Publishable Summary for 15NRM04 ROCOF
Standard Tests and Requirements for Rate-of-Change of Frequency (ROCOF) Measurements in Smart Grids

Overview

This project performed the pre-normative research required to develop new IEEE/IEC/CENELEC standards for rate-of-change-of-frequency (ROCOF) measurements in electricity networks. Network frequency and changes in network frequency are key indicators of network stability and of the balance between electricity supply and demand. This balance is becoming more critical with the increased use of highly-variable renewable energy sources (RES) for electricity generation, and at the same time present ROCOF measurements are inadequate for monitoring this balance.

Need

The increased use of RES is essential if the EU is to meet its 2020 objective of 20 % renewable electricity generation and its further 2050 objectives of at least 50 % renewable electricity generation. Traditional carbon-based electricity generation uses massive rotating machines which provide significant inertia to the grid, able to absorb unpredictable changes in consumer demand. They also act as voltage sources, leading to an almost “perfect” power quality (PQ). By contrast, RES are connected to the network via power-electronic converters. These generally provide negligible contribution to grid inertia, and often have a strong negative contribution to PQ. PQ is further degraded by other new emerging grid components like HVDC (High Voltage DC) Links, and electric vehicle chargers, which are also converter-connected to the grid. ROCOF is required as a metric of system inertia in order for network operators to take control actions in order to maintain system stability. Poor PQ and other short lived events on the electricity supply can cause large ROCOF errors which would lead to false control actions. It is therefore important to understand the conditions in which ROCOF needs to be measured by surveying possible network operational scenarios. Algorithms can then be selected and configured to measure ROCOF and the limitations and eventual expectations of the measurement can be understood, such that control strategies can be pursued by network operators with confidence. IEC/IEEE TC95 WG1 have therefore called for research to be carried out to address the lack of standardisation in this area.

Objectives

A “use case” is defined as a particular situation in the grid where a utility would like to perform a ROCOF measurement. This maybe under normal operating conditions or during an exceptional event such as the sudden disconnection of a large load or generator.

The “wish list” will define the desired specification of accuracy the measurement latency (or measurement update rate) and cost-effectiveness from an end-user point of view for the given use cases.

In order to develop a ROCOF standard, this pre-normative project addressed the following scientific and technical objectives:

1. To evaluate the problem of ROCOF measurement in the context of actual use cases and the “wish list” from an end-user point of view. To develop a library of standard-test-waveforms representative of typical PQ events on electricity networks, including extreme events, in order to adequately test ROCOF algorithms and instrumentation containing these algorithms.
2. To review, develop and optimise algorithms to reliably and accurately measure ROCOF over the full range of network conditions, specifying any use cases where this is not achievable.

3. To implement and test selected ROCOF algorithms utilising the standard waveform library via computer simulations as well as in instrument hardware that will be tested using precisely generated electrical waveforms in the laboratory. This will lead to compliance verification protocols for ROCOF instruments suitable for inclusion in a ROCOF standard (new or pre-existing).
4. To specify a reference signal processing architecture for a ROCOF instrument suitable for inclusion in a ROCOF standard. To use sensitivity analysis to determine the uncertainty specification for each element of the measurement chain (this could include: transducers, analogue signal processing, filtering, analogue to digital convertors, digital signal processing, computational processing) required to manufacture an instrument to implement the selected algorithms and be capable of compliant accuracy measurements for each of the use cases.
5. To work closely with the European and International Standards Developing Organisations, in particular CENELEC TC8X and the working-group/technical committee responsible for IEEE/IEC 60255 118-1, and the users of the standards they develop, to ensure that the outputs of the project are aligned with their needs, communicated quickly to those developing the standards, and in a form that can be incorporated into current standards and used to develop a new internationally accepted standard at the earliest opportunity.

Progress beyond the state of the art

The measurement of ROCOF is a significant problem with the poor PQ waveforms that particularly prevail in low inertia power networks containing RES. This is because a ROCOF measurement first requires frequency to be found using the *d/dt* derivative from phase, before ROCOF is itself determined via a second *d/dt* derivative from frequency. Any noise on the original phase estimate due to poor PQ, transients, fault events, or instrumentation noise are vastly “amplified” by the double derivative causing spurious results.

The problem of the present state-of-the-art in ROCOF measurement is three-fold.

- The users of ROCOF measurements do not appreciate the potential uncertainty of the measurements under imperfect PQ, and sometimes assume that measurement is instant.
- The designers of the measurement devices do not fully understand the required accuracy or latency for particular use cases, or the PQ environment.
- Some algorithms for measuring ROCOF are much less tolerant of poor PQ than others. In particular, instruments from different manufacturers exhibit very different performance. This is easy to understand, since there are no workable standards for ROCOF measurement, so the manufacturers’ algorithms performance also varies widely.

So presently there is a big disconnect between the end-user expectations, the equipment manufacturers who provide ROCOF-measuring devices, the bodies setting standards, and the real-world context of a power network in which the AC network voltages (and currents) deviate from clean sinusoidal conditions.

The instrumentation used to measure ROCOF is overseen by the IEEE/IEC joint standards committee TC95 WG1 (60255-118-1). There is a critical need to develop a standard for ROCOF which will first require some research to determine the various use case scenarios where users have an expectation of ROCOF measurements and an associated library of waveforms. These use cases will become the working conditions for new algorithms that can operate reliably over the range of normal to exceptional power quality scenarios that exist in power networks. Such research is a necessary foundation on which to build a credible, practical and defendable standard that will command the confidence of the international power systems community.

Results

The outputs of the project are primarily focussed on R&D that will provide the basis of a new ROCOF standard(s). This lead to the following outputs:

1) To evaluate the problem of ROCOF measurement in the context of actual use cases and the “wish list” from an end-user point of view. To develop a library of standard-test-waveforms representative of typical PQ events on electricity networks, including extreme events, in order to adequately test ROCOF algorithms and instrumentation containing these algorithms.

A table of use cases has been compiled representing normal and extreme operational conditions in the power grid. Each use case table entry has an expected ROCOF accuracy and measurement latency (which will vary in accordance with the complexity of the use case). This table is being discussed with stakeholders and the agreed version will be suitable for inclusion in an international standard. In order to compile this table, a virtual workshop was held to obtain information from the power industry and instrument manufactures on what they considered to be the required information. The consortium circulated questionnaires and received responses from stakeholders regarding the various scenarios where ROCOF is used in power networks. The responses have been tabulated and the three main uses cases have emerged which cover categories of particular electricity network scenarios:

- “Loss of mains detection”, which protects the power system and personnel from so called island operation using ROCOF to detect island operation.
- “Under frequency load shedding”, where selected customers supplies are progressively cut-off to protect the supply and demand balance which is measured using ROCOF.
- “Frequency response requirement calculation” (synthetic Inertia), uses ROCOF to measure the possible reserve power available for injection to the grid on a short-term basis.

Each use case has different demands in terms of ROCOF accuracy and response time. Within each use case there exist particular examples of waveforms particular examples of ROCOF and events caused by transients and poor power quality which may give rise to spurious ROCOF readings.

A waveform library has been developed which makes these reference waveforms available to researchers and instrument manufacturers who wish to develop and test algorithms.

This work will define the terms of reference for future ROCOF measurements and will set expectations of users as to the accuracy of the ROCOF measurement verses its delay response before updating its readings. This trade-off is governed by the need to reject spurious PQ events.

The report on these use cases and the waveform library (which is subject to future change after consultation) is available at: http://www.rocofmetrology.eu/2018/10/04/september-2018/.

The Objective was fully achieved. The problem of ROCOF measurement was evaluated in the context of actual use cases and the “wish list” of measurement requirements was compiled taking into account the point of view of end-users. A library of standard-test-waveforms representative of typical PQ events on electricity networks was produced.

2) *To review, develop and optimise algorithms to reliably and accurately measure ROCOF over the full range of network conditions, specifying any use cases where this is not achievable.*

An adaptive digital filtering algorithm has been selected for its particular properties in rejecting PQ events and its computationally efficient structure. The commonly used IEEE algorithm is also being used for comparison. The adaptive algorithm was developed by the University of Strathclyde, UK available here: https://pure.strath.ac.uk/ws/portalfiles/portal/23589289/J_2013_IEEE_PD_Roscoe_PandMClassPMUs_ExtendedPostprint.pdf

A rigorous investigation has been completed into the configuration of the digital filters used in the ROCOF algorithm in order to meet the specifications of the use cases from Objective 1. A paper has been submitted for peer-review which includes a table of filter configurations versus tabulated use cases with associated tabulated algorithm configurations. Two project partners have independently simulated the performance of these digital filter configurations against the use case waveforms and the results will be reported in the paper.

These algorithms are being tested in the lab and field as described in Objective 3.

The Objective was fully achieved. Algorithms were reviewed, developed and optimised to reliably and accurately measure ROCOF over the full range of network conditions, and table was produced specifying the accuracy achievable for each use cases.

3) *To implement and test selected ROCOF algorithms utilising the standard waveform library via computer simulations as well as in instrument hardware that will be tested using precisely generated electrical waveforms in the laboratory. This will lead to compliance verification protocols for ROCOF instruments suitable for inclusion in a ROCOF standard (new or pre-existing).*

Two ROCOF algorithms have been implemented in special instruments which digitise the measured grid waveforms. The algorithms must run in real time and the detailed waveform data is captured near any event that exceeds a pre-set ROCOF threshold. This allows post-processing and replay of the events through different algorithms and/or configurations.

Six such instruments have been installed on Bornholm Green Island which contains a high penetration of renewable energy and often operates independently of the nearby Nordic Grid (see Loss of Mains use case above). The new algorithms are being tested in this unique experiment and data from real and spurious ROCOF events is being captured to allow the optimisation of ROCOF algorithms.

One of the algorithms includes a "phase-step ride-through" estimator which attempts to correct the most problematic of use cases, involving sudden changes in phase. This has been tested using data from Bornholm Island. The results have been presented at the CPEM 2018 conference and have been published in a peer reviewed journal.

A laboratory test-bed has been set up which can accurately synthesise use case waveforms (such as idealised versions of those captured on Bornholm). This forms the basis of a recommended ROCOF lab testing set-up suitable for compliance testing of ROCOF instruments. This includes a test procedure and uncertainty budget and will be in a form suitable for inclusion in an international standard.

The Objective was fully achieved. Selected ROCOF algorithms were implemented and tested by utilising the standard waveform library via computer simulations as well as in instrument hardware using precisely generated electrical waveforms in the laboratory. This lead to compliance verification protocols for ROCOF instruments suitable for inclusion in a future ROCOF standard.

4) *To specify a reference signal processing architecture for a ROCOF instrument suitable for inclusion in a ROCOF standard. To use sensitivity analysis to determine the uncertainty specification for each element of the measurement chain (this could include: transducers, analogue signal processing, filtering, analogue to digital convertors, digital signal processing, computational processing) required to manufacture an instrument to implement the selected algorithms and be capable of compliant accuracy measurements for each of the use cases.*

A reference signal processing architecture for a ROCOF instrument in the form of a block diagram and accompanying text for each block has been developed. Monte-Carlo simulations were used with this reference architecture and the results will provide overall predicted uncertainties for the measurement use cases. This also specifies the minimum uncertainty requirements for each block in the measurement chain.

Therefore Objective 4 was fully achieved.

5) *To work closely with the European and International Standards Developing Organisations, in particular CENELEC TC8X and the working-group/technical committee responsible for IEEE/IEC 60255 118-1, and the users of the standards they develop, to ensure that the outputs of the project are aligned with their needs, communicated quickly to those developing the standards, and in a form that can be incorporated into current standards and used to develop a new internationally accepted standard at the earliest opportunity.*

All of the above outputs will be submitted to an international standards committee for consideration on the inclusion in a future ROCOF standard. The project team is engaging in discussions with the standards committees and other stakeholders to ensure that the project outputs align with their requirements and expectations. The consortium have been in regular discussions with the stakeholder community. To date the need for ROCOF standards has been discussed with the following seven standard committees: IEC/IEEE TC95 / WG1 (60255-118-1), IEC TC8 JWG12, BSI GEL/8, UK National Grid working group GC0087, ENSTO-E, ISGAN and SIRFN. The project is particularly engaged with the first two committees and is targeting this research to tangible contributions to ROCOF and grid frequency measurement standards under their control.

The projects results and in particular the use-cases were a key contribution to the meeting of IEC TC8 JWG12 held in Paris in June 2019. The project leader will continue this process after the conclusion of the projects and the outcomes of the project are expected to make a major contribution to a new IEC standard on frequency measurements for distributed generation control.

The Objective was fully achieved. The project outputs are aligned with the needs of IEC TC8 JWG12 (replacing CLC TC8X WG) and IEC/IEEE TC95 / WG1 (60255-118-1). The results have been communicated quickly to those developing the standards and the project outputs have been presented and are expected to form the basis of parts of future international standards.

Impact

A virtual workshop was held to obtain information from the power industry and instrument manufactures on what they considered to be problems associated with ROCOF and the required information the project would have to gather in order to deal possible scenarios. The consortium has circulated questionnaires, based on experience and information from the virtual workshop, on the impact of ROCOF on smart grids PQ stability and received feedback from industry and standards bodies. There has been extensive engagement with IEC/IEEE TC95 / WG1 (60255-118-1) and IEC TC8 JWG12.

A highly successful final project meeting Webinar was attended by 50 people, ranging from China to the west coast of the US. It included all key people we were targeting for, but also had around 20 stakeholders we had not been in contact before. To a significant part, the attendance was the result of the active promotion of the webinar by the Chair of IEC/IEEE TC95 / WG1 (60255-118-1). During the webinar, slides were presented on the projects outputs, with each part followed by discussions. The discussions appeared to be lively and focused, with to-the-point issues. All attendants stayed connected during the 2 hours the webinar lasted and we collected a series of very positive responses afterwards.

A paper on the development and field testing of new ROCOF algorithms was presented to the Conference of Precision Electromagnetic Measurements in July 2018. A further paper was given on Uncertainty of ROCOF calculated by means of Monte Carlo method. The keynote address of the Smart Grids Measurement Conference in June 2018 was made by a member of the project team and a further paper was given on uncertainties.

Impact on industrial and other user communities

This project will establish the foundations for new documentary standards that will normalise ROCOF measurements such that this metric can be used with confidence by utility companies to ensure the stable operation of renewable energy resources (RES). The research will ensure that the new standard is practical, implementable, reliable, rigorous, cost effective and defensible based on testing and analytical evidence. The outputs of the pre-normative research will be directed to the standards committees who will work on a parallel time-scale to this project, to implement a new ROCOF standard in tandem with this research.
Without this pre-normative research, any future standard would risk serious gaps, in which real-world power system scenarios could cause severe errors in ROCOF measurements, potentially leading to blackouts and asset damage. Any new standard unsupported by pre-normative research could quickly lose credibility, potentially delaying the integration of RES and the missing of EU 2050 targets.
Reliable, usable ROCOF measurements underpinned by defensible standardisation will benefit the Power-system operators, RES providers, and instrument manufactures.

Impact on the metrology and scientific communities

ROCOF is a complex measurement parameter which needs to be determined over a wide-range of real-world scenarios. This type of measurement marks a departure from the more traditional NMI activity of laboratory based measurements of single quantities at the highest accuracy. Conversely, ROCOF is a multiple input measurement industrial problem, however its solution lies with the application of the metrological principles of good definition (Objective 1 and 2), piece-wise characterisation/calibration of complex systems (Objective 3), GUM based Monte-Carlo analysis of uncertainties (Objective 4) and analysis/mitigation of non-ideal conditions (Objective 2). These activities add essential experience to the application of metrology to industrial measurements and lead to improvements in measurement capabilities to support their practical implementation. The compliance and calibration procedures developed as part of this project (Objective 4) will give rise to new measurement capabilities for ROCOF at NMIs (which have the potential to form part of CMCs) and second-tier calibration laboratories.

Impact on relevant standards

This project has been conceived to provide essential pre-normative research to enable the publication of new international standards on ROCOF. The project has been particularly connected to IEC/IEEE TC95 / WG1 (60255-118-1), IEC TC8 JWG12 where the project outputs are influencing the development of standards by

both of these committees Such research will provide a rigorous basis for practical and effective standardisation which will command the support of industry.
Such standardisation is essential to ensure that network-critical ROCOF measurements can be made reliably with instrumentation from any manufacturer. As these measurements involve particularly complex parameters and are subject many unpredictable influences, the project will provide input to future standards to define hardware, algorithms, immunity to disturbances and test conditions.

Longer-term economic, social and environmental impacts
ROCOF is vital for the safe and stable large scale integration of renewables into the electricity grid. The use cases identified by the project target various aspects of this long term energy landscape and the project is going on to develop new algorithms to match these use cases. Some examples of the longer term social, environmental and economic impacts include Loss of Mains (LOM) protection for maintenance personnel at serious risk from intermittent unexpected voltages; Under Frequency Load Shedding (UFLS) protection to disconnect loads from a network to maintain the frequency within limits, thus preventing serious power cuts; Generator Frequency Response (synthetic inertia) work, key to reliable and usable SI metrics which will enable stable and secure public power supply when using the very high proportion of renewables predicted in 2050 scenarios.

List of Publications

"Dealing with Front-End White Noise on Differentiated Measurements such as Frequency and ROCOF in Power Systems", Roscoe, A.J., Blair, S.M., Dickerson, W., Rietveld, G., IEEE Transactions on Instrumentation and Measurement, 2018. DOI: 10.1109/TIM.2018.2822438.

"The Case for Redefinition of Frequency and ROCOF to Account for AC Power System Phase Steps, A. J. Roscoe, A. Dyko, B. Marshall, M. Lee, H. Kirkham, G.Rietveld, IEEE Applied Measurements for Power Systems, 2017. DOI: 10.1109/AMPS.2017.8078330

"PMU-based power system analysis of a MV distribution grid", N. Save, M. Popov, A. Jongepier, and G. Rietveld, CIRAD 2017. DOI: 10.1049/oap-cired.2017.1035

"Field Measurement of Frequency and ROCOF in the Presence of Phase Steps", P.S.Wright, P. N. Davis, K. Johnstone, G. Rietveld, and A. J. Roscoe, IEEE Transactions on Instrumentation and Measurement, 2019. DOI: 10.1109/TIM.2018.2882907.

<table>
<tr><td colspan="2">Project start date and duration:</td><td>01 June 2016, 36 months</td></tr>
<tr><td colspan="3">Coordinator: Dr Paul Wright, NPL Tel: +44 20 8943 6367 E-mail: paul.wright@npl.co.uk
Project website address: www.rocofmetrology.eu/</td></tr>
<tr><td>Internal Funded Partners:
1 NPL, United Kingdom
2 CMI, Czech Republic
3 VSL, Netherlands</td><td>External Funded Partners:
4 STRATH, United Kingdom</td><td>Unfunded Partners:</td></tr>
<tr><td colspan="3">RMG: -</td></tr>
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