REPORT

Assessment of higher RoCoF events on demand Customers

High level assessment of short frequency deviations with regards to any possible effects on demand customers.

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Reference to part of this report which may lead to misinterpretation is not permissible.

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EXECUTIVE SUMMARY

Ireland and Northern Ireland are implementing an energy policy to deliver a more sustainable electrical energy generation portfolio with a growing share of Renewable Energy Sources (RES) as a result.

As a consequence of the larger share of RES, inertia in the power system will decline. Simulations of future scenarios show that Rate of Change of Frequency (RoCoF) values would exceed the 0.5 Hz/s limit in the event of the largest single generation or load unit trips on the all-island power system. Thermal power plants are the main source for maintaining system stability and an increased participation of RES generators will therefore need a wider RoCoF range allowance since it partly replaces thermal plants.

To allow for the targeted share of RES generation the Commission for Energy Regulation (CER) agreed on the 4th of April 2014 a Grid Code change in principle. [1] The Grid Code change state a RoCoF of 1 Hz/s measured over a rolling 500ms time window and is planned for both jurisdictions. This measure will help avoiding curtailment of wind generators and the economic and environmental consequences thereof.

Security of supply is a priority and therefore the CER and the Utility Regulator in Northern Ireland (UR), hereafter referred to as the 'Regulatory Authorities' (RAs), directed the Transmission System Operators (TSOs) to investigate any detrimental effects on demand customers as a result of the RoCoF change. This investigation is an addition to studies already commenced, through the three strands:[2]

1. Generator Studies Project;
2. TSO-DSO Implementation Project; and
3. Alternative Solutions Project.

This project report is to investigate and understand any issues for demand customers with regards to the allowance for a higher RoCoF value and to provide a high-level overview. This overview may be used in further studies to assist in maintaining a resilient, sustainable and secure electricity system for the future of the all-island power system.

This short assessment will inform stakeholders if any likely effects on connected demand customer installations exist in the event of an increased level of RoCoF. Ultimately, this assessment will help inform the RAs whether the proposed change can be implemented, together with a line of sight for possible required mitigation actions or further required study area needs.

DNV GL, together with the TSOs, identified 2 categories of load connected, namely:

- Indirect connected load, using a power electronic interface; and
- Direct connected load.

Different types of power electronics were analysed together with 3 typical direct connect loads; synchronous motors, asynchronous motors and resistive loads.

DNV GL concludes in this report that, although most load types could be influenced by RoCoF, the associated risks for demand customers with regards to the proposed higher rate of change of frequency allowance of 1 Hz/s will be low.

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[1] Stated in the published MPID 229

[2] Ref.: EirGrid SONI report, 22/12/2015 – RoCoF Alternative & Complementary Solutions Project, link: http://www.eirgridgroup.com/site-files/library/EirGrid/RoCoF-Alternative-Complementary-Solutions-Project-Phase-2-Report.pdf

1 INTRODUCTION

Background and Context

Ireland and Northern Ireland are progressing an energy policy to deliver a more sustainable energy mix. The target in Ireland is 40% of total electrical energy consumption to come from Renewable Energy Sources (RES) by 2020. Northern Ireland also has an ambition for 40% of all electrical energy consumption to come from RES by 2020.

As a result, the all-island electrical system and its operators are facing some of Europe's most challenging electricity systems to date due to the decarbonisation targets set out by the government. The electrical power system will require to be operated in real-time with SNSP (System Non Synchronous Penetration) levels of up to 75% to be able to achieve the RES electricity 2020 target of a 40 % share of the total energy demand supplied from renewable generation.

With the increased penetration of RES in the generation portfolio, inertia in the system will decline and simulations of future scenarios show that RoCoF values would exceed the 0.5 Hz/s RoCoF limit in the event of a loss of the largest single in-feed or load on the all-island power system.

For this reason the Commission for Energy Regulation (CER) and Utility Regulator in Northern Ireland (UR) together decided[3] to amend the Grid Code (GC) RoCoF requirements[4] that generators must be able to meet. The change aims to help facilitate the 40% RES target of 2020 in conjunction with keeping a resilient electricity system.

These Grid Code modifications can only come into effect following confirmation from the Transmission System Operators (TSOs) that, from a system security perspective, they can be implemented.

To determine compliance, the CER required the TSOs to perform studies regarding three strands, namely:

1. Generator Studies Project;
2. TSO-DSO Implementation Project; and
3. Alternative Solutions Project.

In parallel, the Regulatory Authorities (RAs) have now requested the TSO to investigate if significant (detrimental) consequences for demand customers exist as a result of the RoCoF change.

EirGrid has commissioned DNV GL to carry out a high-level study to investigate and identify potential issues, if any, for Ireland and Northern Ireland demand connections related to the proposed higher RoCoF.

EirGrid and SONI requested DNV GL to independently assess the effects of the proposed higher RoCoF values for all-Island demand customers. This document states the results of 15 days research into possible effects of RoCoF for demand customers. As a consequence, the outcome of the study is mainly qualitative and provides a high-level overview of any issues found. Areas that might need further investigation for specific installations and technology used are highlighted in this report.

[3] The CER 14/081 decision paper of April 4, 2014 states the RoCoF definition and the GC decision made in principle to increase the maximum RoCoF to 1 Hz/s measured over a rolling 500ms time window.

[4] The changes are included in the MPID 229 stating the new Rate-of-Change-of-Frequency (RoCoF) requirements.

It is important to note that this document provides a high-level overview of demand customers and does therefore not specifically address energy generation sites. The terminology 'motor' is used for rotating equipment which reflects electrical devices that use electrical power as opposed to generating electrical power throughout this document.

Structure of the document

The document is structured as follows:

- Section 2 discusses the different load types of demand customers which are found in the various industries;
- Section 3 characterises the different load types and whether higher RoCoF events will have an adverse impact on the machinery used by demand customers;
- Section 4 provides the outline of the conclusions made in this report;
- Section 5 shows the reference documents studied for this piece of work;
- Section 6 lists the abbreviations and acronyms used; and
- The ANNEX provides additional information for references made throughout the document.

2 IDENTIFICATION AND CHARACTERISATION OF DEMAND LOAD TYPES

By analysing the demand of customers, in cooperation with the TSOs, the following industries were selected to represent the typical types of load connected to the electricity system of Ireland and Northern Ireland:

- Pharmaceutical processes;
- Semiconductor fabrication;
- Alumina refining;
- Cement industry;
- Chemical industry;
- Data centres; and
- Critical load including hospitals.

Characterisation

The different industry load characteristics of electrical power systems can be split into two main categories:

- Indirect AC connected (by the use of a power electronic interface between the grid and the load); and
- Direct AC connected.

These two different types of connected loads can be further detailed into subcategories. The subcategories help to more efficiently assess potential affected electrical supply system components of demand customers and whether higher RoCoF events will have an adverse impact for the customer.

For indirect AC connected customers there are two load type subcategories identified:

- Uncontrolled power electronics (rectifiers e.g. B6, B12, B24, etc.); and
- Controlled power electronics (e.g. convertors such as Variable Frequency Drives and inverters such as uninterruptable power sources (UPS) from battery systems).

The direct AC connected load types have been split into three different subcategories, namely:

- Synchronous motors;
- Asynchronous motors; and
- Resistive load.

As earlier indicated, this project is aimed at demand customers and therefore does not specifically address generation of energy. Table 1 lists the different industries that have been selected for analyses and links those industries with the five identified characteristic load categories for each. The bottom of Table 1 shows which load categories could be affected in principle by a higher RoCoF values. More information with regards to the findings is explained in section 3 of this document.

Table 1 - Characterisation of industrial load types

Industrial categories	Indirect AC connected Power Electronics Uncontrolled	Power Electronics Controlled	Direct AC connected Synchronous motors	Asynchronous motors	Resistive load
Pharmaceutical processes		✓			
Semiconductor fabrication		✓			
Alumina refinery	✓	✓	✓	✓	
Cement industry			✓	✓	
Chemical industry		✓		✓	
Data centres		✓			
Critical load including hospitals	✓				
Food & Drink industry	✓	✓	✓	✓	✓
Influenced by RoCoF	✓	✓	✓	✓	

Table 1 shows that most industries will have incorporated different types of loads and therefore include both indirectly and directly connected machinery to the AC grid. The bottom row of the table shows which loads could potentially be adversely affected by the allowance of a higher RoCoF value, however, for the majority of loads used by the demand customers no issues are expected for RoCoF levels up to 1 Hz/s. Please note that Table 1 is used to highlight load types specific to a particular industry as opposed to list all the load types used in that industry.

3 IMPACT ASSESSMENT OF THE DIFFERENT CHARACTERISED LOAD TYPES WITH REGARDS TO HIGHER ROCOF

3.1 Indirect AC connected load

By using power electronics the connected load is decoupled from the mains supply and thus is indirect connected to the AC grid.

Power electronic interfaces are used when the standard AC voltage or frequency does not match the specifications of the connected load or in the case when DC power is required. Power electronics are also used when the load is required to be controlled and adjusted in accordance with the industrial process involved, e.g. speed or temperature adjustments in an accurate fashion.

When assessing the power electronics from a technical perspective, there are two main categories of indirect AC connected load, namely by:

- Uncontrollable power electronics are rectifiers that transform the AC power into DC power.
- Controllable power electronics such as convertors and inverters are able to regulate the voltage output. Inverters, in addition to voltage regulation, will also be able to regulate the frequency. Inverters are typically used for controlling rotating speed of motors on a continuous basis.

3.1.1 Uncontrolled power electronics interface

This category of power electronics cannot be controlled since it just rectifies the AC power into DC without controlling the voltage level. The rectifier is therefore the uncontrolled power electronic interface. However, often behind the rectifier sits additional controlled power electronic technologies that uses the DC output of the rectifier and controls the output by active switching components, accurately measuring and adjusting the output. There are also power electronic interfaces that make use of non-switching components but the efficiency and accuracy of the output is not as good as that for switching mode regulated devices and has therefore been used less in the last 10-15 years. In addition, the non-switching power electronics are mainly used when the input voltage and frequency is fixed and does not require a large compatible voltage or frequency range, e.g. source voltage is 400V ±5%, 50Hz. The non-switching power electronics types, also referred to as linear power supplies, are not affected by RoCoF when unregulated or have very simple regulation circuits.

Switching mode power supplies (SMPS) provide a more accurate output and also allow for different types of power sources in addition to the benefits of reduced weight and improved efficient compared to uncontrolled rectifiers. SMPS units can be complex because of the control circuit used for monitoring and controlling (switching at kilohertz frequencies) the output and thus SMPS devices belong to the controlled category.

The type of connected load behind the uncontrolled power electronic interface will determine if the demand customer will be affected by RoCoF excursions. The rectifier is not effected by the RoCoF event, however, it does not act as a filter for the frequency (and possible voltage) deviation. As a result any equipment attached to the rectifier, e.g. an inverter and its feedback loop, may become unstable in a situation where voltage dips during a RoCoF event. The instability event is likely only triggered by a combination of a rapid frequency change and a voltage deviation.

Table 2 provides a high-level overview of the possible impacts on uncontrolled power electronics for different levels of RoCoF.

Table 2 – Qualitative overview of RoCoF impact on uncontrolled power electronics interfaces

RoCoF [Hz/s]	No. of RoCoF events annually	Impact
0.5	10	No impact reported
1.0	10	No impact expected
1.5	10	Issues could be experienced in some cases for the load connected
2.0	10	Issues could be experienced in some cases for the load connected

We have identified the likely areas which could be affected if the RoCoF impacts the operational behaviour of the power electronics in Table 3.

Table 3 – Identified impact areas for uncontrolled power electronics interface

Areas	Affected
1 - Response of the demand site to the RoCoF event	✓
2 - Impacts on power quality provided to the site	✓
3 - Operational impacts on the demand site	✓
4 - Impacts on embedded generation within the site	✓
5 - Mechanical impacts on the demand site	no
6 - Likely impact on maintenance cycles for the plant	no
7 - Any potential safety issues for the demand site	no

In the majority of situations we are not expecting that demand customers are affected by a 1 Hz/s RoCoF event. The power electronics behind the rectifier could be affected due to a RoCoF event and in that case in point the demand customer could experience power oscillations or direct current or voltage trips. A possible change in harmonic distortion might also occur, impacting power quality to the site. This may result in a loss of production or downtime for the demand site. Embedded electrical generation could come with additional protection which can affect the demand customer in the event of a high RoCoF value when the settings are not aligned. Power oscillations could occur when the inverter behind the rectifier will try to maintain a stable output by changing the set-point for switching and momentarily operating in a less optimal fashion.

Mechanical impacts on the demand site are unlikely however, and therefore impacts on maintenance cycles or any potential safety issues for the demand customer has not been identified.

Typical industries that make use of uncontrolled power electronics are:

- Alumina refinery
- Hospitals
- Food & Drink industry

3.1.2 Controlled power electronics interface

Controlled power electronics are able to vary their frequency and voltage (or current) output on a continuous basis in addition to the features of uncontrolled power electronics. As a result, the equipment is more versatile and in most cases is able to adapt its behaviour through changing parameters in the software or with software upgrades.

Similar statements as for uncontrolled power electronics apply for controlled power electronic interfaces. The exact behaviour of the equipment to larger RoCoF excursions cannot be generalised since the behaviour (reaction to grid events, etc.) of grid-tie power converters are determined entirely by the embedded control algorithms. However, this also means that settings can be modified through changes made in the software as opposed to uncontrolled power electronics.

In principle, controlled power electronic devices will ride through the RoCoF event. In higher RoCoF cases, there is a possibility that protection could cause the devices to trip from the system. The probability of such an event exists but in most cases the software settings can be modified if required.

In situations where an active front end converter successfully rides through a RoCoF event (i.e. does not result in the trip of the entire system), the impact to the load is determined by whether the DC-link voltage remains within its operational limits. If this is not the case it could affect the functionality or performance of the connected downstream load. The probability of such an event is expected to be low and only likely in situations when the voltage dips during a RoCoF in combination with a high load demand.

Table 4 shows the risks of controlled power electronics in the absence of any software parameter changes. The table is likely to show a conservative view and it is expected, as stated previously, that controlled power electronics are, in most cases, able to adapt its behaviour through changing parameters in software or software upgrades.

For loads that are voltage dependent, three load categories can be identified:

- Constant power: power oscillations could occur at larger RoCoF excursions together with DC under or overvoltage due to power imbalance.
- Constant current: Voltage fluctuations at load with tripping if over- or under-voltage limits are reached.
- Constant impedance: Voltage fluctuations at load with tripping if over- or under-voltage limits are reached.

Controlled power electronic interfaces can have different phase-locked-loop (PLL) designs which determine the sensitivities to larger RoCoF excursions and will define the stability. If the RoCoF exceeds the processing capability of the PLL controller, instability and tripping of the interface could occur.[2] As a result, the specification of the power electronics in question needs to be consulted to make sure that the equipment, in combination with the load can remain connected for higher RoCoF events.

At the same time, the rate of change of frequency of 1 Hz/s that is agreed in principle by the CER (14/081 decision paper) is not expected to have an impact on those power electronics. DNV GL suggests that further analysis of certain controlled power electronics is undertaken in instances where there is doubt around the impact of the Grid Code changes and the effects on the power electronics.

Table 4 is conservative because power electronic manufacturers are building their equipment with an international customer portfolio in mind and that in Europe a wider range of RoCoF allowance exists in the different Grid Codes, for example Denmark 2.5 Hz/s over 200 ms and Germany 1 Hz/s over 200 ms.

Within the limited time available for this project, suitable references to the robustness of specific power electronics with regards to RoCoF could not be found, however, it is safe to state that power electronic devices are used in countries like Germany and Denmark without significant compliance issues and that fundamental design changes are unlikely to be incorporated to meet the named countries requirements.

Table 4 - Qualitative overview of RoCoF impact on controlled power electronics interfaces

RoCoF [Hz/s]	No. of RoCoF events annually	Impact
0.5	10	No impact reported
1.0	10	Infrequent and inadvertent tripping could be experienced
1.5	10	Frequent and inadvertent tripping is likely if control not adjusted
2.0	10	Frequent tripping if control not adjusted

Table 4 shows that controlled power electronics are initially more prone to tripping due to RoCoF events as opposed to uncontrolled power electronics (Table 2). However the controlled power electronic settings can be adjusted to mitigate tripping risks that a higher RoCoF level might cause. Initially this means that controlled power electronics might need attention following a change of Grid Code (e.g. RoCoF). In our high-level assessment, however, the risks for infrequent or inadvertent tripping up to a RoCoF level of 1 Hz/s are expected to be low.

We have identified the likely areas for controlled power electronic interfaces which are affected if the RoCoF impacts operational behaviour of power electronics in Table 5.

Table 5 – Identified impact areas for uncontrolled power electronics interface

Areas	Affected
1 - Response of the demand site to the RoCoF event	✓
2 - Impacts on power quality provided to the site	✓
3 - Operational impacts on the demand site	✓
4 - Impacts on embedded generation within the site	✓
5 - Mechanical impacts on the demand site	no
6 - Likely impact on maintenance cycles for the plant	no
7 - Any potential safety issues for the demand site	no

Table 5 shows that the demand customer could be affected to a RoCoF in the event of power oscillations or DC-link voltage trip in extreme cases. With regards to the impacts on power quality provided to the site, possible higher levels of flicker and total harmonic distortion (THD) could be seen as control strategies would, in most cases, compensate for RoCoF events. For operational impacts on the demand site, we cannot exclude the risk with certainty and further investigation is required. In technical terms, although risks are expected to be low, power oscillations which result in possible instability of controllers could occur. The controlled power electronics, such as the convertor, will try to maintain its output stable by changing the set-point for switching and momentarily operating in a less optimal fashion.

It is unlikely that degradation (wear & tear) of the controlled power electronics or its connected load will increase due to higher RoCoF events if the device does not trip. The higher RoCoF strains the control algorithms and not so much the power components. Wear & tear of the system is accelerated in the event of a trip of the system, in which case of equipment and material (transformers, filters, switches, circuit-breakers, capacitors, auxiliaries, etc.) are affected due to the de-energisation and re-energisation.

3.1.3 (Interface) Protection

All grid connected devices have some sort of interface protection to disconnect the connected device under emergency conditions, typically when the grid's parameters are outside of its nominal (or safe) limit values. For low power equipment, this is typically overcurrent protection (fuses, small circuit-breakers), but for larger equipment this functionality is more sophisticated. The implementation of interface protection features are always part of the power electronics system but can be either embedded in the power electronic control software or implemented as a separate protection relay. More information is provided in the Annex of this report.

The type testing of power electronic inverters incorporates compliance tests towards the EN50438 standard of 2008 when used for embedded generation. It shall be noted that this includes a shutdown action in the event of a RoCoF for Ireland and Northern Ireland of 0.4 Hz/s over 500 ms or a 6 degree vector shift over 500 ms. For Denmark and Germany, as an example, this includes a RoCoF value of 2.5 Hz/s over 200 ms, and1 Hz/s over 200 ms respectively.

RoCoF and Vector Shift protection are aimed at anti-islanding, required to avoid dangerous uncontrolled small system island operations. Although this project report does not look at generation, it is important to note that anti-islanding protection might be incorporated in the power electronic devices, especially when used in combination with embedded generation. Since the standard EN50438 specifies 0.4 Hz/s over 500 ms or a 6 degree vector shift over 500 ms. a RoCoF of 1 Hz/s could result in demand customer tripping if anti-islanding protection is installed and therefore protection settings may need to be altered.

3.1.4 UPS systems

There are static Uninterruptable Power Source (UPS) systems using batteries and rotating UPS systems using motors. The functionality of a UPS system is to make sure that if the power source is interrupted the demand customer will receive power from this back-up supply immediately.

It is important to recognise that, although UPS systems are fast acting devices, the technology both static and rotating UPS systems are in principle not designed to supply power in response to a RoCoF event.

Impacts on static or rotating UPS systems have not been investigated and are out of scope of this project, however, a quick scan learns that such equipment is unlikely to be affected by a RoCoF event and therefore resilient.

3.2 Direct AC connected load

Direct AC connected load does not include the use of power electronic interface like convertor or inverters and as a result any change of frequency will be "seen" by the demand customer connected. Different industries will have different direct connected loads. In this sub-section we will explain the likely impacts for the different type of loads that have been identified in Table 1.

Depending on the size of load, typical operation voltage levels are 0.4 kV up to 11 kV. For very large consumers, higher voltages are also used but are less common in Ireland and Northern Ireland with the exception of alumina refineries where the plant is connected at a voltage level of typically 132 kV.

When assessing the direct connected load types from a technical perspective, we have identified three main categories, namely:

- Synchronous motors, these are normally only used for very large loads in the order of 10 MW and above;
- Asynchronous motors, these can be found in most industries and are the most common rotating load demands found for rotating machinery; and
- Resistive loads, these are typically used for heating or lighting and can also be found in most industries.

The subsections below will explain the direct AC connected demand customers in more detail.

3.2.1 Synchronous motors

Synchronous machines are common for generators, however synchronous motors are not used so much in the industry. Only for very large loads, typically between 10 MW and 20 MW, do synchronous motors have the advantage over asynchronous motors (induction motors). Although there are high speed motors for blowers of blast furnaces, most synchronous motors will typically be used for constant and slow rotation operation, e.g. milling in coal plants, centrifugal compressors for large oxygen plants. As a result these motors will have multiple pole pairs which make the equipment robust against RoCoF.

In the list of demand load customers we have listed the following industries using synchronous motors:

- Alumina refinery
- Cement industry

The RoCoF effect on synchronous motors is similar to that of synchronous generators. Simulations show that for motors with a high pole pair number, and thus slow rotation, a real unstable case is rare. Only when a 2 pole motor, for high speed operations, is used in the simulations there are cases, at a RoCoF of 2 Hz/s, where in which the machine loses synchronism.

According to the simulations performed, the risks for different RoCoF values are provided in Table 6.

Table 6 - Qualitative overview of RoCoF impact on synchronous motors

RoCoF [Hz/s]	Nr. of RoCoF events annually	Impact
0.5	10	No impact reported
1.0	10	No impact expected
1.5	10	No impact expected
2.0	10	Possible trip for high speed motors, otherwise no impact expected

Simulation results

- DNV GL designed a simplified simulation model[5] for synchronous motor operations looking at effects to RoCoF events. With the frequency traces provided by the TSOs we have analysed the effects on motor behaviour.
- In general, the characteristics of the synchronous motor make it robust against RoCoF events. The results of the simulations, based on the frequency 0.5, 1, 1.5 and 2 Hz/s traces provided by the TSOs, show that the motor stays within its design parameters and therefore are not likely to trip. If accurate speed is required for the industrial process, however, any RoCoF can present issues due to speed deviations being apparent. Although for processes where accurate motor speed is required a Variable Frequency Drive (VFD) for control will normally be incorporated.

Table 7 – Identified impact areas for synchronous direct connected motors

Areas	Affected
1 - Response of the demand site to the RoCoF event	✓
2 - Impacts on power quality provided to the site	✓
3 - Operational impacts on the demand site	✓
4 - Impacts on embedded generation within the site	✓
5 - Mechanical impacts on the demand site	no
6 - Likely impact on maintenance cycles for the plant	no
7 - Any potential safety issues for the demand site	no

As stated, the motor will respond to a RoCoF event in terms of speed and in that sense the power quality is affected by a RoCoF event. In terms of operational impact, the performance of the motor will slightly change during some seconds. However, the process the motor is used for is likely not to be adversely impacted, and hence, if accurate speed was required a variable frequency drive (VFD) would have been used. Further for the motor there is no need to have any anti-islanding protection installed. The site, however, may have such protection for its connection to the grid when it has embedded electrical energy generation installed. Consequently the demand customer is in that case in point likely to be impacted at rates of 1 Hz/s depending on the anti-islanding protection used.

The simulations show that for a 1 Hz/s RoCoF there is no adverse effect on the mechanics of the motor since the torque stays well in range of its allowance. The highest torque value was 133 % of its nominal value with a duration of some seconds. Therefore any impacts on maintenance cycles or any potential safety issues for the demand customer has not been identified with the exception for some 2 pole >10 MW motors.

3.2.2 Asynchronous

Asynchronous motors or induction motors are the most common machines used in the industry. They are of simple construction and therefore robust and easy to maintain. Asynchronous motors are easy to control and can be used where variable speed operation is required with the help of power electronics.

[5] More details with regards to the simulation models can be found in the Annex

(In the latter situation the load becomes indirectly connected to the grid by means of a controlled power electronic interface.)

From the list of demand load customers we have listed the following industries as using asynchronous motors:

- Alumina refining
- Cement industry
- Chemical industry
- Food & Drink industry

Although asynchronous motors are possibly found anywhere in the industries, the ones in the above list are the most likely applications for direct connection to the grid as opposed to the use of power electronics to control the motor speed.

Asynchronous motors rotate at a slightly lower frequency than grid frequency. This speed differential of the magnetic field and the rotor is called slip. The difference is often stated in percentage which is calculated with the formula:

$$slip\ s\ = \frac{N_s - N}{N_s}$$

Where:

- N = the rotor speed; and
- N_s = the synchronous speed of the magnetic field in the stator.

The slip has an effect on the torque of the asynchronous motor. When the slip increases, the torque developed by the motor increases and vice versa.

When analysing the effect in the short time window of 500ms and therefore looking at the dynamic behaviour when the frequency changes, the following effects are observed;

- Slip decreases if the grid frequency decreases and the developed torque therefore decrease. The other dynamic effect is also true, when the grid frequency increases, the torque increases. The torque is directly related to the power uptake the motor takes from the grid.

The short time window of the rate of change of frequency and therefore the limited total frequency change results in a minimal effect on the asynchronous motor. The motor also contributes to a damped response characteristic for the power system in the event of a RoCoF event due to the counter effect of loss of load or generation. Therefore:

- With a loss of load, the frequency will rise and as a result the asynchronous motor, if directly connected to the grid, will take more power from the grid due to the increase of slip which results in an increase of torque and thus an increase of power uptake from the grid.

- With a loss of generation, the frequency will drop and as a result the asynchronous motor, if directly connected to the grid, will decrease its uptake of power from the grid as a result of the decrease in slip and thus the lower torque.

Table 8 - Qualitative overview of RoCoF impact on Asynchronous motors

RoCoF [Hz/s]	Nr. of RoCoF events annually	Impact
0.5	10	No impact reported
1.0	10	No impact expected
1.5	10	No impact expected
2.0	10	No impact expected

Simulation results

We have designed a simplified simulation model for the asynchronous motor operations looking at effects with regards to RoCoF events. With the frequency traces provided by the TSOs we have analysed the effects on motor behaviour.

In general, the characteristics of the asynchronous motor make it robust against RoCoF events. The results of the simulations, based on the frequency 0.5, 1, 1.5 and 2 Hz/s traces provided by the TSOs, show that the motor stays within its design parameters and therefore are not likely to trip. If accurate speed is required for the industrial process a Variable Frequency Drive (VFD) is incorporated for control.

Figure 1 and Figure 2 show examples of frequency events and the effects on the asynchronous motor.

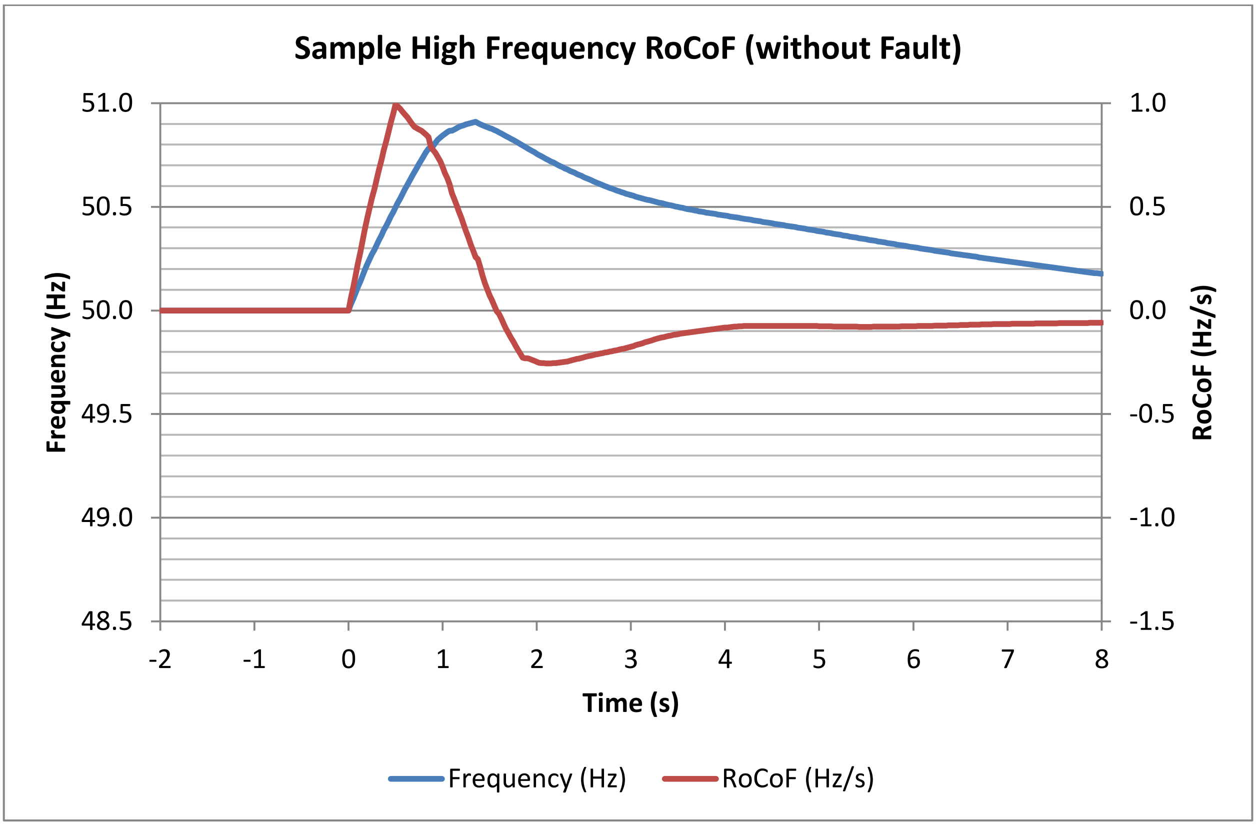

Figure 1 – 1.0 Hz/s High Frequency Trace

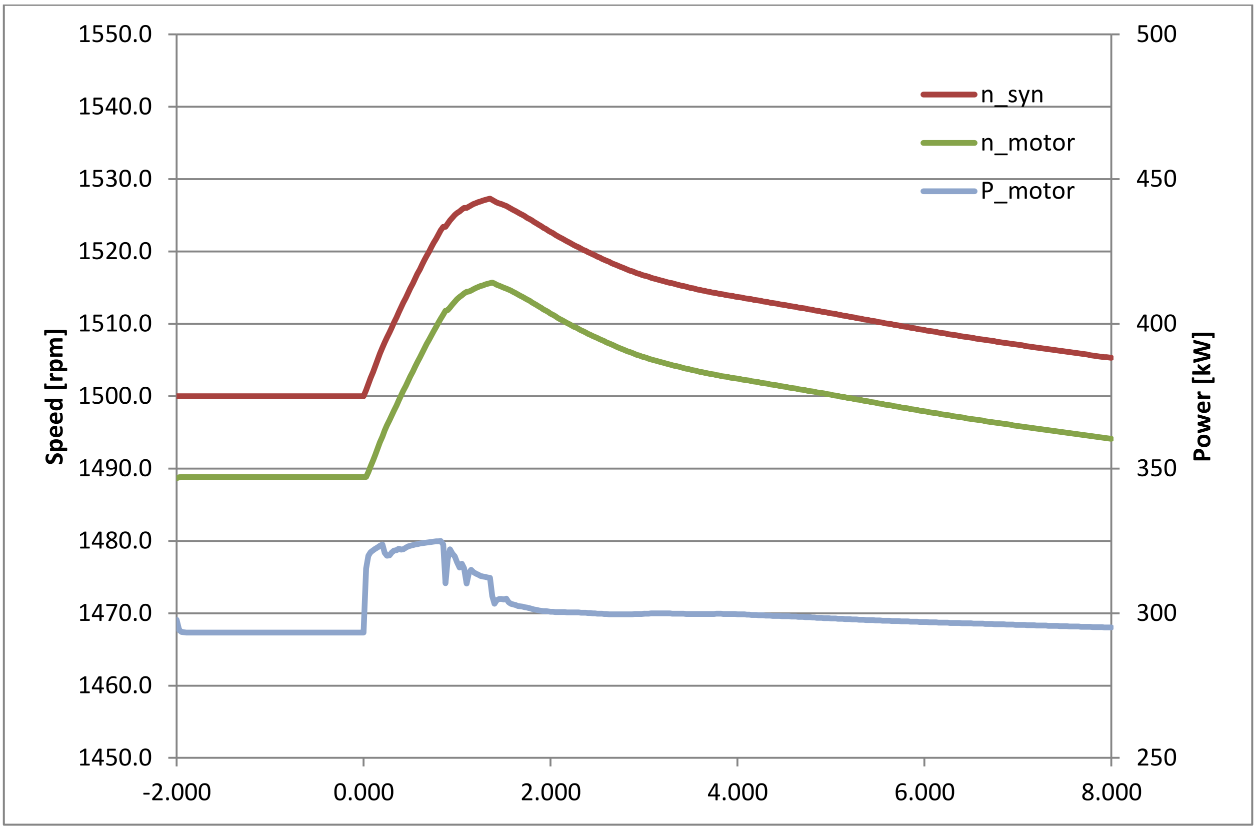

Figure 2 – 325 kW Induction Motor reaction

Similar to the synchronous motor, the asynchronous shows similar results on a generic level when looking at the 7 impacted areas analysed with regards to a RoCoF event.

Table 9 – Identified impact areas for asynchronous direct connected motors

Areas	Affected
1 - Response of the demand site to the RoCoF event	✓
2 - Impacts on power quality provided to the site	✓
3 - Operational impacts on the demand site	✓
4 - Impacts on embedded generation within the site	✓
5 - Mechanical impacts on the demand site	no
6 - Likely impact on maintenance cycles for the plant	no
7 - Any potential safety issues for the demand site	no

The asynchronous motor will see a speed deviation in the event of a RoCoF. Where accurate speed is required for the operation process the motors are likely to be equipped with VFDs. As a result it is unlikely that operations will be adversely impacted during a RoCoF event since the speed deviation, which occurs when directly connected, is small and only exists for a short duration of time.

Further for the motor there is no need to have any anti-islanding protection installed. The site, however, may have such protection for its connection to the grid when it has embedded generation installed.

Consequently the demand customer must ensure their anti-islanding protection is set so it does not trip for RoCoF up to 1Hz/s.

The simulations show that for a 1 Hz/s there is no adverse effect on the mechanics of the motor since the torque stays well in range of its allowance. The highest torque value was 161 % of its nominal value within a sub second duration. Therefore any impacts on maintenance cycles or any potential safety issues for the demand customer has not been identified. However, it is important to note that the torque is depended on the inertia of the motor plus the mechanical load connected. In some cases where a large mechanical attached load exist (without a gearbox interface to the motor) additional studies are advisable. At the same time, in the majority of cases the risks for the machine with a 1 Hz/s RoCoF are deemed to be low.

3.2.3 Resistive load

Resistive loads are typically lighting and electrical heating applications.

For the list of demand load customers we have only listed the food and drink industry for heating processes although in most cases the autoclaves are using power convertors for controlling DC power. In addition, all industries will use lighting and thus have resistive loads.

In practice a resistive load typically has a capacitive or inductive component which is affected by frequency (changes). However, analyses show that there is no large contribution of those components for the loads assumed, e.g. lighting and heating, and are therefore not considered for adverse effects in terms of RoCoF.

For resistive loads there is no frequency element that will have an effect on the power uptake. The formula for a resistive load in a 3 phase AC power system is:

$$P = R * I^2 * 3$$

Where:

- P = power uptake;
- R = resistive load; and
- I = the current.

As a result of above formula, a RoCoF event will not have an effect on a pure resistive load.

Table 10 - Qualitative overview of RoCoF impact on resistive load

RoCoF [Hz/s]	Nr. of RoCoF events annually	Impact
0.5	10	No impact reported
1.0	10	No impact expected
1.5	10	No impact expected
2.0	10	No impact expected

4 CONCLUSION

DNV GL has undertaken a high-level assessment for frequency deviations and the possible effects on demand customers, providing a line of sight for required mitigation actions or the identification of further study areas with regards to the in principle agreed 1 Hz/s RoCoF in the Grid Code.

For this assessment five different load types are identified for a high-level representation of typical demand customers in Ireland and Northern Ireland shown in Table 9.

Table 9 - Characterisation of industrial load types

Industrial categories	**Indirect AC connected** Power Electronics Uncontrolled	Power Electronics Controlled	**Direct AC connected** Synchronous motors	Asynchronous motors	Resistive load
Pharmaceutical processes		✓			
Semiconductor fabrication		✓			
Alumina refinery	✓	✓	✓	✓	
Cement industry			✓	✓	
Chemical industry		✓		✓	
Data centers		✓			
Critical load including hospitals	✓				
Food & Drink industry	✓	✓	✓	✓	✓
Influenced by RoCoF	✓	✓	✓	✓	

DNV GL concludes that, although most load types could be influenced by RoCoF, the risks for the majority of demand customers associated with the higher rate of change of frequency values up to 1 Hz/s are low.

<u>For indirect AC connected loads</u>, in extreme cases, power electronics seem less resilient to high RoCoF values than direct AC connected loads meaning that further investigation may be required for some customers. DNV GL anticipates that in cases where controlled power electronics are initially affected by RoCoF values larger than 1 Hz/s mitigation are possible by changing software parameter settings. As a result, the risks identified in this document will be further mitigated.

<u>Embedded generation.</u> Where demand customers have installed embedded generation the anti-islanding (Loss of Mains [LOM]) protection need checking and possibly changed in accordance with the Grid Code for both direct and indirect connected loads. There might be a risk that controlled power electronic devices, if LOM protection is embedded in the electronics itself, will trip in a 1 Hz/s RoCoF event. However, mitigation is possible when LOM protection is separate or can be altered by changes in

software parameters. The latter applies for most controlled power electronics. For direct connected loads, separate protection relays will be installed with LOM-protection if the grid connection also facilitates embedded generation. The latter might require additional investigation.

Direct connected loads are mostly resilient for the 1 Hz/s RoCoF levels. The simulations performed by DNV GL show that only in some cases 2 pole synchronous motors show not to be suitable for high RoCoF events (an unstable situation was found for a specific >10 MW high speed synchronous motor when a 2 Hz/s frequency deviation was applied). As a result DNV GL advises additional studies where 2 pole (high speed) synchronous motors are applied and are directly connected to the grid. DNV GL anticipates that the number of such large motors in Ireland and Northern Ireland will be small and therefore risks are low.

Effects on demand customers. The additional stress on the equipment simulated, when there is no trip, was found to be within the normal parameters of the machinery. For indirect connected loads there was no direct effect on the demand customer or power electronics found in this high-level assessment. Analysing the direct connected load, the highest additional torque found in a motor was 160.5 % of its nominal load during a sub-second period which is far within a conservative allowable range of 200 %. This value is unlikely to have any effect on the life-time of the equipment assuming ten 1 Hz/s events annually even where some of the frequency trace used also included a system fault as opposed to just a RoCoF event. For large 2 pole synchronous motors and for asynchronous motors where the mechanical load (mass) is significant with regards to the motor itself it should be noted that for RoCoF events greater than 1 Hz/s possible damage could be a result. DNV GL believes, however, that the number of such large motors in Ireland and Northern Ireland will be low. Further analysis should be considered if assurance over these types of motors is required. For all the other load types studied, no clear detrimental effects on demand customers for a RoCoF value of 1 Hz/s measured over 500 ms could be identified and therefore the associated risk is deemed to be low.

5 REFERENCES

References:

[1] X. Cao; I. Abdulhadi; A. Emhemed; C. Booth; G. Burt, "Evaluation of the impact of variable system inertia on the performance of frequency based protection," Developments in Power System Protection (DPSP 2014), 12th IET International Conference on, Year: 2014, Pages: 1 – 6

[2] F.M. Gardner, "Phaselock techniques", Edition:3 , year: 2005.

[3] Anton Ishchenko ,"Virtual Synchronous Machines for Frequency Stabilization in Future Grids with a Significant Share of Decentralized Generation (VSYNC)", Internal project report, September 2009

[4] S. Raza; H. Mokhlis; H. Arof; J. A. Laghari; H. Mohamad, "A Sensitivity Analysis of Different Power System Parameters on Islanding Detection," IEEE Transactions on Sustainable Energy, Year: 2016, Volume: 7, Issue: 2, Pages: 461 – 470

[5] H. H. Zeineldin and J. L. Kirtley, "Performance of the OVP/UVP and OFP/UFP method with voltage and frequency dependent loads," IEEE Trans. Power Del., vol. 24, no. 2, pp. 772–778, Apr. 2009.

[6] EES-UETP Course "Advanced Protection of Distribution Networks with Distributed Generators", Date:- 8 – 10 March 2011, Venue: University of Manchester

[7] Bifaretti; A. Lidozzi; L. Solero; F. Crescimbini, S., "Anti-Islanding Detector Based on a Robust PLL", IEEE Transactions on Industry Applications, Year: 2015, Volume: 51, Issue: 1, Pages: 398 - 405

6 LIST OF ABBREVIATIONS AND ACRONYMS

- Alternative Current (AC)
- Direct Current (DC)
- Distributed Generators (DG)
- Grid Code (GC)
- Insulated-Gate Bipolar Transistor (IGBT)
- Pulse Width Modulation (PWM)
- Rate Of Change Of Frequency (RoCoF)
- Renewable Energy Sources (RES)
- System Non Synchronous Penetration (SNSP)
- Variable Frequency Drive (VFD)
- Uninterruptable Power Source (UPS)
- Loss Of Mains (LOM)
- Under Frequency Load Shedding (UFLS)

ANNEX

(Interface) Protection

All grid connected devices have some sort of interface protection to disconnect the connected device under emergency conditions, typically when the grids parameters are outside of its nominal (or safe) limit values. For low power equipment this is typically overcurrent protection (fuses, small circuit-breakers), but far larger equipment this functionality is more sophisticated.

Controlled Power electronics interfaces often embed this protection functionality within the power electronics control system itself. If this is not possible or unwanted, an external protection relay is used to implement this functionality.

The functionality provided by the more sophisticated interface protection devices, typically include under/over voltage, under/over frequency. It also includes anti-islanding (e.g. loss of mains) protection if the associated power electronics interface is capable of four-quadrant control, such as for embedded generators, grid-connected battery systems, and variable frequency drives with power recuperation capabilities.

Anti-islanding detection techniques

Anti-islanding protection schemes are either based on RoCoF [7] or Vector shift[6] techniques. Their effectiveness (sensitivity vs. stability, no nuisance trips) depends on the inertia of the grid and the use of embedded generation. If the RoCoF events increase they will be interpreted as vector shifts in the frequency, thereby also influencing the protection schemes implementing the vector shift technique.

Existing frequency-based protection, such as distributed generator (DG) frequency based anti-islanding protection and under frequency load shedding (UFLS), potentially mal-operate more frequently under low inertia at high RoCoF excursions conditions [1].

The operation of unexpected under-frequency-load-shedding (UFLS) due to the lower system inertia [resulting in larger RoCoF excursions] will result in interruptions to supplies. Furthermore, if the frequency keeps decreasing, the potential disconnection of DGs which are exporting power and connected downstream of the contracted UFLS disconnection point could also initiate a second stage frequency drop [1].

Active filters

Further research is needed in the area of active harmonic filters tuned to integer multiples of 50 Hz and the influences of larger RoCoF excursions occur. The analyses of active filters are beyond the scope of this project. Questions could be raised with regards to possible unexpected (temporary) increases in THD due to higher RoCoF events and if this might causing violations of Grid Codes or malfunctioning of directly connected or neighbouring equipment.

Simulation model

The calculations for this study are performed using numerical analysis in a semi simplified mathematical model which was previously build for the generator studies by DNV GL. The model has been modified to simulate behaviour of synchronous motors as opposed to synchronous generators. A second model has been built to simulate behaviour of Asynchronous motors as opposed to Synchronous motors. The selected motor characteristics used in the model presenting common electrical loads typically used in the industry were checked by the TSOs. In the model of both the synchronous and asynchronous motors we have simulated the demand customer behaviour using the frequency traces provided by the TSOs and detailed in the next section of this document. The frequency traces, showing the RoCoF, was used to be able to observe the effects on the loads.

RoCoF traces

The EirGrid group, EirGrid and SONI, has provided RoCoF frequency traces for 0.5, 1 and 1.5 - 2 Hz/s which are a combination of measurement and simulations of events in the All-Ireland electricity transmission system. This information was used to make a qualitative analysis of the simplified load simulations models of DNV GL looking at the RoCoF characteristics direct connected loads together with the other qualitative assessments of indirect connected loads.

The Figure 3 shows the trace of a 0.5 Hz/s low frequency event.

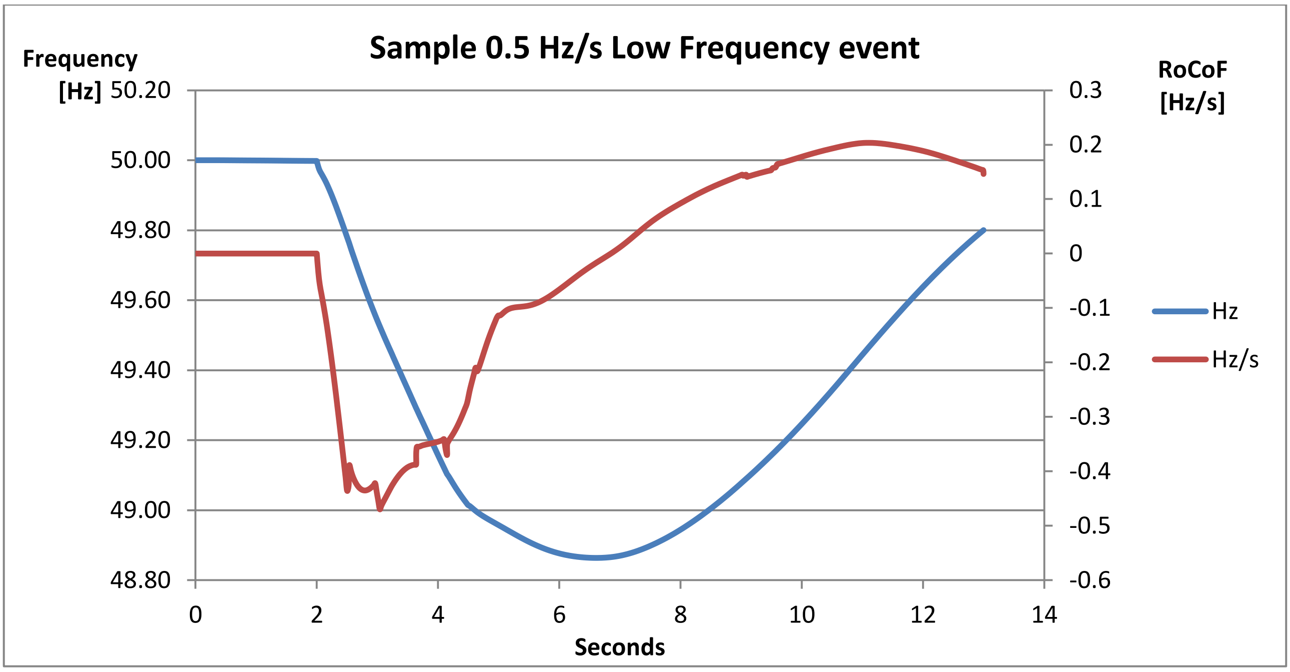

Figure 3 – 0.5Hz/s Low Frequency Trace

The Figure 4 shows the trace of a 1.0 Hz/s high frequency event.

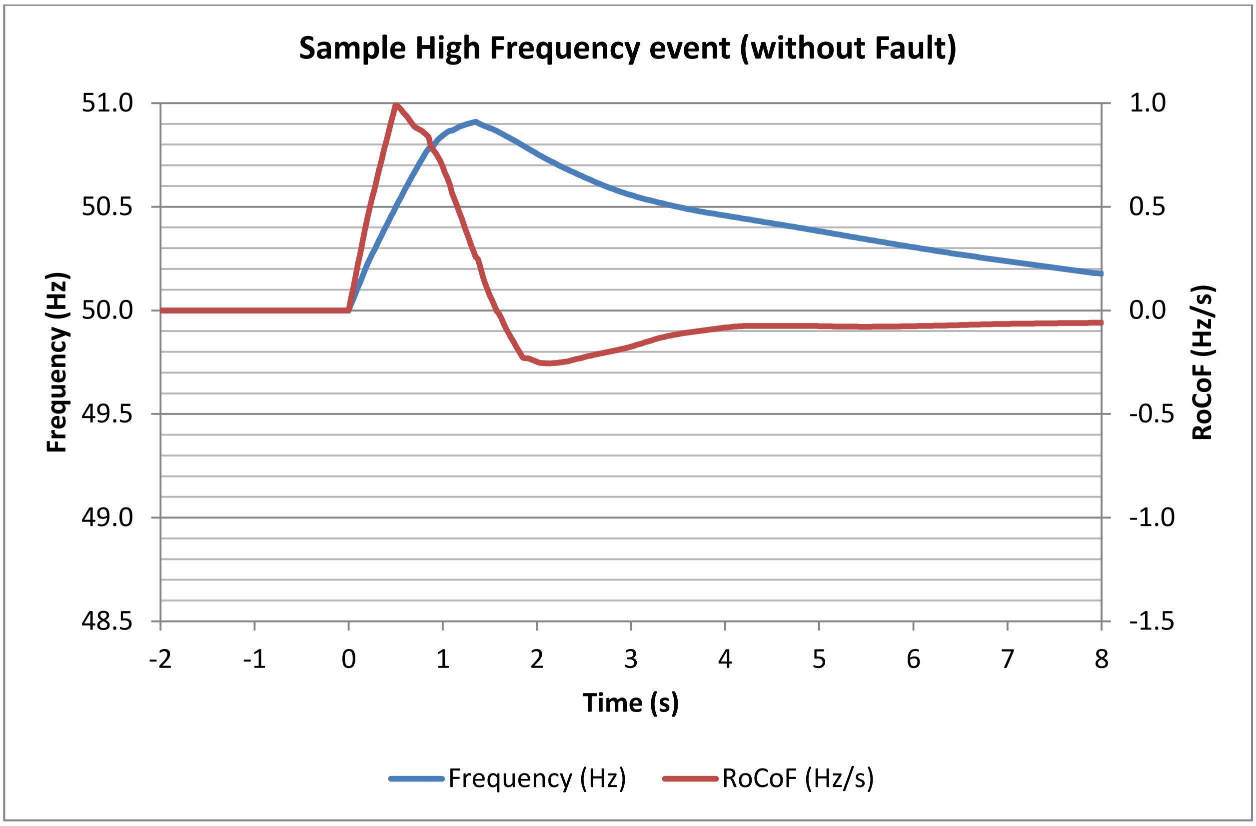

Figure 4 – 1.0 Hz/s High Frequency Trace

The Figure 5 shows the trace of a 1.0 Hz/s high frequency event with an electrical fault.

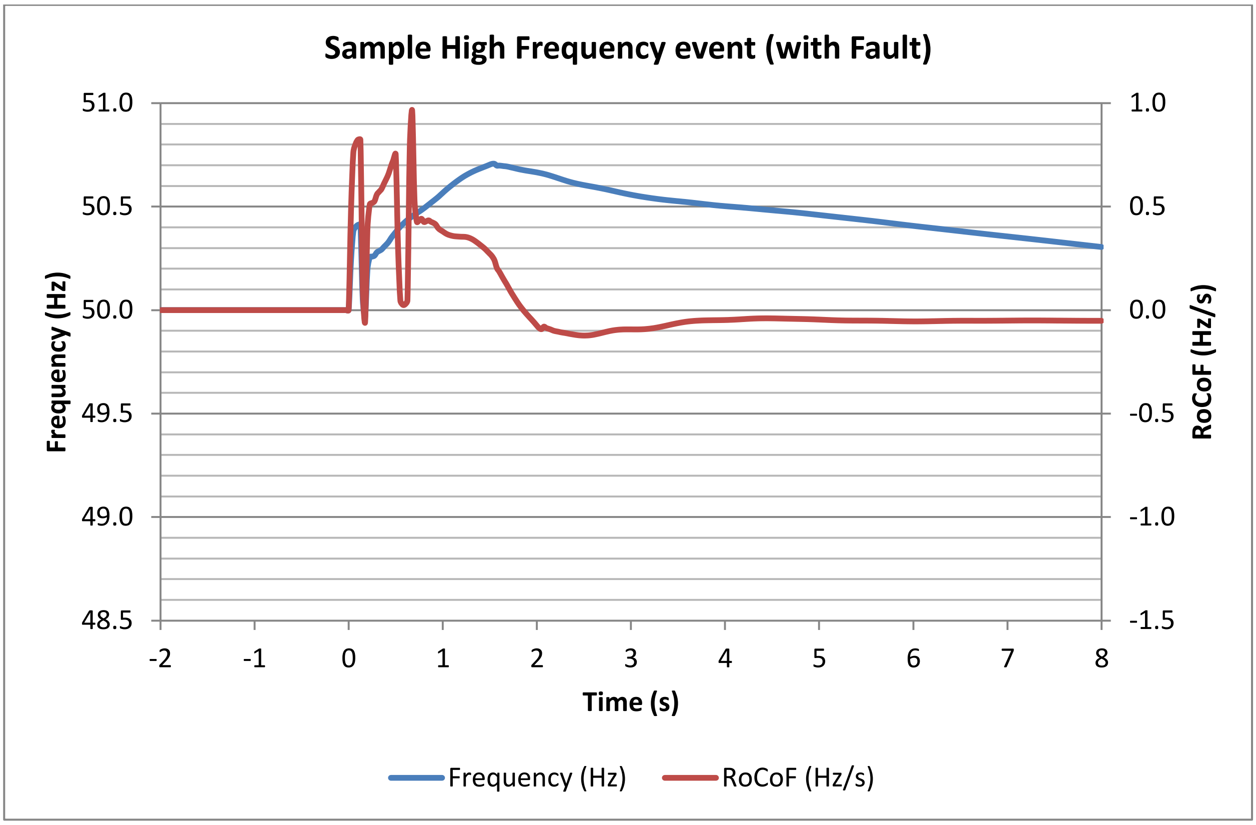

Figure 5 – 1.0 Hz/s High Frequency Trace with an electrical fault

The Figure 6 shows the trace of a 1.0 Hz/s low frequency event.

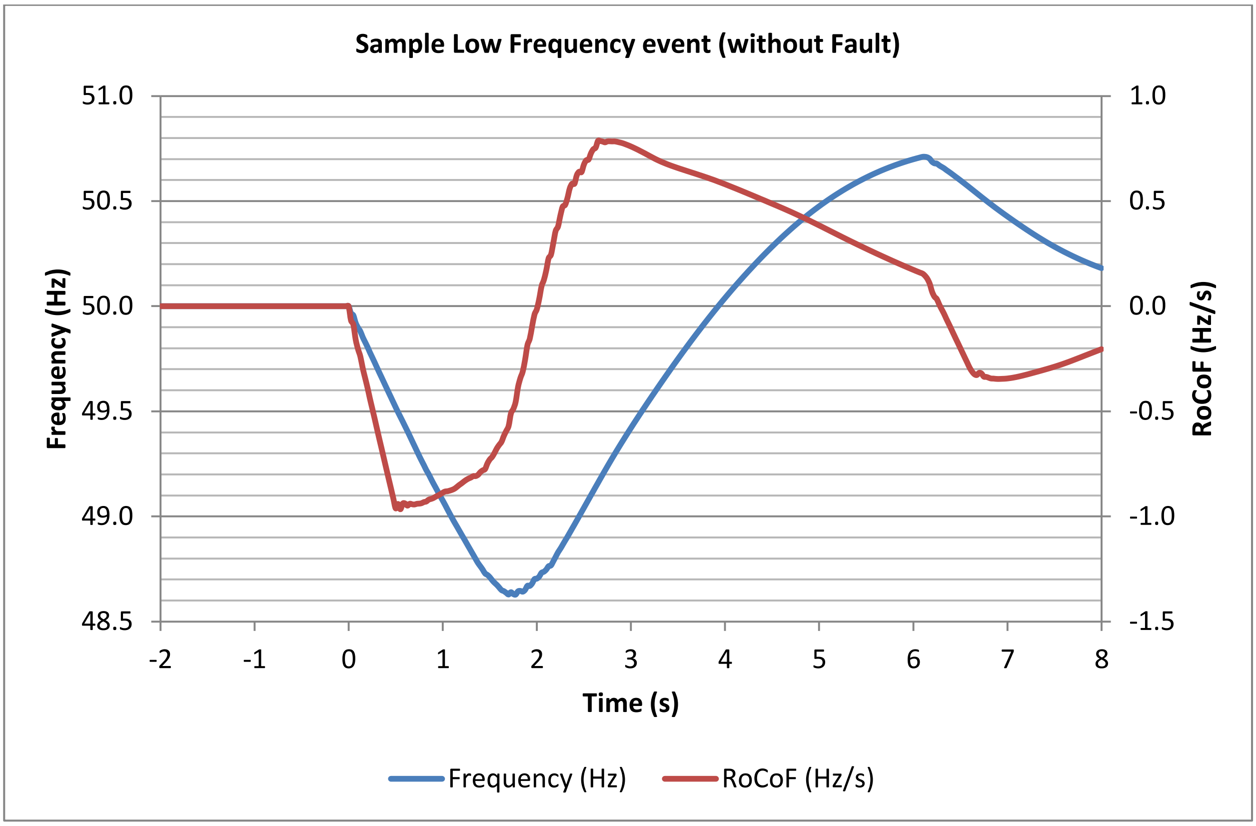

Figure 6 – 1.0 Hz/s Low Frequency Trace

The Figure 7 shows the trace of a 1.0 Hz/s low frequency event with an electrical fault.

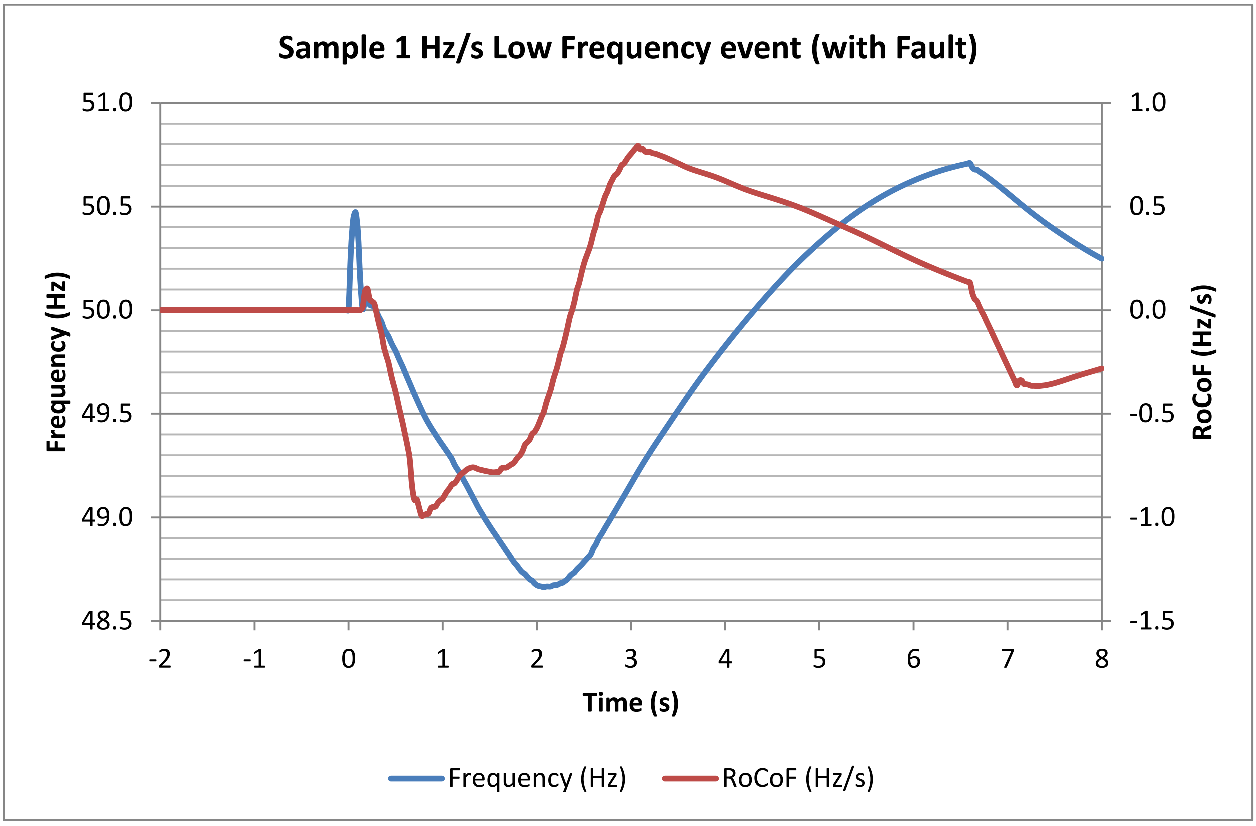

Figure 7 – 1.0 Hz/s Low Frequency Trace with an electrical fault

The Figure 8 shows the trace of a 1.5 Hz/s high frequency event.

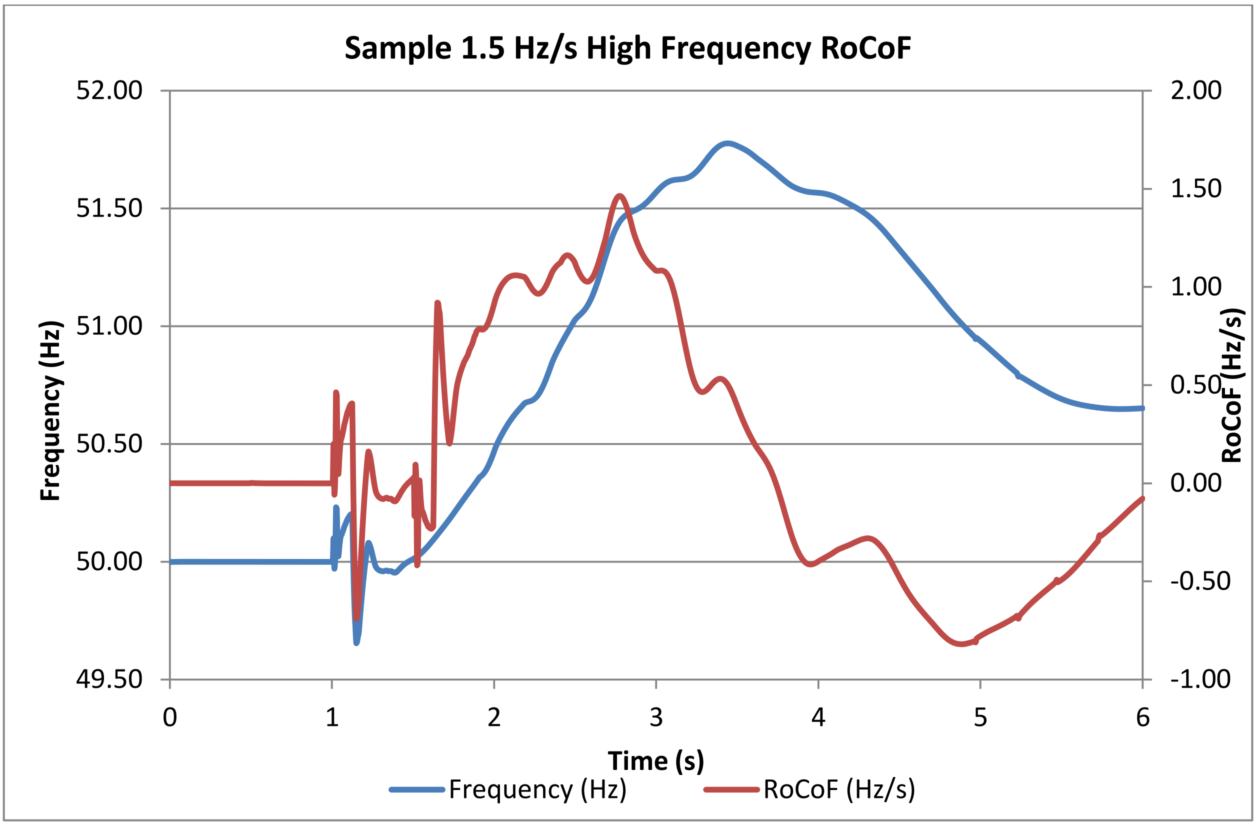

Figure 8 – 1.5 Hz/s High Frequency Trace

The Figure 9 shows the trace of a 2.0 Hz/s low frequency event.

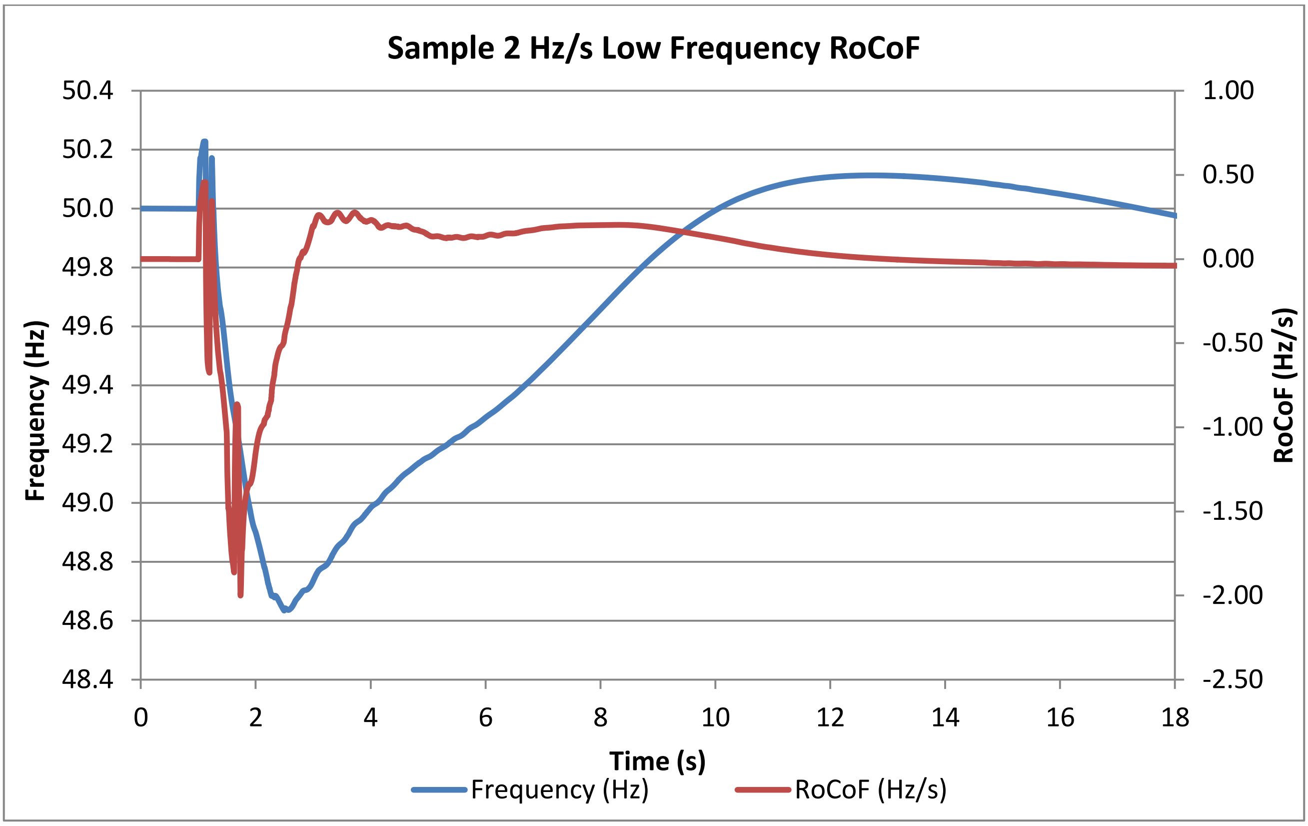

Figure 9 – 2.0 Hz/s Low Frequency Trace

About DNV GL

Driven by our purpose of safeguarding life, property and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. We provide classification and technical assurance along with software and independent expert advisory services to the maritime, oil and gas, and energy industries. We also provide certification services to customers across a wide range of industries. Operating in more than 100 countries, our 16,000 professionals are dedicated to helping our customers make the world safer, smarter and greener.