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 2025

Project Reference Number

NIA2_NGESO020

Project Progress

Project Title

Strength to Connect

Project Reference Number

NIA2_NGESO020

Project Start Date

October 2022

Project Duration

1 year and 6 months

Nominated Project Contact(s)

Dechao Kong (NGESO)

Scope

This project will develop:

- A Deeper understanding of the intricacies of grid strength: Avoiding sudden disconnection of load or generation because of inadequate system strength is a direct benefit to customers and a core duty of the NGESO. In the more complex world of an IBR-dominated network, this needs to be based on a deep and nuanced understanding of at least four distinct aspects of system strength and a change from the traditional one-size-fits-all approach. On the other hand, an over-cautious approach to system strength could put obstacles in the way of new connections, e.g., wind farms.
- New measures and compatibility levels for system strength: The new measures will allow NGESO to carefully judge the type and volume of service provided and avoid over-or under-provision. Similarly, opening up new service definitions that enable IBRs to provide aspects of strength rather than only traditional generators or synchronous compensators creates downward pressure on costs. Further cost savings can be realised by adjusting compatibility levels so that connecting parties do so at lower system strength where possible and by raising transfer limits (rather than reinforcing) where system strength and voltage regulation were previously considered a limit.
- Further considerations to prepare a plan for the trial of new measurers: The market will need to be prepared to bring forward new service types and resources to achieve these benefits from the project. Stakeholder engagement will help gauge the industry's readiness to provide further services, and a trial plan for the pathfinder projects will be prepared to facilitate the introduction of new services.

Objectives

This project will implement a total of four WPs within a pre-defined timescale and budget plan to:

- Find the best measures to assess each potential problem listed in Section 2.1 and define metrics as replacements or refinements for short-circuit level.

- Investigate the capabilities of IBR and other resources to add strength and methods to improve their abilities to work in low grid strength conditions.
- Verify the analytical results with EMT simulations.
- Propose a method to declare compatibility levels for grid strength and tools for locational metrics, including plotting heat maps showing the compatibility levels of the whole system.

The final outputs should include:

- Project Progress Reports for WPs 1-4 as listed in Section 2.2 (Total 4 Reports).
- Final Project Report as a documented guidance on the assessment of IBR capability to add strength and evaluation on their ability to work in low grid strength (Total 1 Report).
- A tool for locational metrics for compatibility level and heat maps to describe the compatibility of the whole system.
- 2-3 Training sessions and documented training materials concluded from the guidance mentioned above to ensure NGESO and relevant network licensees can independently implement grid strength assessment for those problems as mentioned in 2.1-Problem based on methods/tools developed from this project.
- Knowledge dissemination event(s) for NGESO, other relevant Network Licensees and stakeholders during and after delivery of this project.
- Where relevant, the project will seek to publish in well-recognised international journals and at conference events.

Success Criteria

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

- Properly defined levels of grid strength for the four potential problems as mentioned in 2.1 - Problem.
- Properly defined levels to declare compatibility levels for grid strength.
- A developed tool for locational compatibility levels metrics and heat maps to describe compatibility of the whole system.
- Guidance on IBR capability to add strength and an evaluation on their ability to work in low grid strength.

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

National Energy System Operator (“NESO”) has endeavoured to prepare the published report (“Report”) in respect of Strength to Connect, NIA2_NESO020 (“Project”) in a manner which is, as far as possible, objective, using information collected and compiled by NESO and its Project partners (“Publishers”). Any intellectual property rights developed in the course of the Project and used in the Report shall be owned by the Publishers (as agreed between NESO and the Project partners).

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This project has been delayed due to NESO prioritising partners to investigate recent and on-going system dynamic performance issues.

Grid strength is decreasing around the GB system as thermal power plants with synchronous generators (SGs) are decommissioned in favour of inverter-based resources (IBRs) that will interface the renewable energy to meet the UK's net-zero targets. There are four emerging problems associated with the technology transition, these being: substandard voltage regulation, increased recovery times from voltage dips, potential instability of grid-following inverters, and mal operation of protection. Conventionally used metrics of short-circuit level (SCL) and short-circuit ratio (SCR) may no longer be a good all-purpose indicator because IBRs have different disturbance behaviours. Each problem needs a separate assessment the future electricity system with a high penetration of IBRs or IBR-dominance. The composition of SCL and SCR may also need to be re-examined and potentially expanded to incorporate the input from IBRs. The “Strength to Connect” project aims to examine what measures (small signal impedance, synchronising power, over-load current) best indicate stable and secure operation for each known type of network disturbance.

The project originally comprised of four Working Packages, but these have been combined to form 2 Work Packages going forward. The rationale behind this was because the analysis fell into two distinct components, that being small signal stability and large signal

stability. these two Working Packages (WPs) now comprise:

WP1: Grid Strength Assessment and Small Signal Stability Metric Development
This work package has introduced System Strength and identified the key concerns associated with a reducing value of System Strength. Based on this research and issues identified, the development of a metric to be used for small signal stability assessment was developed. The approach used in this phase of the research was to use the whole system admittance information and then using signal injection, the participation factors for the different elements could be obtained, leading to the definition of the Impedance Margin Ratio. Full details can be found in the research manuscript: Zhu, T. C. Green, X. Zhou, Y. Li, D. Kong and Y. Gu, "Impedance Margin Ratio: A New Metric for Small-Signal System Strength," in IEEE Transactions on Power Systems, vol. 39, no. 6, pp. 7291-7303, Nov. 2024

WP2: Large Signal System Strength Metric Development to Replace Short Circuit Ratio
This work package has focused on large signal stability. It evaluated the short circuit contribution from IBRs and how they impact the SCR quantification. The research then focused on Investigating and evaluating improved methods of measuring system strength beyond the traditional SCL and SCR. To assess the validity of the new metric the development of a detailed EMT model with sufficient dynamic behaviour was developed to be used as the benchmark testing platform. Using the EMT model, the maximum power a bus could handle and remain stable was investigated and compared against simulation test cases.

During this project the following tasks have been performed and completed:
Review of system strength concerns
Development of a small signal stability metric which has been called: Impedance Margin Ratio
Quantification of IBR short circuit current and its impact on the SCR value
Investigation into the ability of short circuit current to provide system strength information
Development of a suitable EMT model to evaluate the large signal system strength metrics
Evaluation and comparison of two large signal system strength metrics against standard metrics (SCR) with the proposal of a large signal stability metric based on power flow, which has been called Power Margin ratio.
The progress that has been made completes the technical content of the project.

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

A modification over the original planned approach in this project ishas been to reassess the usage of short circuit current and SCR values, when incorporating the IBR components into the calculations. This will provide further evidence to determine if SCR can still provide system strength information going forward, alongside the additional metrics that have been developed. The updated SCR was used as a starting point for determining the system strength in the large signal domain and was used as a comparison for future metrics to be evaluated against.

Lessons Learnt for Future Projects

WP1 set out to find the best system strength metrics to assess each potential problem as replacements or refinements for short-circuit level.

During WP1, measures of system strength were fully reviewed and newly classified as a small-signal system strength and large-signal system strength based on the different characteristics. Such classification separates the problems under study, making explicit difference in strength evaluation towards different problems. This is recognised as a milestone of this project and influenced the way the project proceeded in the following WP2, i.e., studies on small-signal system strength and large-signal system strength will be carried out in parallel. A new metric to indicated strength in terms of avoidance oscillatory behaviours and small-signal instability is described as small-signal system strength metric and named Impedance Margin Ratio (IMR). Accordingly, a new metric to address large-signal system strength, which is the ability of a system to recover well from large disturbance such as a short-circuit fault at a given node, named as type-dependent short-circuit ratio (TDSCR) was proposed. This progress also led the direction for WP2, in which the development of a large signal metric was undertaken. This metric uses power flow to ascertain the strength of the system and has been called the Power Margin Ratio (PMR) . The key lesson and insight from this part of the work was the use of power flow to help to identify the potential strength of the system. The use of power flow is more straightforward as an approach to use and could be integrated far easier as a screening tool.

One of the three expected benefits of this project was stated as:
Avoidance of sudden disconnection of load or generation because of inadequate system strength is a direct benefit to customers and a core duty of the NESO. In the more complex world of an IBR dominated network, this needs to be based on a deep and nuanced

understanding of at least four distinct aspects of system strength and the putting aside of the traditional one-size-fits-all measures. On the other hand, an over-cautious approach to system strength could put obstacles in the way of new connections of, for instance, wind farms.

The project has made a significant contribution by analysing system strength in ways specific to small and large disturbances. The new metrics for system strength offer a way of assessing the system voltage stiffness towards different dynamics, such as for small perturbations which can cause voltage oscillations, or large perturbations which can cause voltage dips. This work is enabling NESO to understand whether newly connected devices can increase the risk of system being unstable and discover the 'weak point' in the system.
There are also several points/lesson for future projects to take into account or that warrant further exploration, these are:
SCR variants are expected to be improvements on the standard SCR but it does not consider the interactions among adjacent IBRs during large disturbances. To include the interactions, the principles of ESCR could be adapted but the types of the interreacting IBRs will need to be considered, i.e., different combinations of voltage-type and current-type sources in close electrical proximity. Such an extension of SCR will be an item of further work within "Strength to Connect".
SCR style metrics treats IBR as an ideal voltage source with an associated impedance but omits the internal control design of the IBR. The influence of PLL, droop controller and other control loops that are non-linear should be included to study the interactions among IBRs in large-signal conditions in a more accurate way.
The situation that the limited fault current IBR (low fault-current system strength) may lead to mal-operation of protection and failure to properly clear faults has not yet been discussed. This needs to be included in future work.

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 project has achieved several outputs to date. WP1 and WP2 have been completed The learning from the project has been disseminated through:
1) ESIG 2023 Spring Technical Workshop, 29/03/2023 Tucson, AZ, US.
2) 2023 ESO External Engagement Webinar - System Operability Framework (SOF) Development, 27/04/2023 Faraday House, Warwick, UK.
3) Technical report for the NESO covering WP1 and detailing the Impedance Margin Ratio
4) IEEE Transactions on Power Systems publication: Impedance Margin Ratio: a New Metrics for Small-Signal System Strength, URL: https://ieeexplore.ieee.org/document/10452832
5) Knowledge exchange and continued development of the IMR metric via the SYSMet SIF project. SYSMet will incorporate the learning from the Strength-to-Connect project and develop the TRL. Details about the project can be found at: https://smarter.energynetworks.org/projects/sif_shet_024_sysmet-1/
6) Theoretical evaluation to quantify short circuit contribution from IBRs shared to NESO via on-going progress meetings
7) Technical report for NESO covering WP2 and detailing the Power Margin Ratio

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

The following reports are expected to be released on to the Smarter Networks Portal: (link)
Technical reports on each working package (WP1 and WP2) which will give detailed introduction and analysis on the issues being studied and solutions that have been provided.
Matlab code for new system strength calculation for small signal metric.
Presentation slides that have been given in public.
PSCAD EMT model

Planned Implementation

This project has now been completed as of June 2025, which is slightly later than expected because of the prioritisation of

investigations ordered by NESO into on-going system performance issues.
Overall, the project has provided a deeper understanding of system strength and made significant progress in proposing and evaluating new metrics that can highlight areas of concern when operating the system with a high level of IBRs.
There will be several parts that could be developed further and turned into operational or BAU tools for NESO. The first part that is expected to be incorporated into NESO is the improved calculation of short circuit current contribution IBRs, that is described in WP2. The large signal stability metric, PMU, will be tested further internally on a larger system to further understand its effectiveness over SCR.

One of the major outputs from the project was a small-signal stability metric. This metric and the process to incorporate it into a format that the NESO can use will require further development and refinement. This would be a potential next step in order to integrate it into the NESO software and operating procedures, a short follow-on exercise could be pursued to make the metric and its usage more user friendly for the NESO.

Net Benefit Statement

This project has produced several major benefits that are important for the whole power system sector, and especially for the system operator NESO.
The benefits that are applicable to the whole power system sector are:
Greater understanding about System Strength and its different components
Evaluation of existing metrics and their application to different components of system strength
Development and evaluation of a new system strength metric to assess small signal stability
Quantification for IBR short circuit current contribution

Project benefits that are specifically for a system operator or NESO are:
Highlighted the different aspects of system strength and what the contributing factors are which will enable NESO to better manage system strength around the network.
A process to evaluate system strength in the small signal domain with an associated metric (further development of metric required to integrate it into NESO operations).
Enhanced SCR metric that will provide a more accurate representation of system stability which will enable NESO to procure services/response that is more targeted and of the correct quantity.

Other Comments

(Standard NESO Text – do not amend)

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Standards Documents

N/A