	Strathclyde Engagement with the National HVDC Centre: Phase 2 Assessment and Mitigation of Converter Interactions

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1. Project background

The rapid growth in the amount of converter-interfaced renewable sources and HVDC transmission links is significantly changing the characteristics of the GB power grid. The wide timescale control dynamics of converters located in close vicinities can result in coupled effects among the converters and power networks, and can lead to oscillations across a wide frequency range. The gradual reduction of conventional synchronous machine based generations in the GB network will further increase the risk of interactions among HVDC converters and with other actively controlled system components such as wind farms, conventional power stations and FACTS devices. Hence, developing effective methods to identify the source of resonance and to mitigate the stability problems becomes critically important. To assess the system stability and dynamic interactions between grid and converters, the impedance-based stability analysis is an effective method of identifying potential frequencies of disturbance to which an individual converter may be vulnerable to destabilizing behaviour. By using the equivalent impedance of the grid and converters, the system can be considered as an equivalent closed-loop negative feedback system. Thus, the stability assessment can be carried out by applying the Nyquist stability criterion. This method is easily applicable even for systems with delays and other non-rational transfer functions, which may appear difficult to analyse by means of other methods. The method can also be applied for complex systems with multiple inputs and multiple outputs, as in grid connection converter systems.

However, in practice because of the limited accuracy of the frequency dependent models currently available to this analysis, other than identifying the potential mode of instability and its potential presence within a network it has been a challenge to practically define specific conditions where interaction may arise. This has driven to extensive complimentary EMT analysis or analysis restricted to post event study. Due to inherently complex behaviorr of modular multilevel converters (MMCs) such as internal circulating current and submodule (SM) capacitor voltage ripple, accurately modelling the impedance or admittance of MMC is a challenging task. However, the consequences of not modelling these aspects leads to a displacement or deletion of frequencies of interaction and a misestimation of the magnitude of the impedance changes at those points. An alternative way to obtain converter impedances is the use of frequency sweep method in time domain EMT models. However, the accuracy of the obtained impedance measurement from such models can be significantly affected by the setup in the models including the power circuits and controllers, simulation time steps, etc. Therefore, to gain sufficient confidence in the measured impedance and to gain in-depth understanding of the impact of operating conditions and controller setting on MMC impedance and system stability, developing analytical impedance models becomes necessary.

2. Project Objectives

The main objectives of the project are to develop frequency domain network/converter models adequate for small signal stability analyses, time-domain validations of stability assessments, and recommendations for specification and operation requirement when obtaining frequency domain HVDC converter models.

A. Development and validation of impedance-based HVDC system models

Small signal impedance-based MMC models are developed for assessing stability and interactions between converters. The developed analytical small signal MMC models are validated by comparing to the impedances measured from the Simulink and RTDS time domain models using frequency injection/sweep method. Converter impedances for different operating points and control modes are investigated.

B. Development of typical network configuration based on RTDS simulation

Based on the existing simplified 8-bus GB dynamic network model in RSCAD, network representations are developed to reflect real case converter interaction scenarios for analytic stability assessment. A methodology of obtaining network impedance based on time domain simulation is developed and assessed.

C. Impedance based stability assessment

Based on Nyquist stability criterion, the developed simplified network representation and converter impedance models are used to assess stability and interaction of multiple HVDC converters, and to identify potential resonances and instability. Moreover, RTDS time-domain simulations are used to further corroborate the results of frequency domain analyses.

D. Recommendations for frequency domain model of HVDC converters

Recommendations for frequency domain modelling of HVDC converters for stability and system interaction studies are provided. It aims to support the wide stakeholders to adequately set the specifications for vendor-specific frequency domain models that may be required to conduct stability studies to assess the risk associated with future deployments of HVDC systems in GB Network.

3. Methodology

Conventional small signal modelling methods consider the same frequency component for the state variables, and the inputs and the outputs, indicating that a specific frequency input will only generate an output at the same frequency. However, due to the existence of significant steady-state harmonic components in the arm currents and capacitor voltages of MMC converters, it is necessary to consider the MMC internal dynamics and harmonic interaction in the small-signal modelling. This means that an input at one frequency will generate outputs at multiples frequencies (commonly called as harmonics). Thus, the conventional modelling methods become unsuitable and harmonic state space (HSS) modelling technique which considers multi-harmonic interactions is used to develop the analytical MMC models. The HSS modelling simultaneously represents multiple frequency responses in each variable and leads to multidimensional harmonic transfer function based models.

Recently, HSS method has been used to model MMC impedance for stability assessment considering the impact of the internal harmonics, though various problems and limitations still present in the existing modelling methods. Such problems are mainly related to the use of single-phase representation for a three-phase three-wire system, the inadequate representation of the three-phase couplings due to the use of dq-based current control and complex impedance matrices, which make them unsuitable for studying multiple converter interaction. The work thus focuses on the development of accurate MMC impedance model in sequence positive-negative (PN) frame in simplified form suitable for stability analysis. The impact of operating point (active and reactive power set points), outer loop control (active and reactive power control, active power and AC voltage control), and controller turnings (e.g. PLL bandwidth) on MMC impedance and system stability are assessed.

Since converter system stability investigated here is primary related to voltage and for multi-infeed systems, voltage interaction among converter stations can significantly affect system stability. Therefore, in this study, the multi-infeed interaction factors (MIIF) which reflect the relationship between the voltages of converter station AC buses is thus used. Interaction of converters and stability of system with multiple converters in close proximity are studied using the developed models considering MIIIF. However, other measures and indexes, e.g. ESCR may also be used and will be explored in future studies.

4. Project Findings

The project has developed analytical methods to model the small signal impedance of MMCs, the measurements of converter and network impedance from time domain simulation models, stability assessment of single and multiple converters. The main findings are summarized as follows.

On MMCs impedance modelling:

- Significant coupling among the internal harmonics, and between the positive- and negative-sequence brought by external control loops and PLL. To accurately represent the impedance model, sufficient internal harmonic orders (e.g. the 4^{th} harmonics) when using the HSS method must be considered.
- MMC impedances are highly dependent on the operating point (active, reactive power, AC voltage etc.), control structure (PQ, PV control etc.) and control parameters. Thus, in the event of any changes to the parameters at different project stages, it is necessary that the corresponding MMC impedances are revised accordingly to ensure accurate stability analysis.

On AC network impedance measurement:

- The measured impedance of existing AC network model with large synchronous generators is largely inductive, and the dynamics of the synchronous generators and their controls do not affect the impedance of the system seen at the converter connection point due to the fact that their impact frequency (below ten hertz) is much lower than the frequency of interest for converter stability (from tens hertz to hundreds hertz).
- Four different load models provided by RSCAD, i.e., constant power load, polynomial load, ZIP load and exponential load, produce almost identical impedance results due to the large time constant used in RSCAD simulation (0.01s) for determining the variation of load impedance. Thus the traditional method used for load modelling in power system simulation may not be adequate for frequency domain converter interaction analysis.
- The measured network admittances with AC cables show resonances, and the longer the AC cable, the lower the resonance frequency. Thus AC cables in networks need be properly considered for stability analysis.

On stability assessment of single converter system:

- High PLL bandwidth generally reduces the magnitude margin and phase margin of the grid connected MMC system and results in reduced system stability.
- System with PQ outer-loop control tends to be more stable than that with PV control. However, this needs to be closely assessed for particular operating condition and system configuration.
- High active power reduces system stability whereas system instability is more likely to be induced in rectifier operation than inverter operation.
- System stability is affected by multiple factors as described, and thus, the full converter system must be considered when deriving converter impedance and conducting stability assessment.

On stability assessment of multiple converters:

- As voltage interaction among converters can significantly affect system stability, the multi-infeed interaction factors (MIIF) which reflect the relationship between the voltages of converter buses is a useful index when considering multiple converter interactions.

- System with high MIIF where strong couplings between the two MMCs exist is more likely to be unstable than system with low MIIF.
- Similar to the single MMC system, the converter outer loop control, e.g. PV and PQ control, also has significant impact on system stability and needs to be closely examined.

The studies and results presented in the report including the validation using the RSCAD and Simulink time domain models provide confidence of the obtained impedance models using both theoretical analysis and measurement using frequency sweep method, and the effectiveness of the stability assessment method. The work provides solid foundation for further studies to identify states where risk of instability may exist in a multi-infeed converter system, so as to help inform operating away from those network or converter operating states.

5. Guidance on obtaining converter impedance from EMT models

During different stages of a HVDC project, e.g., planning, tender/bid process, post award, and commissioning, various system stability analysis by the developer, ESO and OEM, are carried out. The project has demonstrated the effectiveness of using the presented method for stability assessment, and in the same time highlighted the need for accurate frequency dependent converter impedance model. It is likely that vendor specific frequency dependent converter models will be obtained using frequency sweep measurement based on detailed time domain EMT models in PSCAD or RSCAD. The follow general guidance are provided to ensure the accuracy of the obtained converter impedance.

On EMT simulation model set up:

- The EMT model of the MMC has to contains the full set of controllers including both the inner and outer loops, and control parameters match those to be used in real system;
- Simulation time step needs to be sufficiently small (e.g. less than 10μs) to ensure correct frequency response. When multiples simulation time steps are used (e.g. in RSCAD models), the parts of the system which encounter significantly multiple harmonic interactions, e.g. MMC arms, SM capacitor voltage calculation etc., need to be simulated in a small time step (e.g. 2.5μs) whilst the main control system could be in large time step (e.g. 50μs).

On MMC operation mode and operating point:

- Different operation modes, e.g. PV control, PQ control etc. significantly affect MMC impedance and full consideration of all possible operation scenarios must be given when obtaining the impedances;
- Different operating point, e.g. active/reactive power (both magnitude and direction) and AC voltage, affect MMC impedance. Therefore, wide ranges of impedances are required considering different operating points. If only limited number of studies are permitted, MMC impedances with maximum active power (both rectifier and inverter operation) need to be priorities since system stability is likely to be weak under such conditions.

On impedance measurement using frequency sweep method:

- Measurement accuracy can be impacted by existing small oscillations/transients in the EMT models and therefore, sufficient simulation time must be given for each injected perturbation before measurements are taken;

- The injected perturbation voltage magnitude must be sufficiently large to ensure good signal-to-noise ratio, while in the same time the normal operating point of the system is not affected. A magnitude in the range of 3 to 5% of rated system voltage has been found to be adequate.
- To obtain the impedance matrix in PN frame, separate injections of positive and negative sequence perturbations for each frequency must be adopted to ensure accuracy.