Notes on Completion: Please refer to the appropriate NIA Governance Document to assist in the completion of this form. The full completed submission should not exceed 6 pages in total.

Network Licensees must publish the required Project Progress information on the Smarter Networks Portal by 31st July 2014 and each year thereafter. The Network Licensee(s) must publish Project Progress information for each NIA Project that has developed new learning in the preceding relevant year.

NIA Project Close Down Report Document

Date of Submission

Jul 2024

Project Reference Number

NIA2_NGESO009

Project Progress

Project Title

'D3' - Data-driven Network Dynamic Representation for Derisking the HVDC and Offshore Wind

Project Reference Number

NIA2_NGESO009

Project Start Date

February 2022

Project Duration

2 years and 2 months

Nominated Project Contact(s)

Dechao Kong

Scope

- Development of benchmark testing system in PSCAD/EMTDC Environment for complex power networks with integration of typical Power Electronics Based HVDC and Wind Generation systems.
- Development and validation of frequency-dependent power system model for identifying potential interaction risks.
- Development and validation of advanced model reduction technique to reduce the high-order frequency-dependent model to low-order power system one for system representation, to achieve a good balance between system accuracy and computational efforts via comprehensive data-driven simulations.

Objectives

This project will aim to bridge the current gaps, through the development of new models and technical reports which will mitigate risks when adding new power electronic equipment to the system.

The final outputs will be:

- Developed Testing system and models in PSCAD/EMTDC environment.
- Technical reports for each WP.
- Final project report
- International journal/conference publications.
- Dissemination event to share the outcomes of the project with stakeholders.

Success Criteria

The following will be considered when assessing whether the project is successful:

- Impact on ESO risk management processes
- Contribution to behind the meter DSR regulation processes
- The project delivers against objectives, timescale and budgets as defined in the proposal

- ESO's in-house capability is improved for addressing Control-Interaction challenges
- Knowledge and tools developed in this project can be replicated across network partners to facilitate the increased integration of HVDC and PE systems into GB Electricity Transmission System.

Performance Compared to the Original Project Aims, Objectives and Success Criteria

Project Summary

The project aimed to address the emerging challenges in the Great Britain (GB) electricity network, which is rapidly integrating power electronic-based High Voltage Direct Current (HVDC) and renewable generation systems. These integrations pose significant risks of control interactions between new and existing power electronic equipment. Manufacturers and owners of these systems require detailed grid dynamic models from National Grid Electricity System Operator (ESO) to adjust control parameters and mitigate these risks. However, sharing detailed system information is challenging due to the complexity, confidentiality, and intellectual property issues associated with the system models. This project developed advanced tools to obtain accurate grid dynamic models without revealing confidential data, thus enabling secure sharing with external stakeholders. The project involved three main phases: developing a benchmark system, creating a frequency-dependent power system model, and applying a data-driven method for model order reduction.

Work Package 1 (WP1): Development of Benchmark Testing System

The first work package focused on developing a benchmark testing system in the Power Systems Computer Aided Design/Electromagnetic Transients including DC (PSCAD/EMTDC) environment, integrating typical Power Electronics-based HVDC and Wind Generation systems. This work package aimed to establish a comprehensive screening methodology to identify and prioritise potential control interaction risks in a large, complex, inverter-based resource (IBR)-dominated network.

Throughout WP1, the project team successfully developed two benchmark test systems within the PSCAD/EMTDC environment for complex power networks. These systems incorporated HVDC and Wind Generation systems, allowing for detailed analysis of system interactions. Calculations for Short Circuit Level (SCL), Short Circuit Ratio (SCR), and Effective Short Circuit Ratio (ESCR) were performed based on a measurement approach. It was found that the parameters of Phase-Locked Loop (PLL) significantly impact the stability of power systems. The project team assessed a series of network models based on the modified two-area four-machine test system under different grid strength scenarios. Additionally, a simplified Southeast network was developed with alternating current (AC) and direct current (DC) link-connected wind farms. The dynamic responses of the test systems with synchronous generators, HVDC, and wind farms under system short-circuit faults were observed and compared across different renewable energy penetration levels. The results revealed that high levels of renewable energy penetration pose a threat to system stability and significantly slow down electromagnetic transient (EMT) simulation speeds using PSCAD/EMTDC.

Work Package 2 (WP2): Automation on Impedance Measurements and Stability Analysis

The second work package focused on developing and validating a frequency-dependent power system model and its automation toolbox. This model, based on a single operating point, was validated through EMT time domain simulation and Fast Fourier Transform (FFT) for various test system scenarios. The frequency domain impedance methodology proposed in this work package allows for identifying system oscillation modes and justifying whether they will lead to system instability.

In WP2, the project team developed a transfer function-based impedance methodology to identify potential risks between inverters using the Multiple Infeed Interaction Factor (MIIF) index. This method categorizes risks into high, medium, and low, demonstrated through a complex network case study. For priority cases, in-depth frequency domain impedance modelling was conducted. The interconnected system was perturbed with voltage injection in PSCAD/EMTDC, and measurements of harmonic current and voltage at the Point of Common Coupling (PCC) were taken. MATLAB was used for processing measurement data, and Python scripts were employed for automation, ensuring a streamlined and efficient process. The validation methods, including FFT and time domain EMT simulation, verified the proposed automation toolbox for transfer function-based frequency domain impedance modelling. Case studies with different test system scenarios confirmed that the EMT simulation results matched the impedance model analysis.

Work Package 3 (WP3): Data-Driven Network Dynamic Representation
The third work package aimed to develop and validate a model reduction technique using a data-driven approach. This technique reduces the high-order frequency-dependent model to a lower-order power system representation, balancing system accuracy and computational efforts.
WP3 utilized a data-driven method to cluster data over multiple operating points and generate an aggregated transfer function for a more robust model. The open-source software Scilab was adopted for data processing, providing an alternative to MATLAB. The project team enhanced the multi-run functionality in PSCAD with Python, enabling the setup of multiple operating points and automating the process to avoid errors and improve efficiency. The aggregated transfer function met user-defined accuracy thresholds. This approach created a comprehensive and efficient model reduction, facilitating further analysis by manufacturers. The large amounts of impedance data sets were clustered according to the user-defined threshold, and the aggregated transfer functions were delivered to the manufacturer for further analysis.
Conclusion and Future Work
The project successfully met its objectives, developing advanced tools for obtaining accurate grid dynamic models without revealing confidential data. These tools enable secure sharing with external stakeholders, addressing control interaction risks in a power electronics-dominated network.
The development of a benchmark testing system in WP1 provided a solid foundation for understanding the dynamics of power electronics-integrated networks. WP2 advanced the project's goals by automating impedance measurements and stability analysis, allowing for a detailed examination of system interactions and stability risks. WP3 concluded the project's technical work by applying a data-driven approach to model reduction, ensuring a robust and efficient representation of the power system across multiple operating points.
Future work will involve disseminating project outcomes more widely, obtaining feedback from stakeholders, and selecting manufacturers to trial the proposed models. This will lead to wider adoption and potential Grid Code changes, enhancing ESO's capability to manage control interactions and integrate HVDC and PE systems into the GB Electricity Transmission System. The state-of-the-art data-driven approach developed in this project can be rolled out for future power system stability studies, supporting ESO's transition to a zero-carbon energy system.

Required Modifications to the Planned Approach During the Course of the Project

No changes were required to the planned methodology throughout the course of the project.

Lessons Learnt for Future Projects

The D3 project has highlighted several critical lessons for managing control interaction risks and ensuring system stability. Through the development and application of advanced tools and methodologies, several key insights have emerged that are vital for future projects.

First and foremost, the necessity of a robust screening methodology to identify and prioritise control interaction risks in complex, inverter-based resource (IBR) dominated networks was clearly demonstrated. Developing benchmark systems that accurately simulate these interactions provides a solid foundation for understanding the dynamics of power electronics-integrated networks. This preliminary step is crucial before delving into more sophisticated modelling and analysis.

The adoption of a transfer function-based impedance methodology has proven invaluable for identifying potential risks between inverters. This method, enhanced by automation tools, allows for a detailed examination of system interactions and stability risks. By employing a frequency domain impedance model validated through various simulation techniques, future projects can more accurately predict and mitigate stability issues. This approach also underscores the importance of automating processes to enhance efficiency and accuracy, reducing the likelihood of human error and expediting the analysis.

Another significant lesson is the effectiveness of data-driven methods for model reduction. These techniques enable the aggregation of large data sets across multiple operating points, resulting in a lower order, yet accurate, representation of the power system. Utilising open-source software and enhancing functionalities with programming tools such as Python can streamline this process, making it more accessible and efficient. This approach not only ensures robust modelling but also facilitates easier integration and analysis by external stakeholders.
Future projects should also consider the broader implications of their methodologies and tools. Disseminating outcomes, obtaining feedback from stakeholders, and trialling models with manufacturers are essential steps for wider adoption and potential regulatory changes. The successful application of these advanced tools and techniques can significantly enhance the capability of system operators to manage control interactions and integrate HVDC and power electronics systems, supporting the transition to a zero-carbon energy system.

In conclusion, the lessons learned from this project emphasize the importance of a structured, automated, and data-driven approach to managing the integration of renewable energy and HVDC systems. By adopting these strategies, future projects can achieve greater accuracy, efficiency, and stability in power system operations, paving the way for a more resilient and sustainable energy network.

Note: The following sections are only required for those projects which have been completed since 1st April 2013, or since the previous Project Progress information was reported.

The Outcomes of the Project

The outcomes of the project can be summarised as:

Developed testing system and models in PSCAD/EMTDC environment.
Harmonic injection and measurements module which is applicable for power electronic devices.
Impedance-based stability analysis using an automation toolbox for identifying potential interaction risks.
Development and validation of the model reduction technique. The data-driven approach is adopted to build the reduced order model for the power system under multiple operating points to achieve a good balance between system accuracy and computational efforts.
'D3' Technical report 1: Benchmark power system with HVDC and wind farm.
'D3' Technical report 2: Automation on impedance measurements and stability analysis.
'D3' Final project report: 'D3' - Data-driven Network Dynamic Representation for Derisking the HVDC and Offshore Wind.

Following that:

Internal Dissemination:
WP1 Knowledge Dissemination Event on 30 September 2022;
WP2 Knowledge Dissemination Event on 30 April 2023;
Training session 1: Harmonic injection and impedance measurements on 28 September 2023;
Training session 2: Data-driven based eigenvalue cluster and aggregation on 3 October 2023;
Training session 3: Automation simulation and analysis on 5 October 2023;
Final Knowledge Dissemination for WPs 1-3 on 10 November 2023.

External Dissemination and Publications:
A series of publications following knowledge and capability as built through this project has been published and/or are under development with acceptance of Abstract.

S. Dai and X. -P. Zhang, "Advanced Identification Methods for Power System Oscillations based on Measurements," 2022 IEEE 16th International Conference on Compatibility, Power Electronics, and Power Engineering (CPE-POWERENG), Birmingham, United Kingdom, 2022, pp. 1-6, doi: 10.1109/CPE-POWERENG54966.2022.9880879.
C. Wu, X. P. Zhang, X. Zhou and D. Kong, "Comparative research on DC braking choppers for VSC-HVDC with offshore wind farms," 19th International Conference on AC and DC Power Transmission (ACDC 2023), Glasgow, UK, 2023, pp. 45-51, doi: 10.1049/icp.2023.1306.
D. Li and X. P. Zhang, "An online power system voltage stability index for a VSC HVDC using local measurements," 19th International Conference on AC and DC Power Transmission (ACDC 2023), Glasgow, UK, 2023, pp. 160-165, doi: 10.1049/icp.2023.1324.
S. Dai, C. Wu, D. Li, D. Kong, X. Zhou, and X. P. Zhang, "A Methodology to Derisk HVDC and Offshore Wind Connections to a Network", CIGRE Paris Session 2024. (Synopsis was accepted)

The Case Study of D3 project has also been captured into ESO's Network Innovation Allowance – Annual Summary 2021/22.
https://smarter.energynetworks.org/media/j0ik3ue5/ngeso_nia_annual_summary_2022.pdf
https://reports.nationalgrideso.com/innovationannualsummary/ .

Data Access

Details on how network or consumption data arising in the course of NIA funded projects can be requested by interested parties, and the terms on which such data will be made available by National Grid can be found in our publicly available "Data sharing policy related to NIC/NIA projects" and www.nationalgrideso.com/innovation.

National Grid Electricity System Operator already publishes much of the data arising from our NIC/NIA projects at www.smarternetworks.org. You may wish to check this website before making an application under this policy, in case the data which you are seeking has already been published.

Foreground IPR

The following Foreground IPR will be generated from the project:

- Development of benchmark testing system in PSCAD/EMTDC Environment for complex power networks with integration of typical Power Electronics Based HVDC and Wind Generation systems.
- Development and validation of automation toolbox with data driven approach to build frequency-dependent power system models for identifying potential interaction risks.
- Development and validation of advanced model reduction technique to achieve a good balance between system accuracy and computational efforts via comprehensive data-driven simulations based on multiple operating points/scenarios.

All of the completed reports outlining the approach and methodology will be uploaded onto the Smarter Networks Portal.

Planned Implementation

Following comments from a series of proactive stakeholder engagements through consultations and knowledge dissemination events, the following activities are proposed for transforming D3 project outcomes into effective inputs into ESO's Business as Usual (BAU) activities for risk management of control interaction in future GB system with potential high penetration or event dominance of Inverter-Based Resources (IBRs):

- The well-developed process, methodology and tools can be rolled out for more practical studies for GB regional network(s)
- Larger and more practical testing system can be developed to further validate the effectiveness of the methodology and tools
- In the long run, ESO to develop its own in-house automation tools e.g. based on Python as implemented for data-driven analysis instead of open sourced tools as identified from this D3 project as alternative to MATLAB.

Other Comments

In regard to the UK's net-zero implementation, more and more wind farms (expected total installations of 50GW offshore wind by 2030) and HVDC systems (expected installations of 18GW by 2030) will be integrated with GB electricity transmission system, the developed tool will support ESO to speed up project delivery. Therefore, the developed tool will contribute towards UK's net-zero target.

The following major benefits can be identified for this project.

- Benefit 1: Cost and time for ESO carrying out extensive system dynamic studies for new HVDC installations can be greatly reduced. The developed tool will significantly speed up project delivery of future renewable and HVDC projects, reducing project delivery time and cost. Expected total installations of offshore wind of 50GW and installations of HVDC interconnector of 18GW will be deployed by 2030.
- Benefit 2: The limitations imposed by complexity of system models, confidentiality, and IP issues on sharing system model with the manufacturers or HVDC and wind farm owners can be removed (Black-box approach for the HVDC/PE connectors).

Non-Financial Benefits are also identified as follows:

- The utilization of the developed tool would become a best practice for system operators in other countries, achieving a global impact.
- The outcome of the project will improve ESO capabilities to develop systematic methodologies to de-risk control interactions for future new HVDC/PE installations. The modelling tool and analysis results can help ESO engineers develop insight into the dynamics and stability of power electronic-dominated power systems.

Standards Documents