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Executive Summary

The report is made in response to the agreement between National HVDC Centre and Cardiff University (CU) on the Grid Code Compliance project. Both parties have been working diligently on modelling and simulation activities to accurately represent high voltage direct current (HVDC) based resources in dynamic stability analyses and explore the impacts of varying grid strength on the GB Grid Code connection requirements. This report outlines the activities of CU related to modelling and studies performed on an embedded HVDC link in an offline simulation environment (PSCAD/EMTDC) and validation using real-time experiments (RSCAD/RTDS). These activities are based on the following activities of CU:

- *The convertor model for HVDC link with representative MMC and control structures and realistic control modes and system measurement.*
- *The network test model capable of defining conditions of grid code test as presented to a manufacturer*
- *The network test scenarios capable of defining different grid strength, operating condition, stable, marginal and unstable cases*
- *Sensitivity analysis capable of defining different control approaches, measurement and control modes/priorities*
- *The experimental validation identifying synergies between offline and real-time operation and to understand the uncertainties related to weak grid representation.*

A list of key findings and recommendations from the project activities and from the literature that has occurred in the past couple of years is outlined below. These findings are separated into three distinct categories: System strength-based findings, Grid Code specification study findings, and technical discussions and industry work-related to dynamic modelling need-based findings.

- **System Strength based Analysis and Findings:** These findings highlight the technical risks emerging due to increased penetration of HVDC's and DC connected power plants into the power system mix. Out of this single point failure risks, as network conditions change- and more complex designs emerge is the primary challenge incurred due to reduced system strength compared to a string grid. Moreover, tracking and managing changes occurring over a lifetime has become ever more important due to declining system strength or short circuit level (SCL) at different parts of the network. These changes have given rise to the hidden project interactions, project behaviours and vulnerabilities related inverter-fed generations and in general and to HVDC in particular. Instances of such hidden project behaviours are emerging in the power system, the black system event in Australia in 2016, the low-frequency demand disconnection an event in the GB power system in 2019 to name a few. To this end, through this project we tried to identify the compliance and completeness of codes & standards & data exchange in the current GB Grid Code related to system strength specification in particular to HVDC connections. More specifically in the future with increased uptake of HVDC is expected how the system strength contributes to converter connections and performances, what is the potential risk and how this is currently reflected in the GB Grid Code. It has been found that Short Circuit Ratio (SCR) based analysis can be used to quantify system strength when mandating new connections, however, it is not clear how other convertors will contribute to the system strength; or how this will be reflected into SCR values. Moreover, it has been identified that the GB Grid Code does not demonstrate a min/max SCR at the PCC during the connection process- which will change across the operation. In addition, it is not clear how the technical issues related to system parameter regulation and instability are tracked or revised using converter control re-tuning**.** This raises the question on the accuracy and reasonability of dynamic model parameterization that may be overlooked by system operators due to lack of understanding of the dynamic models, insufficient processes to assure that they have obtained the best available models, and lack of tools to effectively check their validity. This leads to the recommendation on the need to update system modelling and connection requirements of the HVDC schemes low system strength zone as the base cases as quickly as possible with accurate dynamic modelling information from other equipment manufacturers (OEM's) to ensure security and stability studies are accurately identifying potential reliability issues.

- **Grid Code requirement Analysis and Findings:** It is yet to be highlighted that from the list of Grid Code compliance studies/ testing needed to be performed and/or submitted with a new connection request which should be system strength depended. In general, it can be argued that Grid Codes are experience-based- but the experience is changing, but the question remains how and where to map these changes in the current codebase. Out of the main requirements, active power, reactive power, frequency control, voltage regulation and fault ride-through (FRT) demands particular consideration in when system strength-based analysis is considered. Among others, FRT has analysed in detail in this project dues to its dependency on not only system strength and control system but also on its interaction with other system parameters (active power, reactive power and inertia). One of the significant tasks within the project was to look at how different phase-locked loop (PLL) devises impacts the FRT requirements of the HVDC connection when the grid strength is varied using different SCR values. Moreover, the interaction of the HVDC system with a grid with varying grid strength is analysed for different fault types, fast fault current (FFCI) injection schemes and post fault recovery rates. These analyses were performed for stable (SCR=15), marginal (SCR=5) and very weak grid (SCR=2) operation. The study found that different PLL choices and their tuning influence the performance and resilience of the converter, however it is not clear in current Grid Code how data exchange and what choices are being made and what consequences these have. The analysis presented has identified that the most essential concern is the delayed active power recovery of resulting in the inability to follow existing grid code requirements and causing a potential risk of voltage dip induced frequency dip (VDIFD) phenomenon. The grid code requires active power priority to a certain extent which addresses the primary threat posed by the initial power deficit. FFCI service should be focused on mitigating fault propagation and needs to be incentivized for faster response, which will limit the extent to which the secondary threat of delayed recovery stresses other system parameters such as frequency and active/reactive power oscillations. Besides, from fault studies, it was inferred that three-phase to ground fault (3LG) is more severe and pose potential risk to system stability with weak grid operation, however, single line to ground faults are challenging still- and data exchange of models for this is not currently supported within Grid Code. Finally, FFCI compounds voltage regulation and power recovery challenges after a fault and needs to be deployed with care with increased level of retained voltage to provide better response and system stability (to a minimum level of 20% from the current level of 15% for 3LG fault). Different k-factor impacts the FFCI injection and thereby voltage support during fault and requires the careful selection to comply with existing Grid Codes and not drive new or additional instability- requires a balance of factors, which may be different for different network areas.

- **Technical Discussion Findings:** The study also identified an array of modelling issues that need to be addressed in a timely manner. These modelling issues are likely leading to some of the systemic challenges identified in the previous findings. The current Gb Grid Code verification and testing activities are not adequately verifying the dynamic models relative to actual installed equipment performance for a large disturbance response, leading to false expectations that these models are actually representative of installed performance. Incorrect parameterization of the dynamic models is likely caused by inaccurate modelling data provided by the manufacturers and lack of information sharing between the original equipment manufacturer (OEM), contractor, and system operators, and it is a contributor to many of the modelling issues. Similarly, the testing requirement does not mention types of power system models needed for the detailed connection studies and only briefly mentions specification of requirements from a system point of view. Lack of specificity of modelling information may be leading to a lack of detailed studies prior to deployment. Furthermore, it is unclear in these procedures what constitutes a "viable adaptation" and how technological change procedures should apply when network constraints are identified due to these new connections. Specification on interconnection requirements should be broadly improved to ensure adequate modelling information is provided during interconnection and that any changes affecting the electrical performance of the facility are studied prior to implementation by the OEM. system-wide case creation practices will also need to evolve as instantaneous penetrations of inverter-based resources continue to increase. Many entities are experiencing a need for more advanced electromagnetic transient (EMT) modelling in areas of high penetrations of converter fed HVDC resources, and EMT simulations are becoming a standard practice during the interconnection processes. If the real implementation is unknown, the choice becomes a trade-off between dynamic performance and implementation complexity. Whenever priority is the performance following a large disturbance, EMT based screening is recommended.

Cardiff University delivered the project for 8 months from April 2018 to February 2019 with four deliverables split at 2 months each. A final dissemination event was delivered with National HVDC center on March 20th, 2020 which attracted more than 120 participants.