Analysis of the Frequency Response of the Power System Following Large Disturbances

August 2012

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1 Purpose

There is ongoing discussion in the Joint Grid Code Working Group about changing the obligations on generators to be able to ride through rates of change of frequency (RoCoF) in excess of 0.5 Hz/s. This document examines evidence from historical events in Ireland and Northern Ireland power system where high RoCoF values have been experienced. In addition to this, a review of events from relatively small international synchronous systems has also been conducted. Of particular interest were island systems that face similar challenges as Ireland and Northern Ireland in integrating large amounts of non-synchronous generation. Three TSOs were consulted and these were from New Zealand, Hawaii and Cyprus. Events from these power systems are presented in this report. Where possible the RoCoF values presented will be calculated using the TSO's definition of RoCoF based on a 500ms measuring window [1].

2 Background

EirGrid and SONI, the Transmission System Operators (TSOs) in Ireland and Northern Ireland have a responsibility to operate the power system in a secure, safe and reliable manner. Considerable technical challenges exist when integrating large amounts of non-synchronous renewable generation into the power system. In order to achieve Ireland's and Northern Ireland's 2020 targets these technical challenges must be addressed to ensure that the system can operate in a secure manner.

Rate of change of frequency (RoCoF) following a large system disturbance is one of the major issues associated with system security when high levels of non-synchronous generation are connected to the system. Detailed technical studies have indicated that during times of high wind generation following the loss of the single largest credible contingency, values of greater than 0.5Hz/s could be experienced on the all-island power system. Indeed, these values can exceed 0.7 Hz/s for the loss of the largest in-feed on the island depending on the scenario being studied and the method used to calculate RoCoF.

As a result of discrete generation units representing significant proportions of total generation, the all-island power system experiences significant frequency deviations and higher levels of RoCoF compared to larger power systems. The events presented in this report provide evidence into the capability of generators during low frequency events and high RoCoF values.

[1] "GC1 Modification Proposal Form", EirGrid-SONI June 2012

3 Historic events on the Power System of Ireland and Northern Ireland

3.1 Ireland Events

This section describes an event which occurred on the Ireland Power System in 1988. It should be noted that for this event the power systems in Ireland and Northern Ireland were separated and therefore acted as isolated systems.

The event occurred on 31-May-1988 and involved a double tripping of two large thermal units at the same time. The power system experienced a RoCoF of 0.5 Hz/s after the first unit tripped and a RoCoF of 0.9 Hz/s for the second tripping. There were no reports of mechanical failure or cascade tripping of connected generators due to the RoCoF event. A summary of the system data for this event is given in Table 2. It should be noted that the RoCoF was measured from the time of unit tripping to frequency nadir these times are unknown but would give RoCoF have been greater than 500 ms.

Table 1: Summary of system data for May 1988 event.

Date	31-May-1988
Frequency nadir	48.47Hz
RoCoF (Hz/s)	0.9Hz/s
Units in service	Unknown
Load-shedding	Unknown
Estimated RoCoF over 500 ms	Unknown

3.2 Northern Ireland Events

This section describes events which occurred on the Northern Ireland Power System during the time when the power systems in Ireland and Northern Ireland were separated and therefore acted as isolated systems.

3.2.1 Event from 1988

The first event investigated on the Northern Ireland (NI) power system in August 1988. This event involved the tripping of a unit on the system which resulted in a low frequency incident. It should be noted that there was no non-synchronous generation present on the system at this time. The following table summarises the system performance for the event.

Table 2: Summary of system data for August 1988 event

Date	04-Aug-1988
Frequency nadir	48.8 Hz
RoCoF (Hz/s at frequency nadir)	0.73 Hz/s
No. of units in service	Unknown
Load-shedding	Yes
Estimated RoCoF over 500 ms	0.82 Hz/s

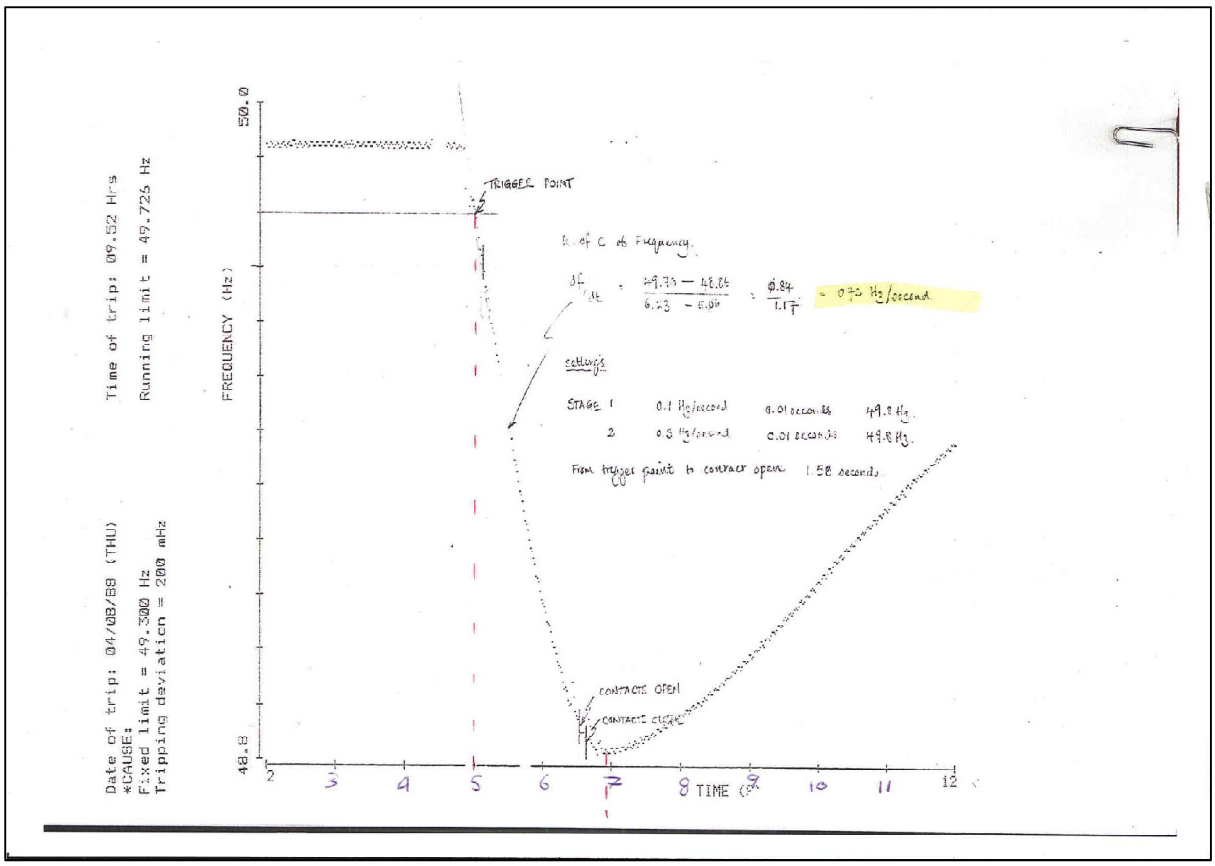

Figure 1: NI system frequency trace 1988

Figure 1 shows the frequency trace from the event in August 1988. There was no record of the unit that tripped however given the severe nature of the fault it suggests that a large machine was most likely generating at a high output and tripped from the system causing a RoCoF of 0.73 Hz/s. It should be noted that that the RoCoF was measured from the point of the unit trip to the frequency nadir which was a time of 1.17 seconds. The RoCoF in this event is higher when measured over a 500 ms window. From the graph this can be estimated to be in the region of 0.82 Hz/s. The smooth frequency trace would suggest that no other generator tripped as a result of low frequency or RoCoF.

There were no reported mechanical failures of units or cascade tripping incidents due to the RoCoF experienced in this event.

3.2.2 Event from 1994

The following event occurred on the Northern Ireland system in February 1994. The power systems in Ireland and Northern Ireland were again separated at the time of this event. This event is one of the most significant events to have occurred on the NI system and resulted in the lowest frequency dip ever recorded on the system.

Salt deposits on the 275 kV bushings at Kilroot power station resulted in the loss of both double circuits and almost 400MW of generation. As a result, the frequency dropped and three units did not respond due to governor mal-operation. During commissioning of these three units the new electronic governors, speed validation settings were not correctly programmed into the software i.e. the units would trip during a low RoCoF event. This incorrect speed validation setting meant the units tripped out due to Rate of Change of Frequency. The event resulted in the frequency on the system dropping to 47.6 Hz and activation all 10 stages of load shedding resulting in 80% of NI customers losing supply. Following the incident the electronic governors were re-programmed correctly. Tests after the event indicated the software on the electronic governors had been adjusted to provide an improved speed validation trip setting of 8.3Hz/sec.

Table 3 summarises the system data for the event. There was no non-synchronous generation present on the system at the time of the event.

Table 3: Summary of system data for February 1994 event

Date	03-Feb-1994
Frequency nadir	47.6 Hz
RoCoF (Hz/s) over 500 ms	3.7 Hz/s
No. of NI units in service prior to fault	10
Load-shedding	Yes

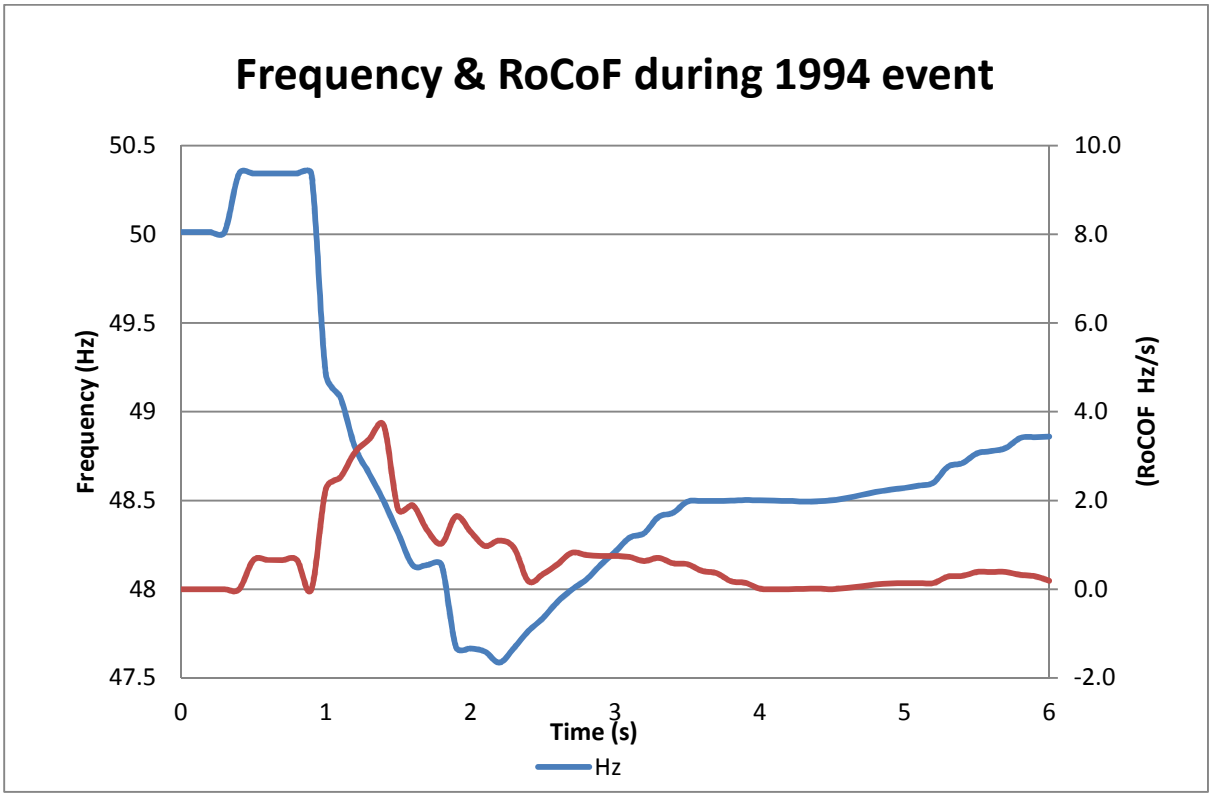

Figure 2: NI system frequency and RoCoF trace 1994

Figure 2 shows the lowest frequency experienced on the Northern Ireland power system on record. The frequency nadir was recorded at 47.6 Hz. An initial RoCoF of 3.7 Hz/s was recorded and a second RoCoF of 1 Hz/s was recorded when the 'lighter' system began to recover. Both RoCoF values were determined over a 500 ms window which is in line with the proposed Grid Code standard. Despite the high RoCOFs experienced for this event there were no reports of mechanical failure of generating units on the system.

3.3 All-Island Events

The following section describes events which occurred on the All-Island power system. In these events the power systems of Ireland and Northern Ireland were coupled.

3.3.1 Event from 2005

The following event occurred in August 2005 due to the mal-operation of the Moyle interconnector protection scheme. This scheme is in place to protect the NI system should the loss of the North-South tie-line occur, i.e. in conditions when NI is importing on Moyle and sending power south on the main north-south tie-line. This event resulted in the sympathetic tripping of a thermal unit on the Ireland system. The system frequency dropped to 48.4 Hz and load-shedding occurring in both Ireland and Northern Ireland. Prior to the fault the Moyle interconnector was importing 115MW and at the frequency nadir was exporting 400MW due to the special protection scheme. The all-island wind generation at the time of the event was 140 MW and the all-island SNSP level was 3.5%. Table 5 summarises the system data for this event.

Table 4: Summary of system data for August 2005 event

Date	05-Aug-2005
Frequency nadir	48.4 Hz
RoCoF (Hz/s) over 500 ms	0.35 Hz/s
No. of EirGrid units in service prior to fault	17
No. of SONI units in service prior to fault	7
All-Island Wind	140 MW
All-Island SNSP	3.5 %
Load-shedding	Yes

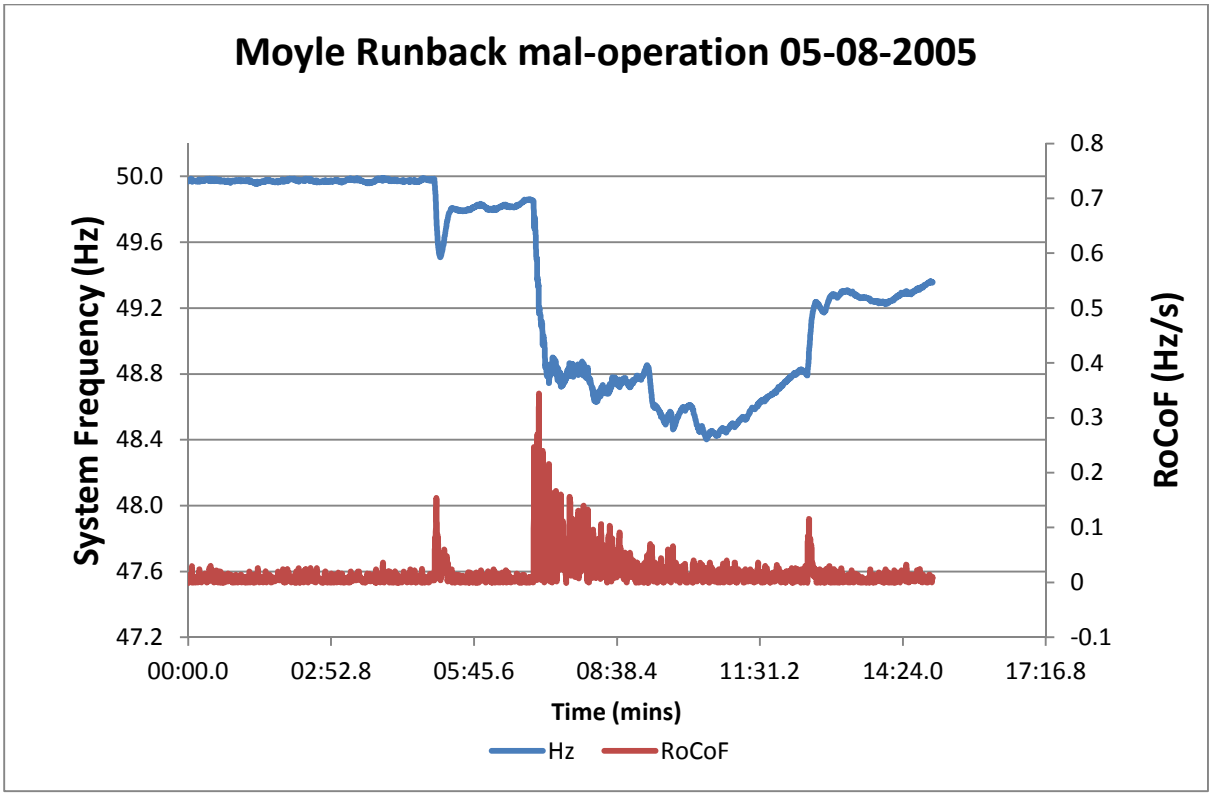

Figure 3: Frequency and RoCoF traces for system event 04-AUG-2005

Figure 3 shows the frequency trace and RoCoF experienced for the mal-operation of the Moyle protection system. The frequency nadir reached 48.4 Hz and multiple blocks of load were shed. The maximum RoCoF recorded was 0.35 Hz/s. No generators were reported to have tripped as a result of the RoCoF event. The RoCoF for this event was determined by using a 500 ms time period.

3.3.2 Event from April 2010

This event occurred in April 2010 due to the tripping of a large thermal unit on the Ireland Power System. There was a significant amount of wind generation on the system at the time of the event of 1040 MW. The all-island SNSP was 30.5% at the time of the event. The system frequency dropped to a nadir of 49.03 Hz resulting in load-shedding on the power system. A summary of the data for the for the event is displayed in Table 5.

Table 5: Summary of system data for April 2010 event

Date	27-Apr-2010
Frequency nadir	49.0 Hz
RoCoF (Hz/s) over 500 ms	0.27 Hz/s
No. of EirGrid units in service prior to fault	25
No. of SONI units in service prior to fault	5
All-Island Wind	1040 MW
All-Island SNSP	30.5 %
Load-shedding	Yes

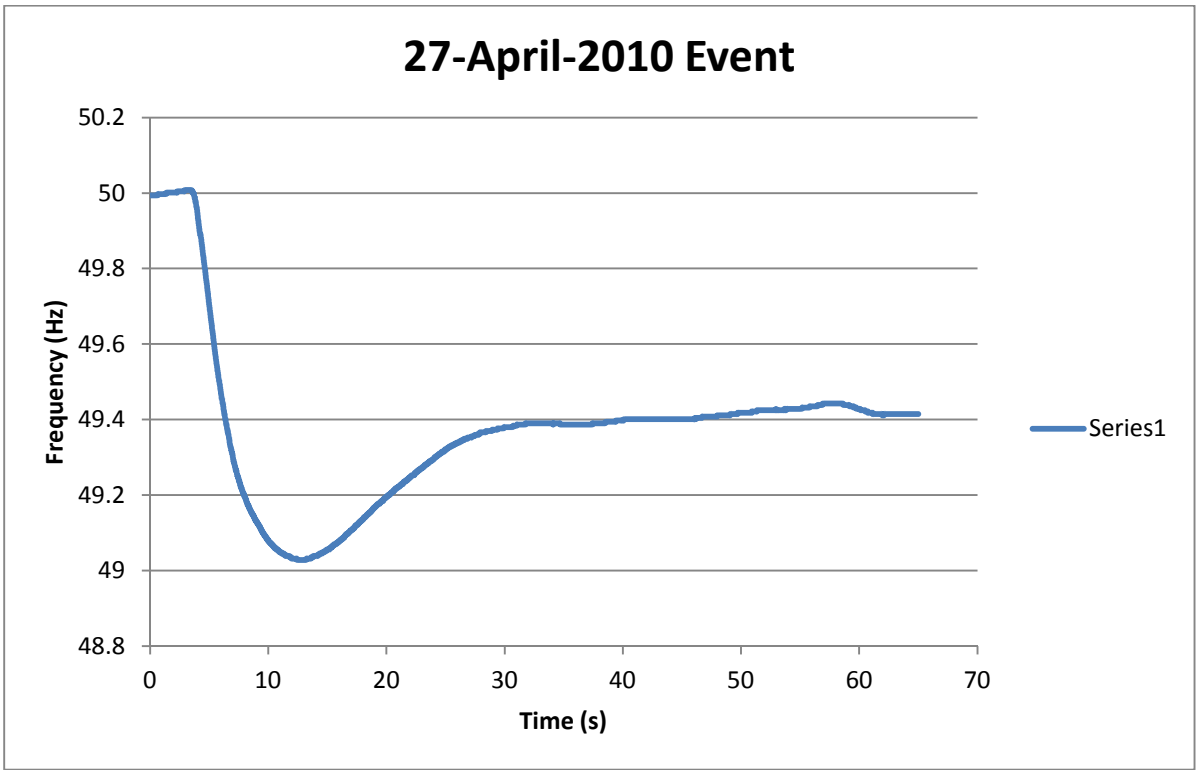

Figure 4: System frequency trace for system event 27-April-2010

The frequency trace in for the event is shown in Figure 5. The frequency nadir was 49.03 Hz and the maximum RoCoF for this event was 0.27 Hz/s measured over 500 ms. No other generator units tripped due to the event and no units reported mechanical damage due to the RoCOF.

3.3.3 Event from November 2010

The following event took place in November 2010 and involved the tripping of a large thermal unit followed with 5 seconds of another large thermal unit (due to a poorly tuned control and instrumentation issue). The systems in Ireland and Northern Ireland were coupled for this event. The all-island wind generation at the time of the event was 563 MW with a flow of 410 MW on the Moyle interconnector. This resulted in an all-island SNSP of 22% at the time of the event. The system frequency dropped to a nadir of 48.9 Hz which caused load-shedding relays to be activated in both jurisdictions. A summary of the system data for the event is given in Table 6.

Table 6: Summary of system data for November 2010 event

Date	27-Nov-2010
Frequency nadir	48.9 Hz
RoCoF (Hz/s) over 500 ms	0.29 Hz/s
No. of EirGrid units in service prior to fault	28
No. of SONI units in service prior to fault	4
All-Island Wind	563 MW
All-Island SNSP	22 %
Load-shedding	Yes

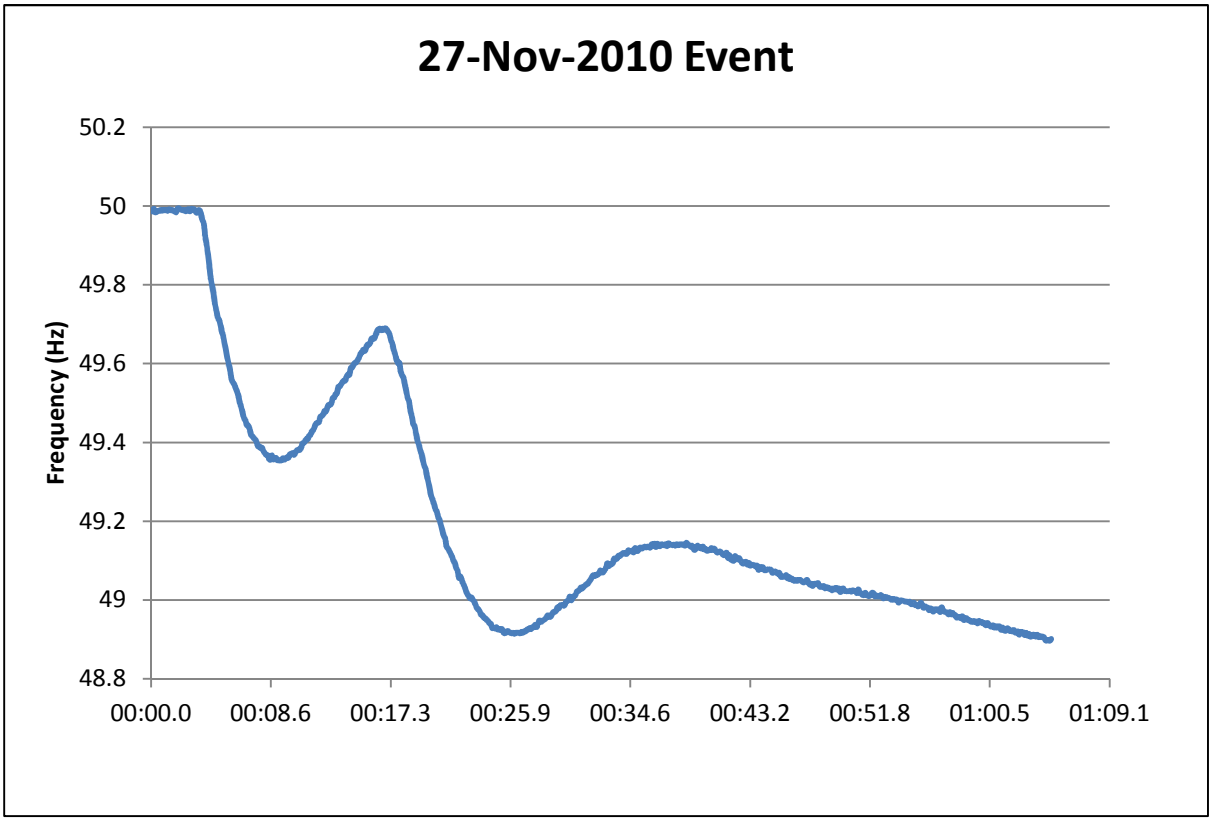

Figure 5: System frequency trace for system event 27-Nov-2010

The frequency trace in figure 4 occurred as a result of a large thermal unit tripping followed by a second thermal unit due to controller issues. The frequency nadir was 48.9 Hz and the maximum RoCoF for this event was 0.29 Hz/s. No other generator units tripped due to the event and no units reported mechanical damage due to the RoCOF.

4 International Review of Frequency Disturbances

As part of the investigation of the frequency response of power systems to large disturbances a consultation with other TSOs was performed. Of particular interest were island nations that face similar challenges as Ireland and Northern Ireland in integrating large amounts of non-synchronous generation. Three TSOs were consulted and these were from New Zealand, Hawaii and Cyprus. Each TSO provided information on standards for rate-of-change-of frequency (RoCoF) and historical events on their systems that caused large RoCoFs. The information provided by each TSO is summarised in this section.

4.1 New Zealand

New Zealand currently does not have a grid code requirement for generators in relation to RoCoF. The TSO does impose frequency limits and time durations for which a generator must stay connected but this does not relate to the rate of change of the frequency on the system.

In 2011 an event occurred on the system on the North Island of New Zealand that caused the frequency to drop to a nadir of 47.5 Hz. This drop in frequency was caused by a loss of 800 MW of generation when the load on the system at the time was 3350 MW. The initial RoCoF for the event was 0.73 Hz/s and there was no evidence of units tripping from the system as a result of this RoCoF. No information was given for the time period used to calculate the RoCoF value for this event.

Analysis of the South Island has been conducted and studies suggested that a RoCoF of approximately 1.5 Hz/s was likely for the loss of a large in-feed. Any future RoCoF standard that would be considered by New Zealand would likely be in the range of this figure. It is expected that a larger amount of non-synchronous generation will connect to the system in the future which could lead to larger RoCoFs occurring on the system.

4.2 Hawaii

Hawaii also does not have a Grid Code standard for rate of change of frequency. However, Hawaii has experienced several events which have resulted in units tripping from the system. Gas units in Hawaii were found to trip for RoCoFs in excess of 0.3 Hz/s. The RoCoF was found to cause the over-temperature protection to trip if the proportional droop response was too fast for the temperature control.

An event on the Hawaiian system in February 2010 which resulted the frequency dropping to 58.7 Hz with a RoCoF of 0.307 Hz/s. The event was initiated by the tripping of a gas unit on the system and resulted in under frequency load shedding relays being activated. No further generation tripped for this event.

A similar event on the system in July 2010 caused the frequency to drop to 57.7 Hz with a RoCoF of 0.373 Hz/s. This resulted in cascade tripping of units. The RoCoF of 0.373 Hz/s was caused by the tripping of a gas turbine unit which in turn led to the tripping of two other gas turbine units. In the aftermath of the event the controllers of the gas turbines were tuned and a position limiter was inserted for the fuel valve of each unit. No information was given for the time period used to calculate the RoCoF values for either events on the Hawaiian system.

Steam units on the system were not found to experience difficulties with these RoCoF events however, it was envisaged that a sustained change in frequency could cause problems for the steam units. Another method proposed for avoiding tripping was to modify droop settings to slow the units' response. A trade-off between changing droop settings of units' and avoiding under-frequency load shedding would also need to be taken into account.

The experience from the events on the Hawaiian system suggests that the issues experienced by conventional units could be rectified by modifying controller parameters. There was no evidence that the events resulted in significant mechanical issues for the units.

4.3 Cyprus

The Cyprus system experienced a fault on its system in January 2012 which resulted in a large RoCoF occurring. The system experienced a RoCoF of 1.3 Hz/s. A plot of the system frequency is shown in Figure 5.

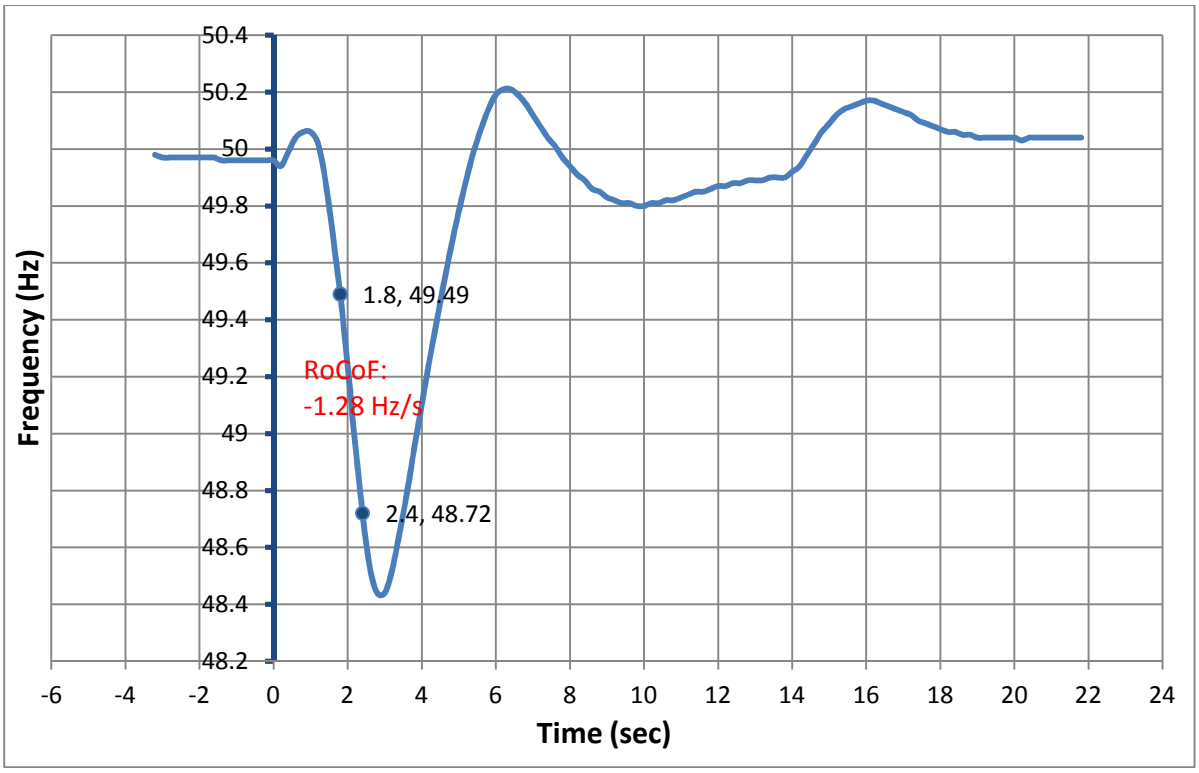

Figure 5: A trace of system frequency for the fault on the Cyprus system in January 2012.

At the time of the event demand on the system was 493 MW and wind generation was 109 MW. The wind penetration at the time of the fault was 22%. The resulting RoCoF on the system caused 68 MW of wind generation to disconnect from the system. There was no loss of conventional generation due to the RoCoF event. The reason that 68 MW of wind generation was disconnected was because protection schemes employed by the wind farms caused the wind farms to disconnect for RoCoFs in excess of 1.25 Hz/s. The TSO has subsequently requested that the trigger settings of the protection be increased to a RoCoF of 1.5 Hz/s. It can be seen from Figure 5 that the RoCoF value of 1.28 Hz/s was determined over a time period of 600 ms. A slightly higher RoCoF value of approximately 1.30 Hz/s would be recorded if a time period of 500 ms were used in the calculation method. There was no loss of conventional generation for the event and the anti-islanding RoCoF protection setting was increased to 1.5 Hz/s.

5 Summary of Results

This section gives an overview of the events described in each section of the report. Table 7 gives a description of the main points of note from each event. The table shows the frequency nadir on the system, the measured RoCoF and the equivalent RoCOF over 500 ms for each event. In addition to this the table presents whether conventional units experienced mechanical failures, direct tripping due to RoCoF or tripping due to control and instrumentation issues.

Table 7: Summary of frequency disturbance events

Event	Freq. Nadir (Hz)	RoCoF (Hz/s)	RoCoF 500 ms (Hz/s)	Gen. Mechanical failures due to RoCoF	Gen. Cascade trip due to RoCoF	Gen. trip due to control issues
Ireland						
31-05-1988	48.5	0.9	-	No	No	-
Northern Ireland						
04-08-1988	48.8	0.73	0.82	No	No	-
03-02-1994	47.6	-	3.7	No	No	Yes
All-Island						
05-08-2005	48.4	-	0.35	No	No	-
27-04-2010	49.0	-	0.27	No	No	-
27-11-2010	48.9	-	0.29	No	No	Yes
International						
New Zealand	47.5	0.73	-	No	No	-
Hawaii	57.7	0.37	-	No	No	Yes
Cyprus		1.28	1.30	No	No	-

The results in Table 7 illustrate that for the cases investigated there is no evidence of significant mechanical damage for conventional units due to high levels of rate of change of frequency. The table also illustrates that there is no evidence of generators tripping directly due to high levels of RoCoF. There were a number of cases where units tripped due to various control and instrumentation issues. In these cases the issues were addressed after the event.

6 Conclusions

This report presents a selection of system events which have occurred on the Power System of Ireland and Northern Ireland over the previous three decades. The events that were most relevant in terms of frequency deviation and rate of change of frequency (RoCoF) were selected and discussed in the report. In addition to this analysis, a consultation with other TSOs was performed to determine if similar challenges and issues have been encountered on other island power systems in relation to rate-of-change-of frequency. RoCoF has been specified as being a significant technical challenge which needs to be addressed in order to increase the amount of non-synchronous renewable generation on the power system. Conventional generator owners have expressed concerns that high RoCoF events could cause significant damage to their plant and cannot guarantee the performance of their plant beyond current Grid Code standards.

With regards to the Ireland and Northern Ireland power systems, in each of the events presented in this report there were severe faults which resulted in the frequency dropping below 49 Hz and significant RoCoF values occurring. These severe frequency transients were more common in earlier decades when there was no interconnection between the two jurisdictions. The RoCoF values seen varied with each fault/loss of generation, system condition and generation mix. In all instances, there was no evidence to suggest that generation tripped out purely due to a RoCoF event or that any conventional unit experienced any damage due to the RoCoF event.

The most significant event to occur in terms of frequency deviation and rate of change of frequency occurred on the Northern Ireland system in 1994 at a time when the systems in Ireland and Northern Ireland were isolated. This event resulted in the frequency dropping to 47.6 Hz and a RoCoF of 3.7 Hz/s occurring. In more recent times the loss of two units in 2010 caused a frequency nadir of 48.9 Hz and a RoCoF of 0.29 Hz/s on the all-island system. In both cases there was no evidence of units tripping due to RoCoF.

It should be noted that in several events examined in this report that wind generation was either non-existent at the time or was at a very low output. As the capacity of wind increases on the system it is expected that at times when non-synchronous penetration is high that similar events could result in lower frequency nadirs and higher RoCoF values. These events may also become more frequent which could cause concerns for the long term wear and tear of conventional generator units. Another point worth noting is that the RoCoF values determined for several events in this report were measured at various time periods. The proposed Grid Code standard states that the rate of change of frequency should be determined over a 500 ms period. This method would provide more onerous measurements than several of the RoCoF measurements provided in this report particularly the older events where longer time periods were used in the calculation method. An estimation of the RoCoF values for a 500 ms time period was specified for the events where possible.

A consultation with other TSOs was also performed and the TSOs of New Zealand, Hawaii and Cyprus provided details of RoCoF standards for their systems and events which have resulted in large RoCoFs occurring on their system.

It was seen in the case of New Zealand and Cyprus that despite large RoCoFs occurring on their systems due to faults, no conventional generation was disconnected from the respective systems. In these systems there was no evidence that a large RoCoF event in the region 0.7-1.3 Hz/s would cause conventional units to trip. In the case of Cyprus there was a loss of wind generation due to wind farm protection schemes being activated by the RoCoF event.

In the case of Hawaii it was found that large RoCoFs on the system could lead to a loss of some of their conventional generation. In the case of one event the RoCoF caused two gas units to subsequently disconnect from the system due to over-temperature protection being activated. The generators took the step of altering some of the controller parameters to prevent the units from tripping in future for a similar event.

There is no evidence from the cases presented in this report to suggest that conventional units would experience significant damage to their plant due to high RoCoF events. Furthermore in the cases of Cyprus and New Zealand it can be seen that the conventional units remained connected to the system for significant RoCoF events. Similarly from the historical review of Irish and Northern Irish events, there was nothing to suggest that conventional units would disconnect from the system due to high RoCoF and no evidence to suggest that any plant was damaged due to these events. Although there is no significant evidence to suggest that high RoCoF events would cause significant issues for conventional generators, the TSOs accept that the information available from actual system events is limited.

Issues around anti-islanding and wind farm protection schemes do exist as these systems may be activated in the event of a high RoCoF. The activation of these protection schemes could lead to significant loss of wind generation on the Transmission and Distribution systems as was the case in Cyprus. The TSOs and DSOs must consider these schemes and the risks that they may pose to the stability of the system in the event of a high RoCoF event.