Synchronized Phasor Measurement on the All-Ireland Electrical Network

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Abstract

Variations in the phase angle difference between a remote 11kV connected wind farm and the centre of Belfast during a typical working day are investigated in the paper. The results obtained using phasor measurement units (PMUs) are compared with the data generated using a PSS/E simulator configured to model the N.Ireland network. The study investigates the effect of changes in the load demand and the wind farm output power on the phase angles at various locations on the network. The paper finally describes how a major system disturbance on the All-Ireland network was monitored and analysed using PMUs located at Queen's University, Belfast and University College Dublin.

I Introduction

A Phasor Measurement Unit (PMU) extracts the positive sequence, fundamental frequency phasors and the local system frequency from the voltage and current signals at a defined location and at known instants in time. The "synchronised" phasors from several PMUs, distributed across the network, are then communicated to a centralised unit that evaluates the operating state of the network. Such systems are now relatively easy to implement because the satellite based **G**lobal **P**ositioning and timing **S**ystem (GPS) is highly reliable, available world wide, extremely accurate and free to use. This ensures, an inexpensive GPS receiver operating within a PMU can evaluate a precise time reference using the signals received from the satellites [1, 2].

II Phasor Measurement in Ireland

PMUs were installed on the electrical network at Queen's University, Belfast (QUB), Elliot's Hill (EH) wind farm and University College of Dublin (UCD), see Fig.1. QUB and UCD were chosen to help understand how the voltage phasors between the South and North of Ireland vary with time. EH provides data on the angular variation in a local area and offers interesting information about the variations in the voltage phasors seen at a wind farm operating within the distribution network.

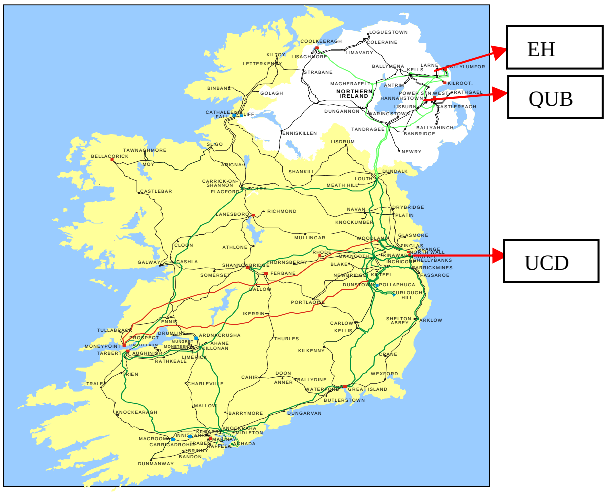

Fig.1 PMUs on the All-Ireland Electrical Network

Fig.2 shows how the UCD-PMU communicates with the QUB-PMU using Ethernet via a high speed internet link; whilst at the EH-PMU, a GSM/GPRS modem operating over a wireless link is used.

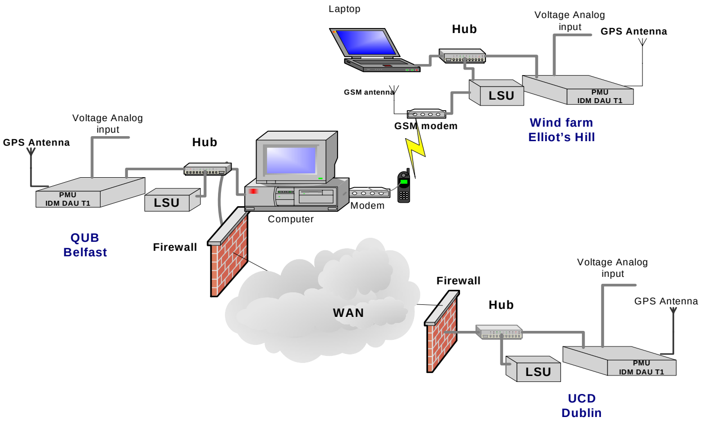

Fig.2 Communication between the PMU's

Before discussing how the PMUs were installed and used on the network, a brief introduction to the equipment used in this study will be given. Each PMU is a Hathaway type-1 IDM Data Acquisition Unit (DAU-T1), see Fig.3.

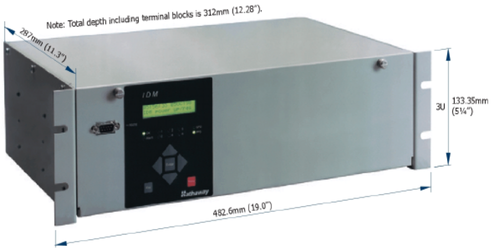

Fig.3 PMU = Hathaway IDM-DAU-T1 data acquisition unit

Each unit, see Fig.4, supports 10 analogue channels, fully isolated from each other and earth. The voltage and current signals are processed in the analogue signal conditioning unit and digitised using a 16 bit analogue to digital (A/D) converter. The digitised data is then sent to the DSP board which calculates using a Fourier algorithm each positive sequence phasor. The unit includes 16 digital input channels, which are used to monitor the status of the external contacts associated with protection relays and/or power system plant. An integral GPS receiver provides a time specified 1 PPS pulse for use in synchronizing the sampling clock of the A/D converter. Accurate time synchronisation ensures sampled data obtained from across the utility network can be accurately compared without the need to compensate for sampling and communication delays. The unit also includes a common communication interface, two serial ports and Ethernet.. This allows remote or local configuration of the unit and ensures real time monitoring is achievable.

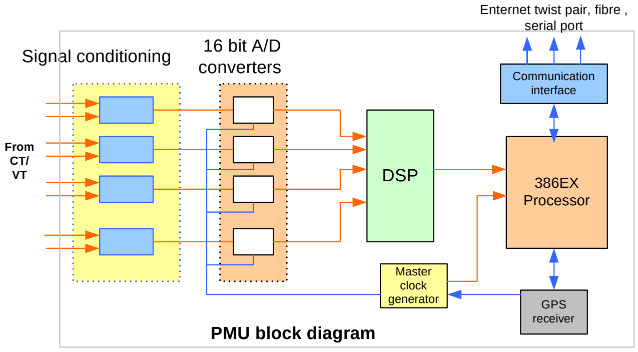

Fig.4 Block diagram of IDM DAU-T1 type PMU

III Phase Differences between Elliot's Hill & Queen's

The time stamped phasor data was continuously measured by the PMUs at EH and QUB (Ashby Building). The data from EH was then communicated to the QUB master, which time aligned the phasors and calculated the angular difference between EH and QUB. The positive sequence phase difference between the voltages measured at EH and QUB (Ashby Building) over a normal summer working day is shown in Fig.5; where each QUB phasor is at the reference angle of 0°.

To limit the amount of data, a new voltage phasor was derived at EH and QUB every 30 minutes. Each phasor consisted of the average value of fifty, one-cycle (20ms) positive sequence phasors acquired for one minute on the hour and half-hour time mark.

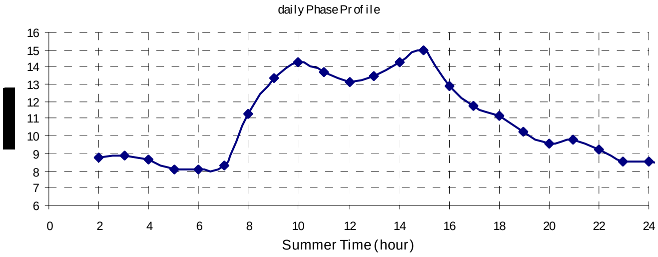

Fig.5 Daily phase profile between EH and QUB.

To understand the significance of this phase difference profile, Fig.6 shows a line diagram that describes the "network" location of QUB and EH. Moving up the feeders that supply these locations it can be seen the point of common coupling is Ballylumford 275kV substation. This implies that the phase difference depends on the load profile of each feeder and the output of the EH wind farm.

Fig.5 shows that on this particular day the angular difference is 8° - 10° degrees when the demand is small (before 8:and after 19:00) and increases to 13° - 15° when the demand is high (between 9am and 4pm). However, the phase difference is also affected by the output of the wind farm, and the easiest and best way to investigate this is to use the N.Ireland Electricity (NIE) PSS/E simulation model.

Since angular difference is closely related to power flow, detailed generation dispatch data on an hourly basis is required to obtain accurate simulation results. NIE provided the data we required for the day of the study chosen in the paper. For confidentiality reasons the data is summarised and presented as the overall demand profile in Fig.7.

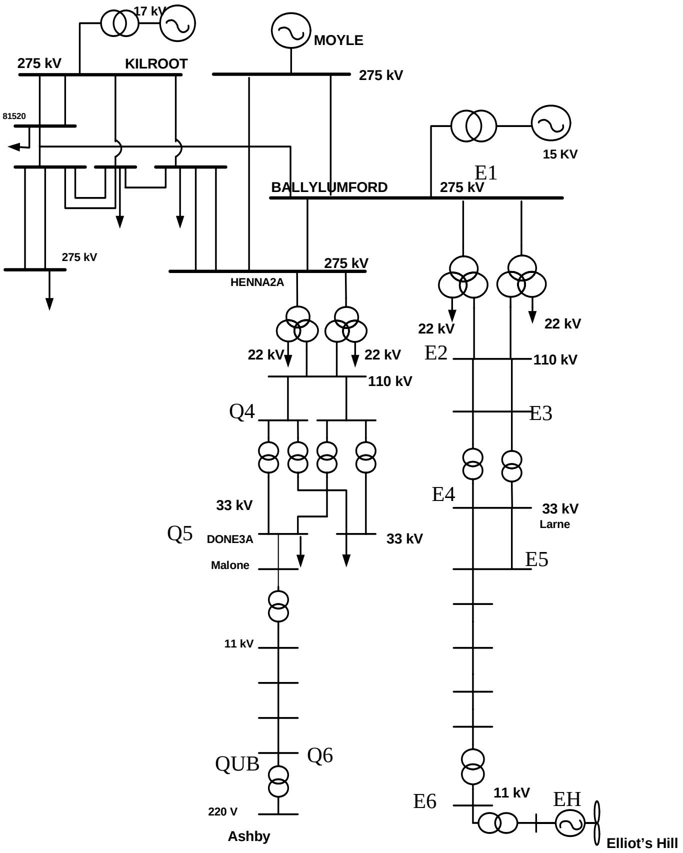

Fig.6 Single diagram of reduced NIE network showing feeders to Elliot's Hill (EH) & QUB (Ashby bldg)

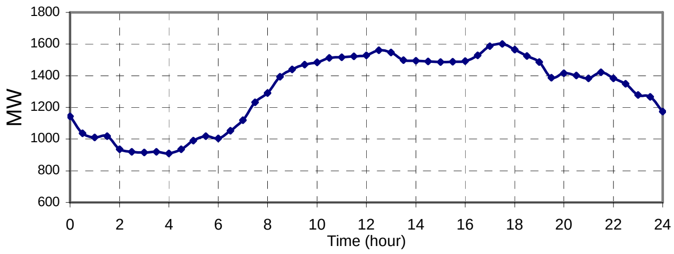

Fig.7   Demand profile in N.Ireland.

The PSS/E simulator, operating using the North Ireland network model, was used to generate the daily phase angle difference profile between EH and QUB. Fig.8 shows a comparison between the simulated profile (blue = lower trace) and the measured profile (red = upper trace). The profiles are reasonably similar, but as expected they are not identical since the actual loads are not known. In the simulator each load is scaled in accordance with the overall demand profile (Fig.7), which obviously does not truly represent the load distribution across the network. However, the similarity between the upper and lower trace in Fig.8 confirms that the simulation model is acceptable.

Comparing the EH-QUB angular difference profile (Fig.8) with the demand profile (Fig.7), one observes that the phase difference profile is not proportional to the demand profile. The peak value of the demand profile occurs at 17:00 and the peak value of the phase angle difference occurs at 15:00. The reason for the difference is related to changes in the wind farm output over the studied day. To verify this, simulations were performed with the wind farm operating at its full MW output value and at no output. The angular difference between EH and QUB for these two extremes are shown in Fig.9.

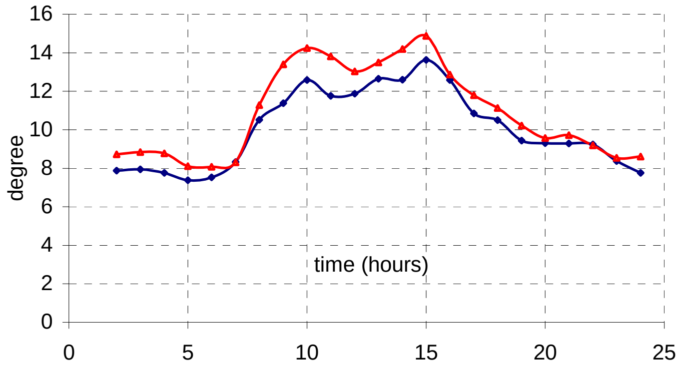

Fig.8 Angular Difference Profile between EH & QUB measurement results .vs. simulation results

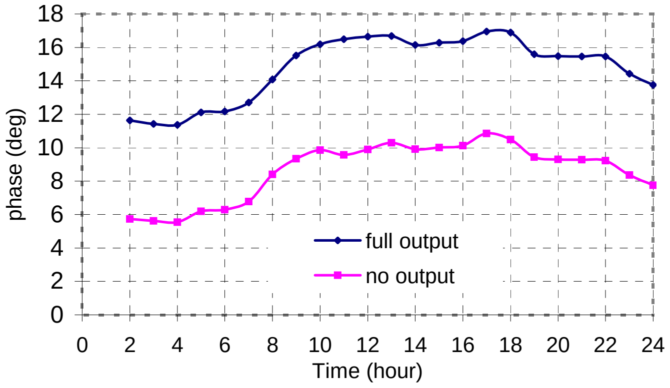

Fig.9: Angular difference between EH and QUB with wind generation at maximum and zero output respectively.

The simulation results in Fig.9 illustrate that the angular difference is proportional to the demand profile in Fig.7. The peak angular difference exactly matches with the peak value of the demand curve at 17:00 and the trough value angular difference matches with the trough of the demand curve at 04:00. This also illustrates that the higher the demand, the higher the angular difference between EH and QUB, and the higher the wind generation output, the larger the angular differences under the same load conditions. It is obvious that the angular difference between EH and QUB is highly sensitive to the output of the wind farm. It can be seen clearly that the angular difference curve is stepped up once the wind farm output increases. It is assumed that the increase of the wind farm output reduces the angular difference between EH and Ballylumford 275kV substation (Bal), whilst the angular difference between QUB and Bal remains constant under the same load conditions. If the angular difference between QUB and Bal is greater than the difference between EH and Bal, increasing the wind farm output would result in an increase in the angular difference between EH and QUB and vice versa.

To verify the above analysis, a close look at the phase distribution along the network (Fig.6) is required. The degree of the angular variation between the wind farm substation and the upstream mid-voltage substation is of particular interest. Since the simulation model adequately represents the voltage phases across the network, the phase information along the network was collected from the simulation results. Four simulation cases were chosen. The first two are for power flow simulations with the 10:00 demand value and the output of the wind farm at zero and maximum values (4.9MW) respectively. The latter two assume a 05:00 demand value and the output of the wind farm at zero and maximum respectively. Note:- 10:00 represents a peak load and 05:00 represents a light load. The simulation results of the phase angle distribution along the network with different wind farm outputs are detailed in table 1.

Table I–Effect on voltage angles of demand/generation

Time	10:00AM		5:00 AM	
windfarm output	0 MW	4.9 MW	0 MW	4.9 MW
Bus No	phase (deg)	phase (deg)	phase (deg)	phase (deg)
E6	-11.5	-4.8	-5.9	0.3
E5	-11.0	-9.4	-5.5	-4.1
E3	-6.1	-5.9	-2.7	-2.3
E1	-4.3	-4.2	-2.3	-2.1
Q4	-9.5	-9.4	-5.99	-5.83
Q5	-14.5	-14.4	-8.75	-8.6
Q6	-21.1	-20.9	-12.2	-12.0

Table 1 shows that the wind farm output significantly affects the angular variation between EH and QUB. When the EH wind farm is operating at maximum output the angular difference between EH (E6) and Ballylumford (E1) is reduced to a low value (-0.6°) when the demand is high (10am), as compared to 6.2° when the wind farm output is zero. This is because the angle at E6 reduces from -11.5° at zero output to -4.8° at maximum output. Similarly at 5am when the demand is low the angle at E6 changes from -5.9° at zero output to +0.3° at maximum output. As expected the output of the wind farm has almost no effect on the angular difference between QUB (Q6) and Ballylumford (E1). This confirms the statement mentioned in the previous paragraph:- an increase in wind farm output results in an increase in the angular difference between EH and QUB under the same load condition. When considering the same wind farm output, the heavier the load the greater the angular difference between EH and QUB. When the wind farm output is zero the angular difference between EH and QUB is 9.6° at 10am and 6.3° at 5 am. Whilst for maximum wind farm output (4.9MW) the angular difference is 16.1° at 10am and 12.3° at 5am.

The angular difference between the EH wind farm and each substation on the feeder is illustrated in Fig.10; where bus numbers 1,2,3,4,5,6 represents E1, E2, E3, E4, E5 and E6 in the network of Fig.6. The heavier the load conditions in the network, the larger the angular difference. Similarly, under the same load conditions, the higher the wind farm output, the less the angular difference between the wind generation and upstream substations. In this case, the maximum angular variation between the primary side of the 110/33kV substation (E3) and wind farm (E6) is only a few degrees (less than 6 degree as shown in Fig.10). This means that the idea of using the voltage phase at the 110/33 kV substation as a reference to control synchronized islanded operation is feasible [3,4].

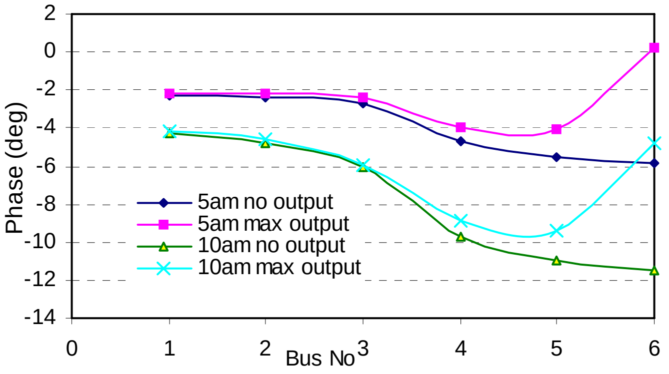

Fig.10 Phase difference between the EH wind farm and the busbars on the Ballylumford to EH feeder.

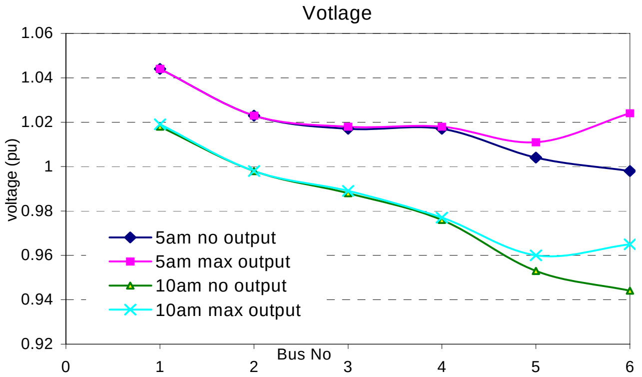

Fig.11 Voltage profile along the feeder between the EH wind farm and Ballylumford (Bal).

The voltage magnitude profile shown in Fig.11 was used to examine the effect of the EH wind farm. As expected, the output of wind generation will raise the local voltage profile compared with no wind generation under the same load conditions. This may benefit the network under heavy load conditions, but it could also raise the voltage to an undesired level when the network is experiencing a light load.

IV Comparison of PMU data from QUB & UCD, Dublin

It is of considerable interest to observe and analyse the system dynamic behaviour following disturbances on the All-Ireland electrical network, but for space reasons only one incident "5th August 2005" is shown and analysed. The effect of the incident on the power frequency is shown in Fig.12. Before the event, the system was operating at 49.98Hz and the demand on the ESB network (Ireland) was 3,302MW of which 377MW was imported from NIE (N.Ireland). At 10:22 a special protection scheme (SPS) incorrectly detected the separation of the NIE and ESB systems and instigated the "run-back" of the Moyle DC interconnector to Scotland. *Note:- The SPS is designed to prevent an over-frequency in N.Ireland following the loss of the NIE-ESB AC interconnector.* The power flow on Moyle changed from importing 115MW to exporting 168MW, i.e. equivalent to the loss of 238MW of generation. This caused the frequency to drop to 49.52Hz and reduced the power flow on the NIE-ESB AC Interconnector from 377MW to 215MW. *Note:- The system generation availability was 4880MW before the event which is sufficient for system recovery.* The system frequency then recovered to 49.83 Hz as shown in Fig.13. The red & blue traces are the measured frequencies at QUB & UCD respectively during a 20s period immediately after the first event.

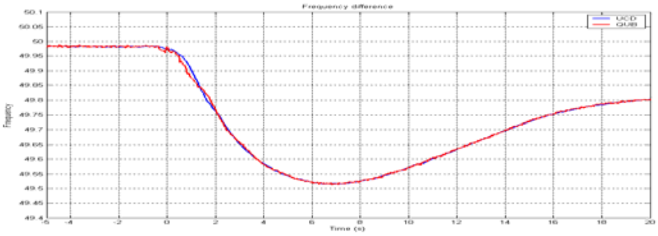

Fig.13 Frequency measured at UCD and QUB immediately after the start of the event.

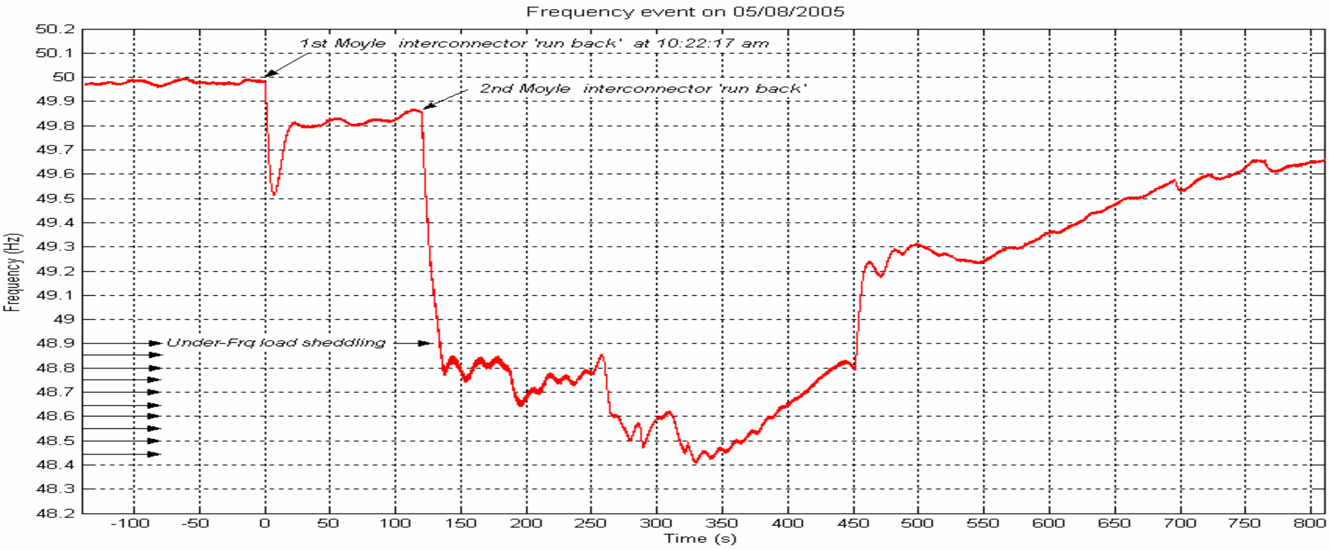

Fig.12 Frequency profile on 5th August 2005.

The frequency and phase difference between QUB & UCD over a 10s period after this event are shown in Fig.14. During this period the angle difference between QUB & UCD changed from -9º to -3.5º; due to the reduction in power flow on the interconnector.

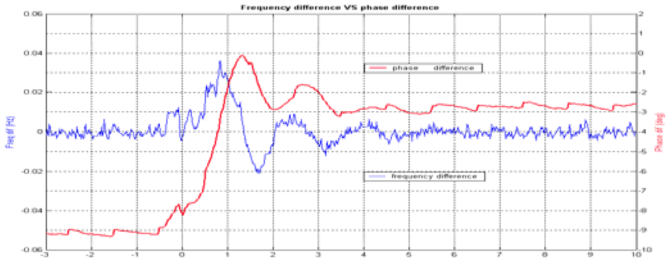

Fig.14 Frequency difference vs. relative phase between UCD and QUB.

Fig.12 shows that 2 minutes after the first run-back, the Moyle interconnector run-back again operated incorrectly and further increased the export of power to Scotland by 248MW (total of 416MW). This incorrect operation resulted in the frequency dropping to 48.4Hz. Interruptible customers interconnector to Scotland. *Note:- The SPS is designed to prevent an over-frequency in N.Ireland following the loss of the NIE-ESB AC interconnector.* The power flow on Moyle changed from importing 115MW to exporting 168MW, i.e. equivalent to the loss of 238MW of generation. This caused the frequency to drop to 49.52Hz and reduced the power flow on the NIE-ESB AC Interconnector from 377MW to 215MW. *Note:- The system generation availability was 4880MW before the event which is sufficient for system recovery.* The system frequency then recovered to 49.83 Hz as shown in Fig.12.

The demand profile of the ESB network (Republic of Ireland) on the 5th August compared to the forecast load profile is presented in Fig.15; there is significant load reduction following the event due to load shedding.

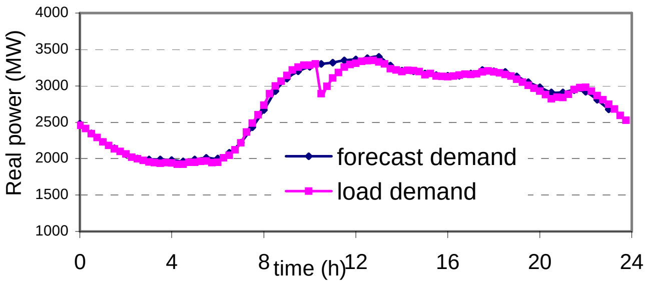

Fig.15 Forecasted & actual demand profile in ESB network

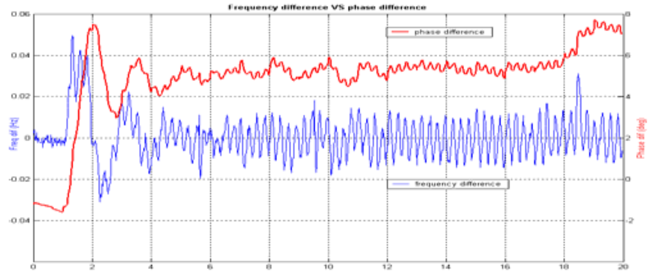

Fig.16 Frequency difference and relative phase between UCD and QUB.

Fig.16 describes the impact of the second incident on the frequency difference (blue) and the phase difference (red) between QUB & UCD

V Conclusions

The paper described how three synchronous Phasor Measurement Units (PMUs) were installed on the All-Ireland electrical network and how they can be used to monitor the behaviour of the network.

During normal steady state operation the phase difference between the PMUs is relatively stable, which supports the concept of GPS synchronised islands, as described in references [3 & 4]. Results detailing how the angular difference between Elliot's Hill wind farm and Queens University of Belfast changes during a normal summer working day were presented and then analysed using data from a PSS/E simulation model of the NIE network. In conclusion the higher the load demand the greater the angular difference; and the higher the wind farm output the lower the angular difference.

Section IV concentrated on how PMUs in Belfast and Dublin could be used to monitor the dynamic behaviour of a transmission network during a major disturbance. The presented example showed that the relative frequency and phase information between two remote locations provides valuable system dynamic information and allows the electromechanical swing phenomena to be observed directly. The presented disturbance and other events (not described) showed that the measured inter-area oscillation frequency between Dublin and Belfast varied between 0.6 and 0.9Hz. The variation of this oscillation frequency depends on the severity of the disturbance, the load condition and generating plant operation condition. During normal operation several oscillation modes exist, but only one dominant mode appeared during this disturbance.

References

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