizing of active semiconductor switches and passive components such as SM capacitors and arm inductors as they account for the impact of modulation and capacitor voltage balancing.
- The averaged MMC model is suitable for simulation studies that involve a large number of MMCs such as multi-terminal DC grids. However, the averaged MMC model ignores the inter-submodule dynamics and effects of capacitor voltage balancing during its development. Therefore it is not recommended for detailed power electronics studies such as components sizing as it does not retain information at SM levels.
- FB and hybrid MMCs can provide full control of DC and AC current during DC faults conditions. The developed models can be used for a variety of system studies with high computational efficiency and accuracy examining the enhanced control and operation provided by FB and hybrid MMCs in future DC grids.

The development and analysis of the three-terminal DC grid based on averaged HB MMC converter model emphasis on the different control modes for the system operator that offer different system response and dynamics during normal steady-state operation and AC faults, and in particular:

- The developed MMC converter models are well suited for use in DC grid studies with high fidelity and control flexibility, and can be connected to AC networks and island wind farm systems.
- DC grid operated with conventional control method where one of the converter terminals strictly regulates the DC voltage at a specified value, with the remaining converters regulating active powers, potentially risks total loss of controllability due to severe DC over- or under-voltage during faults on the AC side of the DC voltage controlling station.
- Using droop control to modify the power orders of the power controlling terminals according to DC voltage variation enhances DC voltage regulation during AC fault conditions and provides power sharing among the connected AC grids.
- The developed DC grid model provides excellent flexibility for further investigation into DC grid operations with different DC voltage control and power dispatch strategies, the interaction of AC and DC grids including voltage and/or frequency stability, system protection, integration of renewables etc.