

Internet Based Phasor Measurement System for Phase Control of Synchronous Islands

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Abstract—The contribution of embedded generation to the connected capacity of the power system is increasing. In order to make best use of this resource, splitting the distribution network, also known as islanding, is being considered by some utilities. Operating the island in synchronism with the main network is preferred as this prevents out of phase reconnection of the island. This paper examines the technical challenges involved with emphasis on wide area telecommunications delay and time synchronization. The development of a phasor measurement and phase control system is shown and an experimental demonstration of a phase difference controller presented.

Index Terms—Phasor Measurement, Internet, Islanding, Time synchronization

I. INTRODUCTION

EMBEDDED generation has traditionally accounted for a relatively insignificant capacity on the UK and Irish electrical systems. However, recent economic incentives have seen a substantial increase in the use of embedded diesel generators for peak lopping savings and environmental concerns have prompted government policy leading to a rapid growth in the renewable energy sector, especially wind energy and increasingly combined heat and power schemes. In Northern Ireland alone, there are over 140 MW of diesel generators for peak-opping duty (7.5% of peak demand) [1].

The UK electricity supply regulations impose a number of rudimentary protection requirements on embedded generators, including under and over voltage and frequency, and loss-of-mains detection (other forms of protection may be specified depending on the nature, size and capacity of the embedded generator). The requirements for the loss-of-mains detector are set out in Engineering Recommendation G59 [2] in the UK and Engineering Recommendation G10 [3] in the Republic of Ireland. The technologies advocated are Rate-of-Change-of-Frequency (ROCOF) and Vector Shift (VS).

In practice both technologies have demonstrated a

questionable performance history, as discussed in [4]. Nuisance trips are frequently observed in the presence of normal network events, such as line switching operations, and failure to detect a valid trip condition is also probable when the power imbalance between the generator and the grid is low.

It has been proposed that better use can be made of the embedded generation when at the time of a disturbance, instead of disconnecting the embedded generation, the grid is split such that a power island is formed [5-6]. While this prevents power outages, it poses a number of technical challenges with respect to the protection of the power island. Of critical importance is reconnection of the island to the main system grid. It is proposed in [6] that the embedded generators be controlled so that the island remains in phase with the system, allowing the network to be reconnected at any time with a minimal transient.

This paper discusses the telecommunications requirements of such a scheme and details the construction of a laboratory test facility and phasor measurement unit (PMU) to demonstrate how safe re-closure of a synchronous island may be achieved.

II. PHASE REQUIREMENT FOR SUCCESSFUL SYNCHRONOUS ISLANDING RE-CLOSURE

This section gives a brief overview of the target phase angle parameters for the safe re-closure of a Synchronous Island back to the main system grid.

A. Cause of Phase Mismatch

A detailed description of how phase mismatch between the islanded part of the network and the main grid develops is given in [6], a summary follows here.

Consider the system in Fig. 1. A diesel generator has become islanded from the system and operates supplying a local load with zero phase difference. At $t = 0$, an extra load is applied to the generator.

When the extra load is applied, the generator frequency will fall. A traditional genset controller without phase control will aim to restore frequency to the set-point as quickly as possible with minimal overshoot, as shown in Fig. 2. As a consequence the phase difference between the island and system is no longer zero.

If a phase controller is now added to the system, the expected response is described by Fig. 3. In this case the

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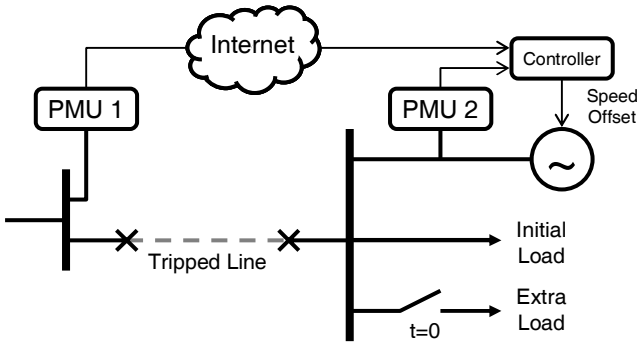


Fig. 1. Schematic of a synchronous island including control system.

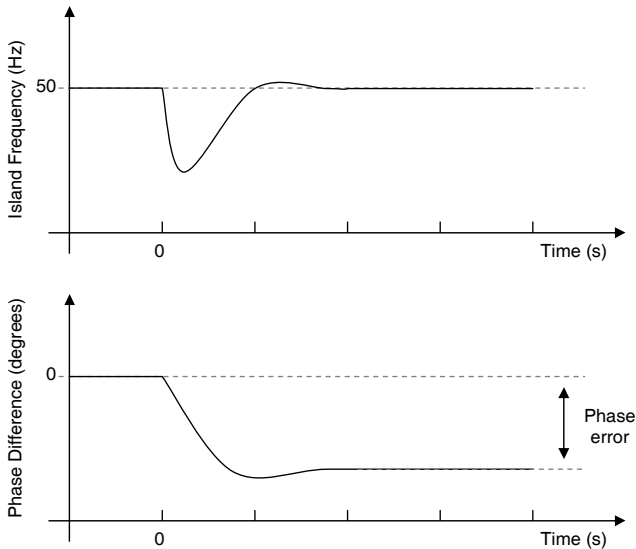


Fig. 2. Sketched response of generator to step increase in load using a traditional controller.

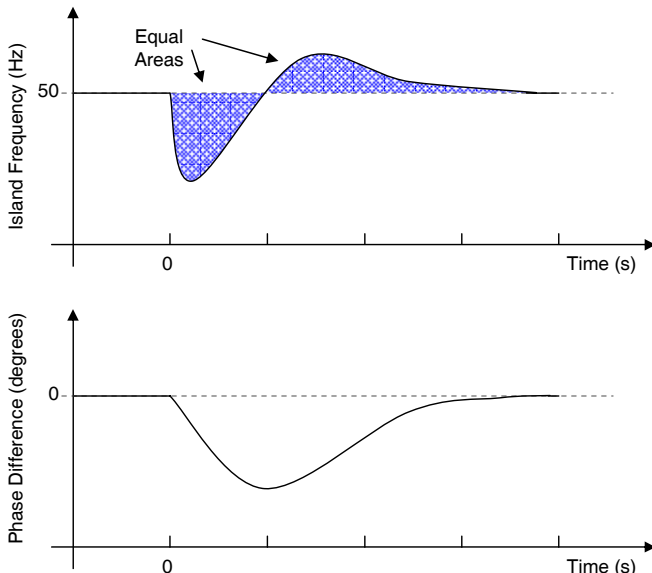


Fig. 3. Sketched response of generator to step increase in load using a phase difference controller.

generator frequency set-point is temporarily disturbed so as to slightly over-speed the generator until zero phase difference is restored.

The more detailed simulated and experimental analysis in

[7] asserts that small salient pole alternators, such as those typically used in embedded diesel generators, can withstand synchronization at phase mismatches of 50 to 60 degrees without electrical or mechanical damage.

B. The Internet as a reference Phasor medium

To facilitate operation of an isolated part of the network as a synchronous island it is necessary to communicate a reference Phasor from some point on the interconnect system to the islanded generator. Fig. 1 proposes the use of the Internet as the medium over which the reference Phasor should be sent.

Telecommunications media may be generally regarded as falling into one of two categories, dedicated or shared. Power systems have traditionally used dedicated telecoms for almost everything. At transmission level, fibre optics and pilot wires within the earth conductor are common, while distribution substations may employ leased telephone lines. The expense incurred by the power system by the failure of these telecoms can be great, thereby justifying the cost.

Outside of distribution substations, on the distribution network itself, the effect of a telecoms failure is much less severe. For this reason the telecoms used to operate the phase difference controller must be low cost. This largely necessitates the use of shared telecoms, the most persuasive of which is the Internet.

The authors have previously reported on an experimental analysis of Internet protocol delays [8]. It was found that a typical wired ADSL Internet connection can achieve end-to-end delays of less than 40 ms, while more recent research has shown a wireless WiMax Internet connection can achieve end-to-end delays of less than 75 ms. Many Internet Service Providers adhere to the ITU recommendation for delays less than 150 ms [9] owing to the popularity of VoIP.

The authors have conducted simulations on a phase controlled diesel generator model that indicates when using phase prediction in the control loop a delay of 300 ms could be tolerated. The authors also propose that should the telecoms fail to deliver data within this limit that the embedded generator be shutdown by its local controller. This effectively fail-safes a synchronous islanded system to the current loss of mains requirements [2-3].

III. PHASOR MEASUREMENT UNITS

A. Commercial PMUs

Manufacturers of commercial PMUs by and large follow the IEEE Standard for Synchrophasors for Power Systems [10]. The actual protocols they use to interconnect their devices are somewhat less defined, and are to some extent designed to allow interoperability with that manufacturer's own products.

The authors have implemented a phasor measurement system in the Northern Ireland utility network which is comprised of a single brand of Phasor Measurement Units. Not all of these units are currently Internet connected, so all

rely on storing their data locally for periodic collection on portable hard disk drive. This renders them unsuitable for real-time experimentation.

The prohibitive cost and lack of availability of other brands of PMU have prohibited assessments of other products, but it is noted that some manufacturers claim the phasor data is available immediately after acquisition.

B. Laboratory PMU

To facilitate the development of a wide area phase difference controller, the authors have developed a PMU of their own design. The key requirements were that the PMU implement IEEE Synchrophasor standard [10], make the data immediately available in an easily intelligible form and be synchronized to some readily available time reference. While the measurement component of [10] has been fully implemented, the authors have as yet implemented only a part of the data representation component.

The laboratory PMU is based around a modern personal computer architecture and incorporates a National Instruments 6025E data acquisition card for taking measurements. The software used is Microsoft Windows XP and National Instruments Labview.

The standard [10] specifies that for a 50 Hz system that a PMU should report at rates of 10 Hz and 25 Hz. As will be discussed in section IV, it was found that PC clocks cannot be relied upon to accurately discipline such a reporting rate to a real-world time reference. For this reason an external clock was developed and the external trigger of the National Instruments 6025E card utilized.

The sampling rate of the card is set to 10 kHz and the number of samples per frame is set to 400. Whether the PMU is operated at a reporting rate of 10 Hz or 25 Hz, the calculations are based on nominally 2-cycles of the waveform at a line frequency of 50 Hz.

The captured waveforms are passed to the Labview built-in ‘‘Tone Measurements’’ function. This applies a Fast Fourier Transform (FFT) to determine the amplitude, frequency and phase (of the first sample) of the input signal.

To simplify data transmission, and in a break from [10], the synchrophasor data is framed in a simple comma-delimited string with similarities to NMEA 0183 [11]. The structure is ‘\$<PMU ID>,<Time in UTC>,<Voltage>,<Freq>,<Phase>*’.

The data frame may be sent in a number of ways. The software has been primarily designed to transmit the data frame using the User Datagram Protocol (UDP) which is suitable for routing over the Internet. This is an essential aspect of the proposed phase difference controller. Other forms of communication available are RS232, logging to a file and even an analogue representation.

IV. TIME SYNCHRONIZATION

Personal computer motherboards have on-board ‘‘real-time clocks’’ (RTC) as standard. The use of the term ‘‘real-time’’ in this case is something of a misnomer since the clocks have a

questionable accuracy. Firstly, the clock is set to local time, rather than a standard reference such as Coordinated Universal Time (UTC). This means that the application must translate this local time to UTC. Secondly, it is widely observed that PC clocks often drift by several seconds in a day, in extreme cases by over a minute. Finally, the clock only reports time to the nearest second [12-13].

Operating systems may attempt to improve the usefulness of the RTC by interpolating between seconds using one of the many counters available on the PC (for instance on the BIOS or on the CPU). The Microsoft Windows operating system has never interpolated the second interval to a high precision. Depending on the model of CPU used, Windows could offer a clock granularity of 10 ms on older PCs, while on modern multi-core PCs the granularity of the Windows clock is as low as 16 ms [14]. UNIX and its clones have traditionally offered a clock granularity of 1 ms. Neither operating system gives a time of sufficient resolution.

The problem is compounded because most PC clocks are not synchronized to a time reference. That is to say, the ‘tick’ of the second does not correlate with the ‘tick’ of a time reference such as UTC. While the Network Time Protocol (NTP) allows for some degree of synchronization, its accuracy across a local area network may be of the order of 1 ms, while across a wide area network its accuracy may be of the order of tens of milliseconds.

It was determined that a PC based PMU would need an external, hardware clock to provide the time reference.

A. GPS Disciplined PIC Time Reference

The hardware clock that has been developed is based around a Microchip 18F452 PIC (Programmable Integrated Circuit) microprocessor and a Garmin GPS15 embedded GPS (Global Positioning System) receiver. This connects directly to the PC for absolute time synchronization, and directly to the National Instruments data acquisition card for measurement synchronization, Fig. 4.

The principal of operation is as follows. On power-up, the

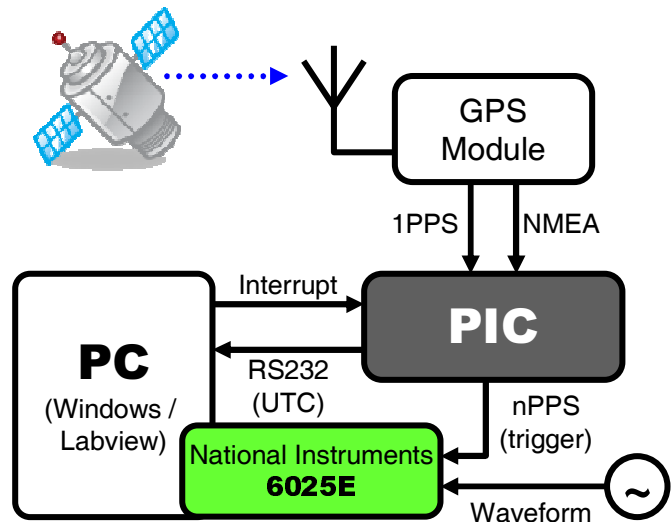


Fig. 4. Schematic of PIC based external clock connected to a PC with data acquisition card

PIC listens to the NMEA 0183 messages transmitted by the GPS module by RS232. The message identified as “\$GPRMC” contains information as to the status of the satellite lock. Once the PIC determines that a valid satellite lock is established it reads the time, also in the same message string and corrected to UTC. Once the absolute time is established, the PIC enables its interrupt driven program and updates the time according to the 1-Pulse-Per-Second (1PPS) signal from the GPS module.

The frequency of the 1PPS signal is multiplied by ‘ n ’, by a Phase Locked Loop (PLL), to provide the required sampling rates; ‘ n ’ can be set to 10, 25 or 50. By continually reading an onboard timer and establishing the period of the 1PPS signal, the PIC sets a second timer to interrupt at multiples of ‘ $2n$ ’. The second timer interrupt toggles the state of the output pin, yielding a square wave with 1:1 duty cycle at 10, 25 or 50 Hz. This n PPS signal is re-synchronized to the 1PPS on every rising edge of the 1PPS signal, Fig. 5. This signal is used as the trigger for the data acquisition card.

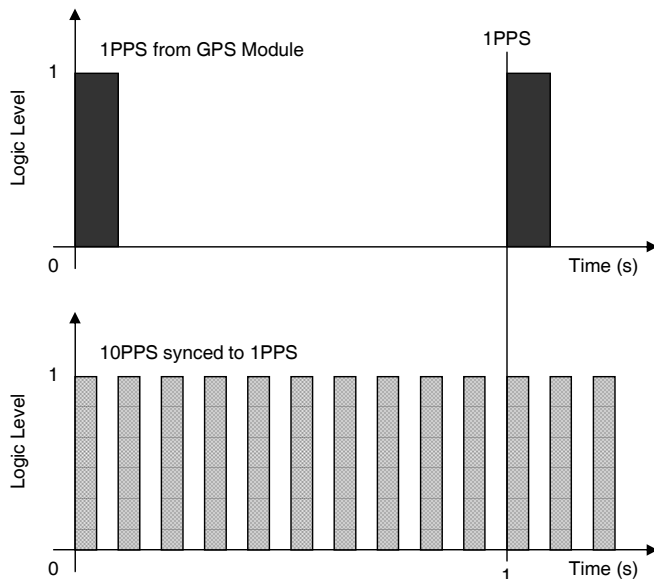


Fig. 5. Example of PLL output with a $\times 10$ multiplier.

At any time, the PC can trigger an interrupt on the PIC by toggling a bit on its parallel port (printer port). The PIC records the time (UTC) at which this interrupt occurs with sub-millisecond accuracy and returns the value to the PC asynchronously via RS232. If the PC reads its internal CPU counter (which has sub nanosecond accuracy) at the same moment the interrupt is sent it is able to synchronize itself with the UTC time reference.

In this way, the measurements taken by the data acquisition card are both synchronized with a time reference and time stamped according to the same reference.

V. EXPERIMENTAL DEMONSTRATION

An experiment was devised to test the viability of phase controlling an alternator using the Internet as the communications medium.

The phase of the mains supply is determined by a PMU and transmitted over a secure, Virtual Private Network Internet connection. Further details of this system are available in [8]. This is relayed on to a second PMU containing a control loop to govern the speed and phase of the alternator. See Fig. 6. The mains circuit breaker is open.

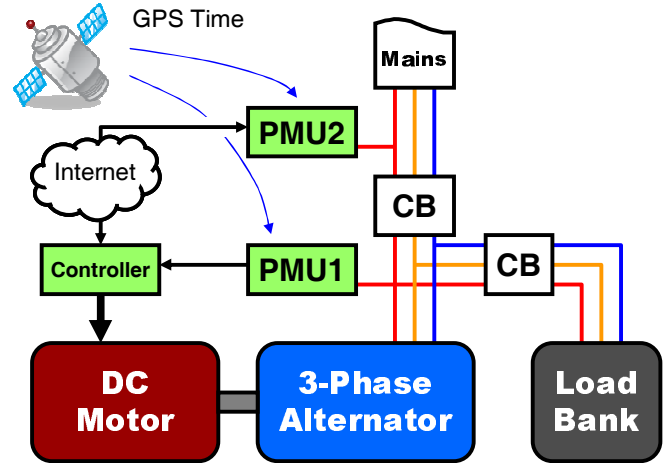


Fig. 6. Experimental phase control system.

The phase difference controller was implemented in the Labview environment on a PC running Microsoft Windows. The controller was a simple Proportional/Integral (PI) type and runs in synchronism with the phasor measurement sampling rate (25 Hz). The telecommunications delay was nominally 65 ms, with random jitter of the order of several milliseconds. The alternator is rated for 6 kW.

The first test shows the response of the alternator to a load acceptance of 1.5 kW (25 % rating), Fig. 7. The peak phase error was 77.6° while the maximum frequency deviation was +0.43 Hz (0.86 %). The controller settles in 2.2 seconds. Thus for such load disturbances within the island, synchronism with the remainder of the utility system can be maintained within acceptable limits [6].

The next test shows the response of the alternator to a load acceptance of 3 kW (50 % rating), Fig. 8. In this case the peak phase error is 122.8° with a maximum frequency deviation of +0.80 Hz (1.60 %). The controller takes a much

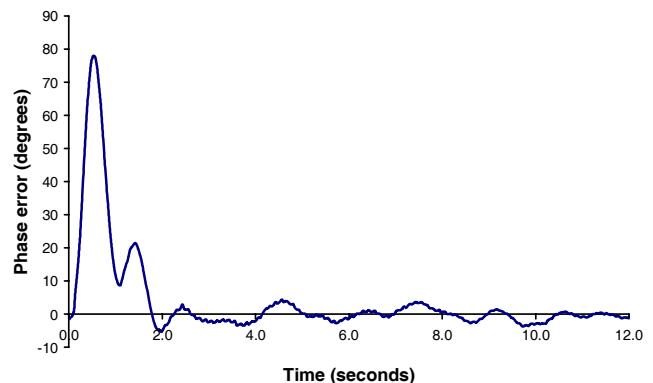


Fig. 7. Controller response to a 25 % step load acceptance.

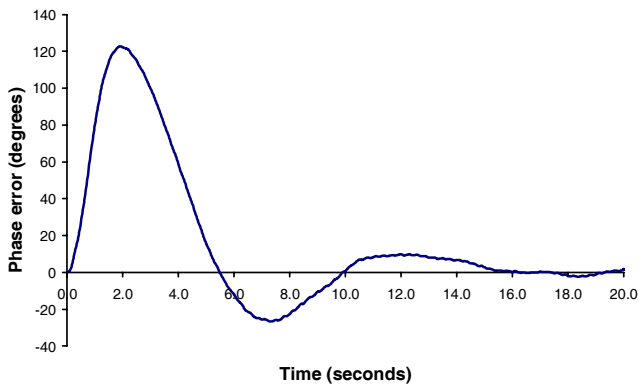


Fig. 8. Controller response to a 50 % step load acceptance.

longer 14 seconds to settle. Clearly, for such large percentage load changes, the island cannot be regarded as remaining in synchronism with the remainder of the utility.

The experiment has demonstrated that the Internet is a capable communications medium for phase control, although the response of the controller could be much improved. Retuning to operate over a wider range of load variations and adoption of a superior control method, such as PID control or a fuzzy logic controller, could yield a faster, smoother response.

The authors also propose that the system can be enhanced by extrapolating the phase error between received phasor measurements to compensate for the telecoms delay and for missed measurements (telecoms loss).

Future testing will expose the phase controller to system phase variation (by selecting sites sufficiently far apart), system transients and local load transients in order to evaluate the tracking performance of the phase control system.

VI. CONCLUSION

The concept of islanding a power system distribution network in synchronism with the main utility network is gaining consideration as a means of reducing the occurrence of power outages and improving utilization of embedded generation.

This paper has reviewed the technical challenges involved in phase control of a single generator and discusses the development of a phasor measurement system to allow phase control of an alternator over Internet Protocol.

An experimental demonstration of a phase difference controller operating via the Internet is presented, showing the response of the alternator to local load acceptances. This demonstrates that phase control is effective over a variable time delay telecoms link such as the Internet.

Ongoing research will consider an improved phase controller with a more sophisticated control algorithm. Forward phase prediction is proposed as a method of compensation for telecoms delay. The phase control scheme will also be extended to include multi-generator operation with load sharing.

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