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# Synchrophasor Broadcast over Internet Protocol for Distributed Generator Synchronization

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***Abstract*-- Synchronous islanded operation involves continuously holding an islanded power network in virtual synchronism with the main power system to aid paralleling and avoid potentially damaging out-of-synchronism re-closure. This requires phase control of the generators in the island and the transmission of a reference signal from a secure location on the main power system. Global Positioning System (GPS) time synchronized phasor measurements transmitted via Internet Protocol (IP) are used for the reference signal. However, while offering a low cost and readily available solution for distribution networks, IP communications has a variable latency and is susceptible to packet loss, which can make time-critical control applications difficult. This paper investigates the ability of the phase control system to tolerate communications latency. Phasor measurement conditioning algorithms that can tolerate latency are used in the phase control loop of a 50 kVA diesel generator.**

***Index Terms*—Broadband Communication, Distributed Generation, Diesel-Driven Generators, Latency, Phasor Measurement Unit (PMU), Power System Islanding, Real-Time Control, Synchrophasors, Synchronization Control**

## I. Introduction

TIME stamped phasor measurements synchronized using the Global Positioning System (GPS) or otherwise, known as synchrophasors, and Internet Protocol (IP) communications can offer solutions to many present and potentially to future power system applications [1], [2], [3]. Distribution power system islanding and microgrids are applications which can particularly benefit from these technologies [4], [5]. A development of this is synchronous islanded operation [6] in which islanded power networks can be held in synchronism with another system for ease of paralleling. Thus, potentially damaging out-of-synchronism re-closure can be avoided, even when re-close can occur unexpectedly due to the presence of automatic re-closing breakers.

Synchronous islanded operation has the potential to aid system restoration, including back-synchronization of distribution network areas isolated for maintenance or reconnection of geographical islands to the main power system. In these cases there is some distance between the distributed generation to be controlled, and the point of common coupling. To allow maximum flexibility of future autonomous islanding schemes forming part of active distribution networks and Smart Grids, it is assumed that knowledge of the exact point of disconnection is not required, and that it will not be possible to install synch-check relays at every point of disconnection.

To be feasible, a suitable generator control system must be in place, and a reference signal should be transmitted from a secure part of the power system, such as a transmission substation, preferably in the same electrical region as the distributed generator, such as a transmission system substation. To ensure that the phase difference is minimized at the point of common coupling (PCC) between the two systems, some knowledge of the cross system voltage phase shift between the PCC and the reference location, and between the PCC and the islanded distributed generator is required. The cross system voltage phase shift varies throughout the day and year due to power flows, such as load demand and distributed generator power output. These relatively small phase variations can be monitored and used to provide an offset to the phase controller.

Previous work by the authors conducted on a 50 kVA diesel generator has proved the concept and shown that the required control is achievable [6], although analogue transmission of the reference signal was employed, which has limited practical use. In [7], synchrophasor measurements transmitted over IP were used successfully in a laboratory demonstration on a synchronous machine, thus demonstrating the suitability of this technique for synchronous islanding control applications. The phasor measurement units (PMU) developed by the authors were designed with real-time control and protection applications specifically in mind. As shown by Fig. 1 (a), the units comprise a peripheral box containing a commercial GPS time engine and analog-to-digital conversion with the measurement algorithms implemented in Labview on a PC, thus providing a flexible and low cost PMU system.

Although the suitability of IP communications for power system control depends on the application [8], the potential to exploit IP communications in distribution networks is attractive as they are low-cost, readily available, and the same network can be used for many different functions. However, IP

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communication's major disadvantages for power system applications are security [9] and latency.

This paper focuses on the effect of communications latency on the synchronous island control of a 50 kVA diesel generator. Initially, the control system is demonstrated by holding the diesel generator in synchronism with a remote reference signal from a wind farm site approximately 100 km away. Although not an ideal site for the reference bus, a wind farm offers challenges to test the control system, both in terms of variable power output which causes the relative phase angle to change, and limited communications options due to the remote location. The reference signal is transmitted over an IP network containing a wireless 'WiMax' data link. WiMax has the potential to provide the last-mile link to distributed generator and power utility sites in remote locations [10].

Synchrophasor data were recorded from the all-Ireland power system during various states of operation and, to allow repeatable experimentation, these were used as the reference signal. The effect of communications latency is then investigated by applying both fixed and variable time delays to the pre-recorded reference signals. Phase conditioning algorithms, which add some tolerance to the latency, are incorporated into the control system. The performance of these algorithms are assessed for both island load disturbances and frequency events in the reference power system. The diesel generator control algorithms are facilitated by Mathworks xPC Target.

## II. Experimental Arrangement

Synchronous islanded operation is demonstrated on a 50 kVA diesel generator. The experimental arrangement, shown in Fig. 1(b), has been upgraded from that in [6] to include the facilities necessary for IP based transmission of the reference signal, and the use of synchrophasors. The improvements mean that the time error caused by transmission can easily be removed; low-cost shared communications, such as Internet, can be used; the reference signal can be switched between different reference PMU locations; and an improved accuracy of phase difference and frequency is achieved.

### *A. Phasor Measurement*

The Phasor Measurement Unit (PMU) used in the control system is an in-house unit developed at Queen's University Belfast [7], and is shown in Fig. 1(a). It has been designed to follow, where appropriate, the IEEE Std C37.118-2005 synchrophasor standard [11].

Three-phase mains voltage is stepped down by Hall-effect voltage transducers and fed to a Data Acquisition Card. Samples of the waveform are taken at a rate of 6 kHz with the sampling window controlled by a GPS disciplined oscillator. The GPS disciplined oscillator is a PIC microcontroller programmed with a fuzzy-logic Phase-Locked-Loop (PLL) which multiplies the 1-pulse-per-second marker from a Garmin GPS Engine by the rates specified in IEEE C37.118; that is 10, 25 and 50 Hz. A rate of 10 Hz is used for the experiments in this paper. Additionally, the PIC microcontroller provides a means of synchronizing any PC to coordinated universal time (UTC).

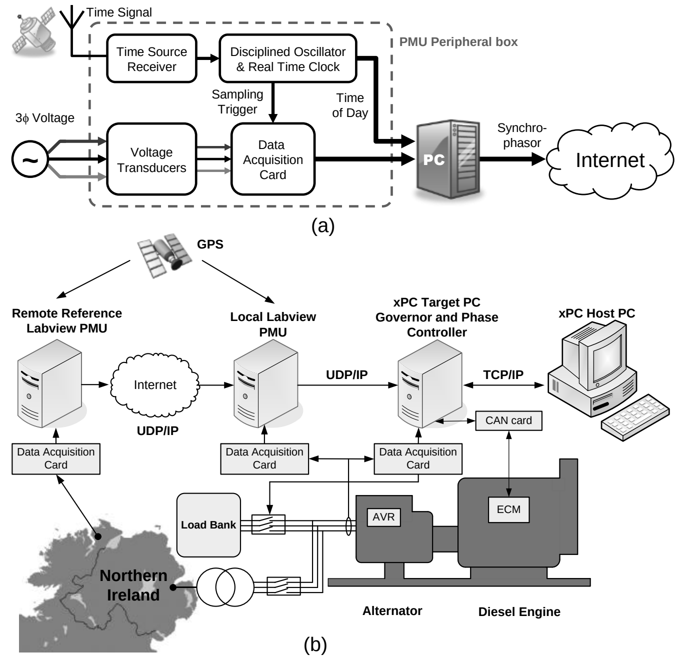



Fig. 1. Experimental arrangement. (b) Phasor measurement unit. (a) Overall diagram of experiment

Each sampling window captures 240 samples, nominally 2 cycles, which are processed by a single-frequency Fast Fourier Transform (FFT) within the Labview platform. The FFT extracts voltage magnitude, frequency and phase angle of the fundamental component and is subsequently converted to a positive sequence phasor. At the time of the experiment an implementation of C37.118 messaging could not be found for Labview so an alternative transmission format was devised. A comma delimited text string is formed for transmission, containing the PMU reference, time stamp, voltage magnitude, frequency and phase angle, using a format adapted from NMEA 0183 [12]:

$QUB0X,<timestamp>,<vmag>,<freq>,<phase>*<checksum>

### *B. Data Transmission, Collation and Input to Mathworks xPC*

Reference data packets are transmitted every 100 ms from the reference PMU to a central server using User Datagram Protocol (UDP) via a Virtual Private Network (VPN). UDP is a simple messaged based connectionless protocol; receipt of a packet cannot be guaranteed, however transmission time is reduced. This is considered preferable for time sensitive applications, in which a dropped packet is preferable to a delayed packet. Ideally, a 'virtual circuit' style routing protocol, such as those being devised for Voice over Internet Protocol (VoIP), would have been used but the Labview development environment has limited support for such protocols.

Since there are many clients in the laboratory requiring Synchrophasor data, the central server relays data to the local PMU at the diesel generator using UDP over Internet Group Management Protocol (UDP/IGMP) multicast [13]. The central server relays data to the local PMU at the diesel generator using a sister protocol of UDP called multicast. The local PMU operates in the same manner as the reference PMU. The two sets of data are combined into a single text string to be sent to the Mathworks xPC target PC, where the control algorithm is run:

$XPC,<time1>,<freq1>,<phase1>,<time2>,<freq2>,<phase2>*

### C. Delay Tolerant Algorithms

It is important that the control algorithm be as tolerant as possible to communications delay. The cumulative probability distribution of round-trip delays for 32 byte packets of data over a hard-wired Asymmetric Digital Subscriber Line (ADSL) connection and a wireless WiMax connection are shown in Fig. 2. The modal round trip time of ADSL is 44 ms, >98% of 'pings' are returned within 52 ms and 100% within 154 ms. WiMax, in this implementation, has a slightly reduced performance with a modal round trip time of 57 ms, >98% of pings returned within 284 ms and 100% within 598 ms. This WiMax channel is operating at extreme fringe reception, with respect to received signal strength, and represents the poorest possible connection that maintains connectivity.

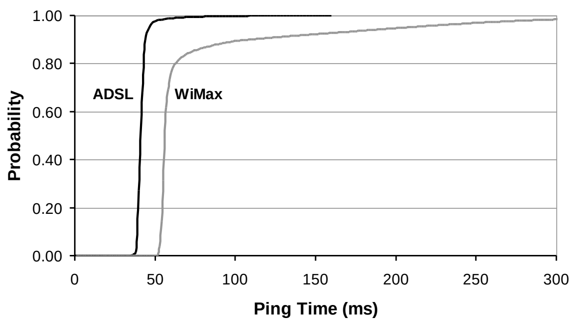



Fig. 2. Cumulative probability distribution for ADSL and WiMax round-trip ping times.

The xPC model accepts and holds PMU updates with a time-stamp greater than the previous one, thus out of sequence data is not used. The interactions of Mathworks xPC Target based algorithms are shown by Fig. 3. Two different methods of phasor conditioning that deal with the time delay have been investigated:

1. Alignment of phasors in the time domain.
2. Extrapolation of the reference phasor.

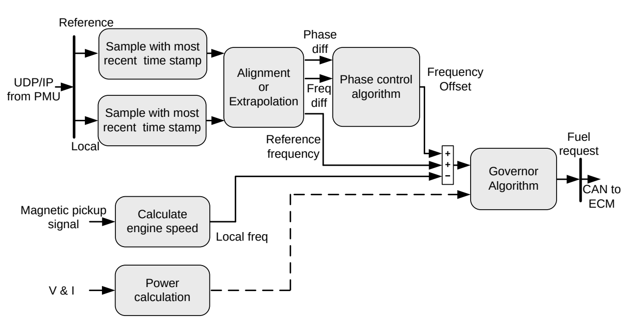



Fig. 3. Signal conditioning and control algorithms on xPC target PC

#### 1) Alignment of Phasors in Time Domain

The time stamps are used to align local and reference PMU data in the time domain and is achieved by storing previous data. This removes the time error introduced by the delayed reference signal but, due to the additional delay in both reference and local feedback information reaching the controller algorithm, or alignment delay, the stability of the system can be reduced [14].

#### 2) Reference Phasor Extrapolation

Fortunately, the reference power system frequency is relatively stable, having a constant or slowly varying frequency. The PMU data contains all the information necessary to extrapolate from the latest received data and predict the reference system phase angle at the time of the latest local PMU measurement. As shown by equation (1), the phase angle at the current time, $\theta_{(t2)}$, can be estimated from the latest reference frequency measurement, $f_{(t1)}$, time difference between latest local and reference time stamps, $t_{(t2-t1)}$, and the initial reference phase angle, $\theta_{(t1)}$. This removes the alignment delay and improves stability. Further, this algorithm helps reduce the effect of variable delays and packet loss, both of which are characteristic of the IP network used in the experiment.

$$\theta_{(t2)} = \theta_{(t1)} + 2\pi f_{(t1)} t_{(t2-t1)} \qquad (1)$$

If a power system event occurs during the transmission time of the reference signal, an error is inevitably introduced. The maximum time delay in the presence of power system frequency events will need to be determined.

### D. Governor and Phase Control Algorithm

The governor and phase control algorithms are contained on the Mathworks xPC target PC. A fuzzy hybrid Proportional, Integral, Derivative (PID) governor with supplementary input of real power is used [15]. The real power input significantly improves frequency response as it enables the governor to react more rapidly than when relying solely upon speed error, which is rate limited by inertia. The xPC target PC communicates with the diesel generator's Engine Control Module (ECM) over a Controller Area Network (CAN) interface. The phase difference controller is from [6] realized using a fuzzy logic structure.

### E. Diesel Generator

The diesel generator has a prime power rating of 40 kW electrical, has 4-cylinders and is naturally aspirated. At 1500 rpm there is a fuelling opportunity every 20 ms. The engine has an electronically controlled direct injection fuelling system, which is managed by the ECM. Communication between the ECM and the fuel pump is achieved over a CAN interface.

The alternator is rated at 50 kVA with 0.8 power factor. It has a 4-pole salient-pole construction. Voltage is controlled to a nominal level of 415 V by a standard product analogue Automatic Voltage Regulator (AVR). Matching voltage magnitude, in addition to phase and frequency, is a requirement of synchronization, however, the author's have previously shown that when voltage magnitude is held within statutory limits, the effect on the synchronization transient is relatively minor [16].

## III. Synchronization to a Remote Reference Over Internet Protocol

When operated in synchronous island mode, employing a reference signal transmitted from a wind farm site approximately 100 km away, the steady-state phase variation of the diesel generator is as shown in Fig. 4. With constant load, the phase difference can generally be held within a ±10° band. Voltage phase shift variations over the course of the day will also have an effect, and may need to be compensated [17].

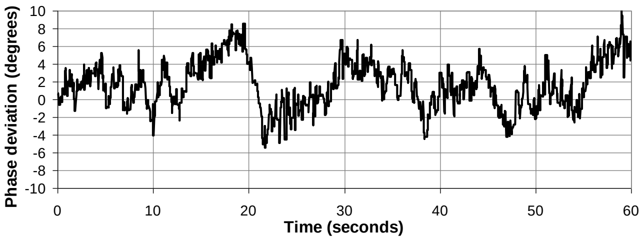
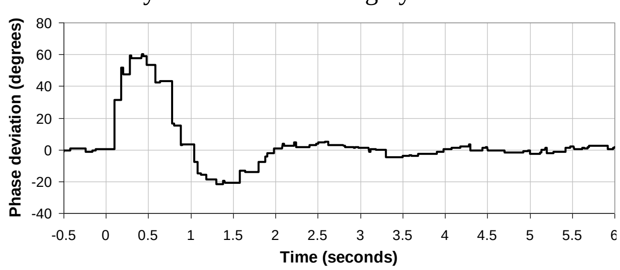
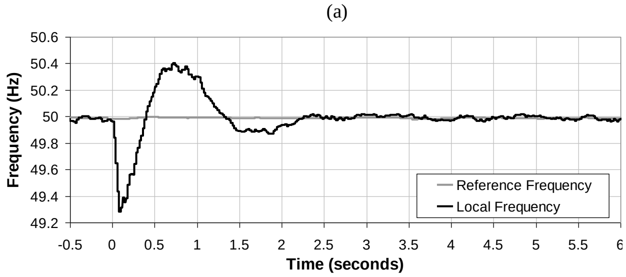



Fig. 4. Steady-state phase variation of diesel generator

While being held in synchronism with a remote reference signal containing a WiMax communications link, the diesel generator is subjected to a load disturbance. The fuzzy hybrid PID governor with supplementary input of real power is used and a 10 kW load is applied, i.e. 25% rated load. The phase transient in Fig. 5(a) and frequency transient in Fig. 5(b) result. The phase difference is held within ±60° during the disturbance, and the frequency transient exhibits the necessary overshoot to return phase difference to zero. Note that the staggered effect in the phase difference plot is caused by communications latency and the 10 Hz sampling rate. The latency of the UDP/IP transmitted reference signal averaged <100 ms, and minimal performance degradation was observed. The effect of time delay is discussed thoroughly in the next section.




(a)




(b)

Fig. 5 Transient following 10 kW, 25%, load application. (a) Phase difference transient. (b) Frequency transient

## IV. Effect of Communication Delay on Control System Performance

The synchronous island control system relies upon the transmission of a reference signal from a secure part of the power network. It is necessary to determine the effect that communications delay has on the performance of the control system. Thus, a series of tests have been performed on the diesel generator, where the control system is subjected to different reference signal delays, and their effect evaluated. Two types of test are performed, representing island load disturbances and reference system events.

For the island load disturbance, a 10 kW load is applied, which leads to a maximum phase deviation of 50° to 60° with this control setup. To aid consistency of results, a pre-recorded reference signal of frequency and phase angle from the all-Ireland power system in steady-state is used.

For the reference system event, pre-recorded data from a typical event is used, caused by the loss of 7.5 % of the island's total committed generation capacity. During this test the island load is held constant.

These tests compare the two methods of phasor conditioning used at the input of the phase controller; phasor time alignment and reference phasor extrapolation.

### A. *Island Load Disturbance with Fixed Time Delay*

The 10 kW load disturbance test is performed using the phasor time alignment method and then the reference phasor extrapolation method described by equation (1). The reference signal is subjected to fixed time delays ranging from 0 seconds to 2 seconds. The measurement of performance used is the settling time to within ± 20° following the disturbance, and the results are plotted in Fig. 6.

When using the time alignment method, it can be seen in Fig. 6 that as time delay increases, the system becomes less stable and the ± 20° settling time increases. A fixed delay of 0.5 seconds, as shown by Fig. 7, is the last stable measurement taken. When a fixed delay of greater than 0.5 seconds is employed, the system oscillates indefinitely following the disturbance. The reference extrapolation shows no such performance degradation. In fact, if the reference system remains stable, performance degradation is only introduced by measurement errors in the reference frequency and time, and the accuracy of the algorithm. This is observed in Fig. 7 by comparing the 0 second and 0.5 seconds delay cases. As the phasor measurements have very high accuracy the islanded system could potentially be held in synchronism for 10's of seconds after a reference phasor update.

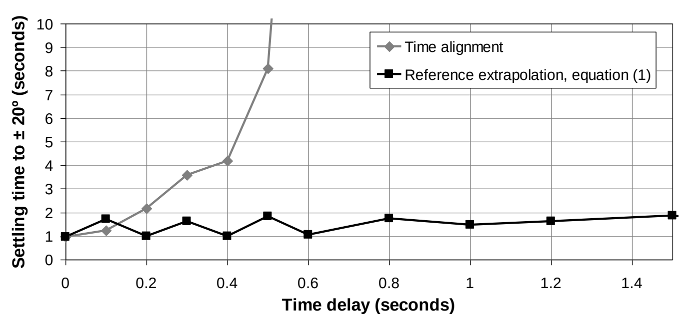



Fig. 6. Performance comparison of phasor conditioning methods for different fixed time delays following 10 kW load acceptance in islanded system

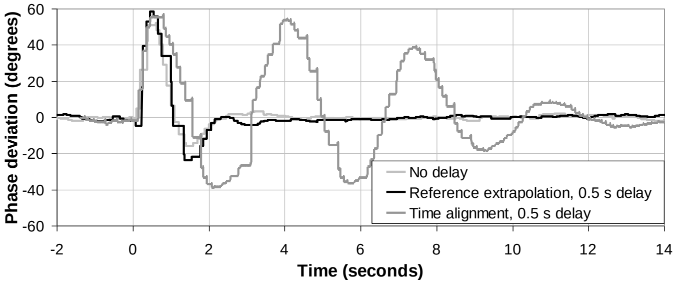



Fig. 7. Comparison of reference extrapolation and time alignment methods following 10 kW load acceptance with 0.5 second fixed time delay

### B. Reference System Event with Fixed Time Delay

The reference phasor extrapolation method relies on the assumption that the reference system has a reasonably constant or slowly changing frequency. Thus the effect of an event on the reference system, such as a generation loss or a frequency oscillation, must also be investigated. The typical event used has a frequency transient as shown in Fig. 8. The rate-of-change of frequency peaks at 0.3 Hz/s, with a sustained 0.2 Hz/s for several seconds. As previously mentioned this event was caused by the loss of 7.5% of Ireland's total committed generation capacity. No island load disturbance is applied during this test.

Fig. 9 compares the two methods of phasor conditioning. The measure of performance is the maximum phase deviation during the event. The performance of both methods degrades with increasing fixed delay, with 60° phase deviations being caused by fixed delays between 0.6 and 0.7 seconds. The reference phasor extrapolation method, by equation (1), appears to offer only a marginal improvement. However, it does aid the stability of the system, remaining stable even with the maximum tested fixed delay of 2 seconds. The phasor alignment method becomes unstable with a fixed delay of 1.0 second. The stability of the reference phasor extrapolation method compared to phasor time alignment can be seen in Fig. 10 for 1.0 second fixed time delays. Although 60° is exceeded, the system stabilises when reference extrapolation is used.

Frequency transients with higher rate-of-change of frequency will result in 60° phase deviation being exceeded at lower fixed time delays.

### C. More Severe Reference System Frequency Event

The frequency event in Fig. 8 was amongst the most severe events, in terms of rate-of-change of frequency, recorded by the authors from the all-Ireland power system. However, if isolated, it is possible that the Northern Ireland system could experience an event with a rate-of-change of frequency in excess of this. Thus, a fictional event was created with twice the rate-of-change of frequency of Fig. 8, a sustained 0.4 Hz/s peaking at 0.6 Hz/s. The reference extrapolation phasor conditioning method, by equation (1), was applied to the control system. The results shown in Fig. 11 indicate that 60° is now reached by a fixed delay of 0.3 seconds. This is, predictably, shorter than that in Fig. 9.

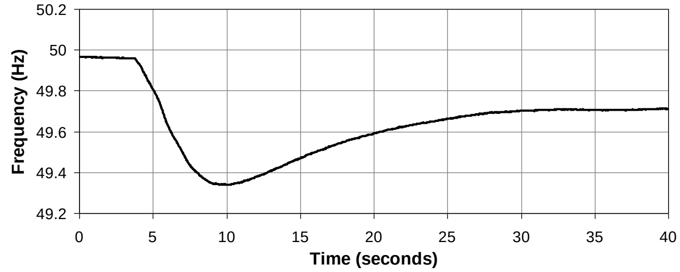



Fig. 8. Frequency transient of pre-recorded 'typical' event

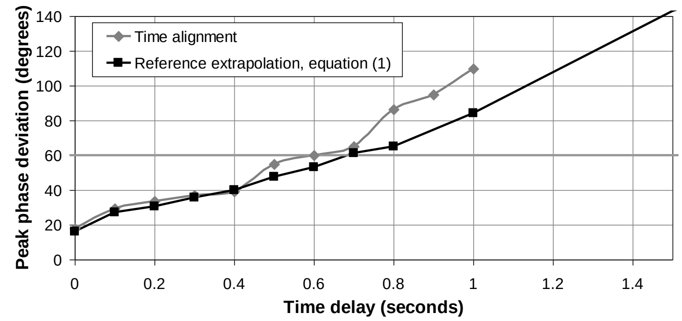



Fig. 9. Performance comparison of phasor conditioning methods during reference system event

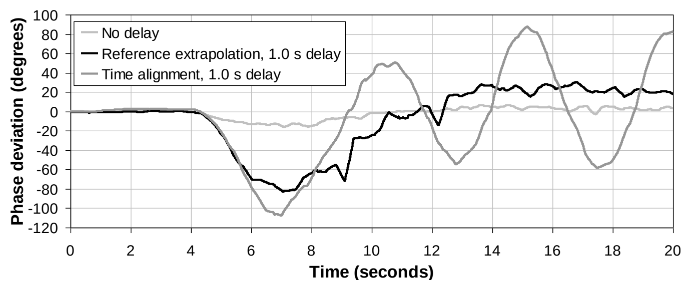



Fig. 10. Comparison of phasor conditioning methods during reference system event and 1.0 s fixed delay

### D. Derivative Input to Reference Phasor Extrapolation Method

An improvement can be achieved by using rate-of-change of frequency, or frequency derivative, as an input to the extrapolation algorithm. Equation (2) is used to achieve this.

$$\theta_{(t2)} = \theta_{(t1)} + 2\pi f_{(t1)} t_{(t2-t1)} + \frac{df}{dt}\pi\left(t_{(t2-t1)}\right)^2 \qquad (2)$$

The PMU used in the demonstration has been designed for real-time applications, and so the *df/dt*, which requires calculation over a longer period of time, is not transmitted with the other measurements, but calculated at the receiver. For the purposes of this control system, to prevent problems associated with derivative inputs, *df/dt* is calculated over a period of 0.5 seconds, serving as a derivative pre-filter. Even with this smoothing, an improvement in performance over reference extrapolation by equation (1) is observed in Fig. 11. A fixed delay of 0.45 seconds is now required to reach 60°. Maximum allowable time delay is defined by a combination of the largest possible reference system event, the probability of this occurring, and the operator's confidence. From these results, a maximum time delay of 0.3 seconds is suggested. Thus, to ensure that out-of-synchronism re-closure does not become a possibility, after 0.3 seconds has passed since the last phasor measurement update the island must revert to a condition of either complete shut-down or fragment into areas defined by synch-check relays, most likely resulting in loss of load.

A 0.3 second delay is in excess of the one-way delays for IP communications previously reported in section II. C.

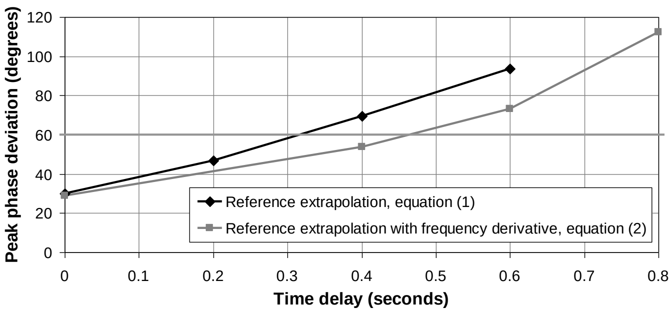



Fig. 11. Event with double the rate-of-change of frequency of the typical event, comparing reference extrapolation method by equations (1) and (2)

## *E. Effect of Variable Time Delay*

Subjecting the reference signal to fixed delays is useful to characterize the performance of the phase conditioning algorithms and the phase controller under different circumstances. However, variable delay, out-of-sequence arrival of packets and packet loss are all characteristics more typical of IP communications.

The round-trip times of 32 byte packets of data between Queen's University and a WiMax connected wind farm site approximately 100 km away were recorded. The probability distribution of the returned packets, in 10 ms bins, is shown in Fig. 12. The median round-trip time was 56 ms, and data loss, that is timed-out packets, was approximately 16%.

A section of the recorded data with particularly long delay and variability was chosen. The probability density of returned packets is also shown in Fig. 12, where the median round-trip time was 277 ms. A delay sequence covering part of this data, including data loss, is shown in Fig. 13. This sequence is applied to the pre-recorded reference system data to create a synchrophasor broadcast with a variable delay, which is then used as an input to the control system.

In order to give the phasor conditioning and control system a more severe test, round-trip rather than one-way time delays were applied. The results are presented in Fig. 14 for the time alignment method and reference extrapolation by equation (1), and similar observations to those for the fixed time delay can be made.

It is interesting to note that the performance degradation caused by variable delay is similar to applying a fixed delay with the median value of the variable delay sequence. This is observed by comparing the results of Fig. 13 with what would be expected for a fixed delay of 277 ms in Fig. 6 and Fig. 9.

The extrapolation method is robust to variable delay and packet loss. It can be concluded that the control system will indeed work satisfactorily when employing IP communications from the reference system, even where a wireless data link forms part of the connection. This is particularly beneficial as distributed generation may be installed in a remote location with limited communication options.

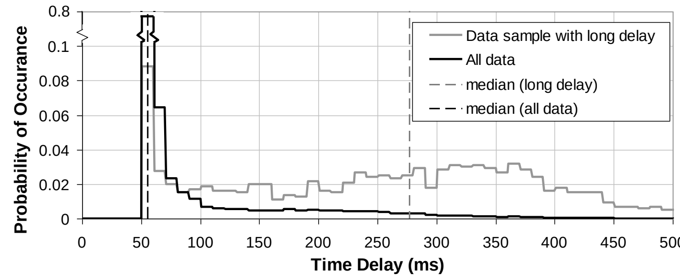



Fig. 12. Probability density, using 10 ms bins, for recorded round-trip delays; all data and section of data with long delay

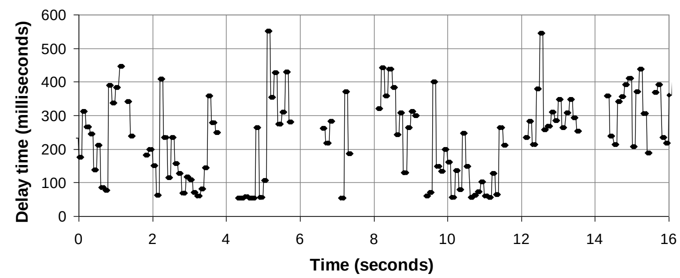



Fig. 13. Recorded round-trip time delay in IP communications – long delay section sequence used for results in Fig. 14(a) and Fig. 14(b)

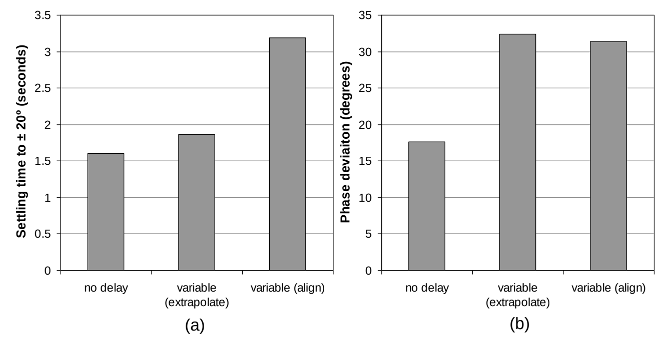



Fig. 14. Effect of round-trip IP communications time delays on control system performance. (a) Load disturbance in island. (b) Frequency event in reference power system

# V. Conclusion

Single-set synchronous islanded operation of a 50 kVA diesel generator was performed using a reference signal transmitted over Internet Protocol. This incorporates synchrophasor measurements, taken using the in-house PMU developed specifically to provide a flexible and low cost solution for real-time control system applications.

The diesel generator was held in synchronism with the all-Ireland power system using a remote reference signal at a wind farm site located approximately 100 km away. Phasor measurements were transmitted over Internet Protocol. Results were presented which show that, with an enhanced governor and phase controller, a load disturbance of 10 kW (25%) can be endured while holding the phase difference within ±60°. This was comparable with previous testing on the diesel generator with a rather more limited dedicated analogue communications link.

Tests also show that when using an appropriate phase conditioning algorithm, the control system can be made relatively robust to fixed communications delay. The reference phasor extrapolation method can allow phase to be controlled during long communication delays even when load disturbances occur in the island. However, because this method relies upon a steady-state reference system, when a frequency event occurs in the reference system an error is introduced. For the most part, delays of up to 0.3 seconds will be tolerable. A rate-of-change of frequency input gave an improvement in performance, due to better phase tracking during ramping of the reference system frequency.

The proposed control system was also tested in the presence of variable time delays which are characteristic of IP communications. Similar results to those for the fixed time delay indicate that the phase conditioning algorithms are equally effective in the presence of variable delay and packet loss.

These techniques can aid grid synchronization of distributed generation, including back-synchronization schemes. Furthermore, they have been shown to be capable of facilitating autonomous islanded operation of distributed generation in future Smart Grids. There is potential to adapt the system to run multiple islands simultaneously and for islands which contain multiple sources, which will require additional control and communications capability.

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## VII. Biographies

**Robert J. Best** (M'09, S'07) was born in Belfast, Northern Ireland, in 1980. He received the M.Eng. and Ph.D. degrees from Queen's University Belfast, Belfast, U.K., in 2004 and 2008, respectively.

He is currently a Research Fellow with the Electrical Power and Energy Research Cluster at Queen's University Belfast, with research interests in power system islanding, distributed generation and electric machinery. His placements as an undergraduate were with Northern Ireland Electricity and Helsinki Energy.

Dr. Best is a member of the IET.

**D. John Morrow** (M'99) was born in Dungannon, Northern Ireland, in 1959. He received the B.Sc and Ph.D. degrees from Queen's University Belfast, Belfast, U.K., in 1982 and 1987, respectively.

Since 1987, he has been a Lecturer in electrical engineering at Queen's University Belfast, Belfast, U.K., with research and consulting interests in electric power systems, power system instrumentation, and embedded generation.

Dr. Morrow is a member of the IET and also a member of the IEEE PES Excitation Systems Subcommittee

**David M. Laverty** (S'07) was born in Belfast, Northern Ireland, in 1984. He received the M.Eng degree from Queen's University Belfast, Belfast, UK, in 2006.

Since graduating he has been with the Electrical Power and Energy Research Cluster at Queen's University Belfast, Belfast, UK. His placements as an undergraduate were with Northern Ireland Electricity and Universität Paderborn, Germany. He is currently working towards the Ph.D degree in power system islanding.

Mr. Laverty is a member of the IET.

**Peter A. Crossley** (M'95) was born in the U.K. in 1956. He received the B.Sc. degree from the University of Manchester (formerly UMIST), Manchester, U.K., in 1977 and the Ph.D. degree from the University of Cambridge, Cambridge, U.K., in 1983.

He is Director of the Joule Centre, Manchester, UK, and a Professor of Electrical Engineering at the University of Manchester. He has been involved in the design and application of protection systems for many years, with GEC, ALSTOM, Queen's University Belfast, and The University of Manchester. He has published numerous technical papers on power system protection, embedded generation, and condition monitoring.

Dr. Crossley is an active member of various CIGRE, IEEE, and IET committees on protection and control.