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NIA Project Close Down Report Document

Date of Submission

Jan 2026

Project Reference Number

NIA2_NGESO050

Project Progress

Project Title

Enhanced RMS (e-RMS) models for stability assurance

Project Reference Number

NIA2_NGESO050

Funding Licensee(s)

NESO - National Energy System Operator

Project Start Date

January 2024

Project Duration

1 year and 10 months

Nominated Project Contact(s)

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Scope

System-wide simulation with existing RMS models (e.g. 'GB-master') or localised EMT simulation often do not foresee IBR-driven instability problems. System-wide EMT simulation or co-simulation with vendor specific IBR models is an option but could be prohibitively slow and is unable to readily identify the root cause of the instabilities. In principle, an RMS model with adequate modelling detail and parameters tuned for the prevailing operating condition should capture instability problems within a certain frequency range, allow root cause analysis and hence, effective mitigation. In the context, this project would develop e-RMS model of IBRs as Digital Twin of a high-fidelity IBR model (in EMT) mimicking a real one. This way the operating point dependency of the RMS model of an IBR can be captured while addressing modelling adequacy in the sub-synchronous frequency range.

This project will enable the ESO to:

- Analyse stability of IBR-dominated systems with enhanced RMS modelling in PowerFactory
- Perform system wide studies for a much larger number of scenarios than what is possible with EMT simulation
- Use e-RMS models for planning and operational studies including near-real time applications
- Utilise root cause analysis to develop early warning systems and effective mitigation of potential instability problems.

With threats of unforeseen instabilities mitigated, higher fractions of renewables can be accommodated without compromising the security of supply. This will facilitate the net zero transition while ensuring secure and affordable supply for consumers.

Objectives

The specific objectives of the project are to develop:

- an e-RMS model of the equivalent GB test system with Digital Twins of IBRs driven by the EMT simulation model (as benchmark) mimicking the real system
- a methodology for validating the modelling adequacy and accuracy of the e-RMS model by replicating event response
- software tool for stability analysis, identification of the root cause of instability and early warning system – all based on the e-RMS model.

Success Criteria

The project will be deemed successful if the following criteria are met :

- Benchmarking the event response from e-RMS model against the EMT model
- Validation of root cause from e-RMS model against known disturbance trigger in EMT model
- Accuracy of early warning system, optimality of mitigation measure against IBR-driven instability

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

The overall objective of the e-RMS project was to establish modelling adequacy of IBR-dominated power grids, develop a method to analyse sub-synchronous oscillations (SSO) and validate the performance of the developed method. The work was structured under three technical work packages: WP1) Modelling adequacy of IBR-dominated grids, WP2) Root cause analysis of SSO using IBR digital twins, and WP3) Performance validation. Each WP has been successfully completed, with the outcomes largely meeting the original aims and success criteria.

WP1 – Modelling adequacy of IBR-dominated grids
A modelling framework was established to bridge the gap between the simplicity of RMS (positive sequence phasor-domain) models and the accuracy but heavy computational demand of electromagnetic transient point-on-wave (EMT-PoW or EMT-abc) simulations. The EMT-dq approach ('dq' stands for direct and quadrature axes of a synchronously rotating reference frame), formulated in a synchronously rotating dq reference frame, was implemented to accurately capture SSO with significantly reduced computational burden.

We successfully demonstrated that EMT-dq models retain similar accuracy as EMT-PoW for small-signal analysis of SSO while enabling frequency-domain interpretation of oscillatory behaviour which is something EMT-PoW does not readily support. Validation against EMT-PoW simulations on IEEE benchmark test systems confirmed the capability of EMT-dq to detect poorly damped SSO modes that RMS models fail to capture. This meets the WP1 objectives of developing an efficient, accurate, and scalable modelling method that captures SSO in IBR-dominated power grids.

WP2 – Root cause analysis of SSO
This work package aimed to establish a data-driven framework to estimate linearised, grey-box models of IBRs from black-box IBR models or connected to the rest of the grid model with known network topology and parameters. The Eigensystem Realisation Algorithm (ERA) was applied to the closed-loop pulse response of each IBR connected to the network, allowing estimation of its transfer function while connected to the simulation model of the rest of the grid. This avoids the need for tedious impedance scanning of standalone IBRs under a range of operating conditions.

Minimal realisation and model reduction techniques were employed to ensure scalability of the proposed method for large-scale systems. The estimated models were benchmarked against the known IBR reference models, and the frequency responses showed excellent alignment. Furthermore, the relative participation of IBRs in the poorly damped SSO modes and the electrical spread of SSO across the system closely matched that of the actual models, confirming the accuracy and interpretability. WP2 therefore met its aim of establishing and validating an early warning, vulnerability assessment and root cause analysis framework.

WP3 – Performance validation
The final work package focused on validating the proposed EMT-dq and SSO analysis methodologies on both standard IEEE test systems and a practical network case provided by NESO. Using IEEE 9-bus and 39-bus systems with 100% IBR penetration, both approaches were rigorously benchmarked against EMT-PoW simulations under varying operating points and control bandwidths. The EMT-dq method showed high similarity in both time- and frequency-domain analyses, while the digital twin approach reliably identified the IBRs with dominant participation.

Following NESO's recommendation, a reduced North Scotland transmission system was modelled in PSCAD for validation. Power flows matched closely with NESO's PowerFactory base case. However, despite extensive efforts (such as replacing more synchronous generation with IBR equivalents, altering IBR control bandwidths, and modifying system strength at the boundaries) the system remained heavily damped and did not exhibit the expected poorly damped SSO. This practical limitation, acknowledged by NESO, restricted the opportunity to validate the methods under SSO-prone conditions in North Scotland. Nonetheless, this outcome provided valuable insight into the difficulty of reproducing real-world SSO conditions in transmission systems with strong damping.

Overall, WP3 successfully delivered benchmark validation on IEEE systems and demonstrated end-to-end integration of the proposed techniques fulfilling the primary research and technical objectives of the project.

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

The validation of the methods developed in this project was originally planned on a 36-bus reduced equivalent of the GB transmission system. However, the 36-bus test system has zonal representation with different types of resources such as synchronous generators (SGs), inverter-based resources (IBRs) and loads within an area connected to a single bus representing that zone. This was deemed inadequate to capture poorly damped sub-synchronous oscillations (SSO) induced by adverse interaction among IBRs due to the possibility of collocated SGs with automatic voltage regulators (AVRs) masking relevant effects. Hence, a decision was made to use a reduced equivalent of transmission system in north of Scotland where poorly damped SSO have been observed on the ground in recent years. This was not meant to replicate the actual SSO events but just use a test case which is grounded in reality.

Lessons Learnt for Future Projects

Although use of pulse response in conjunction with eigensystem realisation algorithm (ERA) avoids tedious dynamic frequency scans and enables in-situ estimation of IBR models, it is challenging to use probing-based methods in a real system. Hence, 'probing-free' or 'offline probing' methods needs to be investigated and a suitable trade-off between zero (or less) probing and compromise in accuracy needs to be analysed.

In addition, theoretically guaranteed match between estimated and actual model at selected frequencies needs to be established. That way, one-shot multi-sine probing with sufficiently high frequency resolution will guarantee very close match to improve the accuracy of the estimated IBR models and hence, that of SSO analysis.

For the North Scotland test system, IBR plants need to be modelled properly with power plant controller (PPC) and voltage regulation device (STATCOM) at the point of interconnection. Such IBR plant models should be sanity checked by benchmarking the admittance spectra with respect to that of actual IBR plant models.

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

1. Two technical reports on 1) Modelling of North Scotland test system and 2) Modelling adequacy and analysis of SSO were delivered.

2. Algorithms and Matlab scripts for estimating IBR models and analysing root cause of poorly damped SSO were shared. A user interface was created and demonstrated to NESO.

3. A PSCAD model of a reduced equivalent North Scotland test case was developed with generic IBR models and network data and operating condition provided by NESO.

4. Two research publications on In-situ estimation of IBR models for SSO analysis; and RMS vs EMT trade-offs for SSO studies (https://ieeexplore.ieee.org/document/11082650) resulted from this project.

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 NESO can be found in our publicly available "Data sharing policy related to NIA projects (and formerly NIC)" and [Innovation | National Energy System Operator](#).

National Energy System Operator already publishes much of the data arising from our 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

Methods:

1. EMT-dq modelling in synchronously rotating dq reference frame validated against EMT-abc to perform frequency domain analysis
2. In-situ estimation of IBR transfer function
3. Identify the root cause and geographical spread of SSO

Tools

1. Algorithms and MATLAB/Simulink code for implementing above methods
2. A standalone Windows Application to perform root cause analysis and vulnerability assessment in EMT-dq domain

Reports and publications

Two final reports on:

1. Modelling adequacy and analysis of sub-synchronous oscillations
2. Modelling of North Scotland test system

Two publications:

> M. S. Javaid, B. Chaudhuri, F. Teng and Z. Akhtar, "EMT — RMS Modeling Trade-Off for IBR-Driven Sub-Synchronous Oscillations," in IEEE Transactions on Power Systems, doi: 10.1109/TPWRS.2025.3588893.
https://ieeexplore.ieee.org/document/11082650

> J. Gao, M.S. Javaid, D. Bhattacharjee, Y Chen and B. Chaudhuri, "In Situ Estimation of IBR Models for Analyzing Sub-S

Planned Implementation

The project demonstrated the potential of using pulse response in conjunction with the eigensystem realisation (ERA) algorithm to enable in-situ estimation of IBR models without the need for exhaustive dynamic impedance scans. However, practical implementation in real systems remains challenging due to the reliance on probing signals. The next step will be to develop and validate probing-free technique using interpolation and/or as a linear parameter varying (LPV) system. A structured evaluation will be conducted to determine the optimum balance between reduced (or zero) probing and acceptable loss in estimation accuracy.

Further work is recommended to establish a theoretical guarantee of frequency-domain consistency between the estimated and actual IBR models. This involves investigating one-shot multi-sine probing methods with high frequency resolution to ensure exact agreement at selected frequencies. Such improvements are expected to enhance the accuracy of estimated IBR models and thereby improve confidence in SSO analysis.

For the North Scotland test system, future studies should implement detailed IBR plant models that include both the power plant controller (PPC) and the voltage regulation device (STATCOM) at the point of interconnection. These models should undergo sanity checks through admittance benchmarking against measured spectra from actual IBR plant models. This step will be essential for validating model accuracy and ensuring reliable use in system-level studies.

Net Benefit Statement

The e-RMS project has delivered a framework to enhance NESO's capability to assess, diagnose and mitigate sub-synchronous oscillations (SSO) induced by inverter-based resources (IBR). The original aim of the project was to establish modelling adequacy for IBR-dominated grids, develop a scalable method for SSO analysis, and validate its accuracy against high-fidelity electromagnetic transient (EMT) benchmarks. These objectives have been successfully achieved across the work packages.

The project delivered a validated EMT-dq modelling framework that bridges the gap between traditional RMS models and computationally intensive EMT point-on-wave (EMT-abc) simulation. This provides EMT-level fidelity for SSO assessment at a fraction of the computational cost allowing a large number of scenario checks. For instance, in EMT-dq a 5 second simulation for a 5-bus test system is around 20 times faster than EMT-abc, and it scales with number of buses, as shown in [1]. The project also delivered a root-cause and early-warning analysis framework via in-situ estimation of IBR transfer functions without exhaustive offline impedance scan. End-to-end validation was completed using IEEE 9-bus and 39-bus systems with 100% IBR penetration.

Two main benefits of eRMS modelling are 1) significant reduction in computational burden using EMT-dq and 2) associated frequency domain insight and spatiotemporal characterisation of SSO. Faster SSO screening using eRMS directly supports more efficient planning studies, quicker post-event forensic diagnostics, and more practical integration into operational decision-support workflows. In-situ estimation of IBR transfer function eliminates the need for repeated impedance scans on standalone IBRs under multiple operating conditions. Instead, IBR dynamics are estimated directly from closed-loop pulse responses while connected to the network. In addition to speed and efficiency, eRMS modelling provides early-warning, root cause and vulnerability assessment capability. It not only detects the risk of poorly damped SSO modes but also identifies which specific IBRs contribute and how SSO propagate electrically across the grid. This enables preventive rather than purely reactive SSO management, improving stability guarantee under high renewable penetration.

While the North Scotland test case did not exhibit poorly damped SSO due to various reasons, this outcome as provided valuable operational learning on the importance of detailed realistic modelling power plant control (PPC) and terminal STATCOM of IBR plants (e.g., wind farms) for future GB-scale studies.

Looking ahead, the following benefits are expected as the eRMS method progress toward further development and deployment. These include:
1. Estimation of IBR transfer function using LPV/interpolation techniques near real-time to develop a digital twin of IBR-dominated grids for control room application.
2. More realistic system-wide SSO studies using IBR plant-level models.
3. Direct integration into operational tools for connection compliance assessment, and real-time early warning.

Strategically, the eRMS project directly supports Ofgem and NESO priorities by enabling faster analysis of IBR-induced SSO and its root cause and geographical spread without relying on tedious EMT-abc simulation. This represents a material contribution to system operability, resilience, and the cost-efficient delivery of the UK's net-zero transition.

Reference[1] "EMT - RMS Modeling Trade-Off for IBR-Driven Sub-Synchronous Oscillations," in IEEE Transactions on Power Systems, doi: 10.1109/TPWRS.2025.3588893.

Other Comments

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