Differential ROCOF Relay for Loss-of-Mains Protection of Renewable Generation using Phasor Measurement over Internet Protocol

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Differential ROCOF Relay for Loss-of-Mains Protection of Renewable Generation using Phasor Measurement over Internet Protocol

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SUMMARY

Renewable Generation typically falls into the category of embedded generation subject to Loss-of-Mains protection requirements. Loss-of-Mains protection is intended to avoid out of synchronism connection of an operating embedded generator to the utility supply after restoration of a fault. Present day technologies, such as ROCOF and Vector Shift are widely known to suffer from nuisance tripping and mal-operation caused by system-wide disturbances. This paper examines the use of modern day technologies to provide enhanced Loss-of-Mains protection using synchrophasor measurements delivered over Internet Protocol telecommunications. It will be shown that such a technique reduces the impact of nuisance tripping and allows embedded generation to ride through faults.

KEYWORDS

LOSS-OF-MAINS, PROTECTION, SYNCHROPHASOR, PMU, INTERNET PROTOCOL

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1. INTRODUCTION

Embedded generation has typically accounted for only a small fraction of available capacity on the network. However, the last decade has seen a substantial increase in the installed capacity of sustainable energy sources such as wind and local generation such as combined heat and power (CHP). In Northern Ireland alone, there are over 140 MW of diesel generators for peak-lopping duty (7.5% of peak demand) [1].

This has radically altered the distribution network landscape. Where previously the distribution network could have reasonably been considered a simple unidirectional system, delivering power from substation to consumer, now a typical distribution network is a complex entity with intricate power flows.

In order to simplify protection of the distribution network, the traditional attitude to embedded generation is that it should be disconnected from the network during faults. This allowed for the existing single ended protection systems to function as intended, with power flow only outbound from the distribution substations. This is achieved using Loss-of-Mains protection relays.

In the UK, the requirements for the Loss-of-Mains relay are set out in Engineering Recommendation G59 [2], which advocates two technologies for the detector. These are Rate-of-Change-of-Frequency (ROCOF) and Vector Shift (VS). This is similar around the globe.

In practice both technologies have demonstrated a questionable performance history, as discussed in [3]. 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.

Differential Loss-of-Mains detectors have been proposed which aim to improve upon ROCOF and VS relays by differentiating between local and system wide events through a telecoms signal from a secure point on the network [4,5]. To date, such technologies have been out of reach due to a lack of availability of telecommunications, but advancements in that sector such as WiMax and long range ADSL are overcoming this obstacle.

Additionally, the cost of Synchrophasor measurement technology has reduced greatly. Previously limited to only dedicated Phasor Measurement Units and event recorders, the technology is now affordable to offer as a function in other devices. This has led to the suggestion that Synchrophasor measurements be used for Loss-of-Mains detection by angle difference [6].

This paper discusses the practical implementation of a Loss-of-Mains scheme by Synchrophasor angle variation using the WiMax wireless Internet Protocol technology. A prototype developed in Labview will be discussed.

2. SYNCHROPHASOR MEASUREMENT

A phasor is a complex number which represents the magnitude and phase angle of a waveform in an AC system. Synchrophasors are phasors measured with respect to a global time base, typically Coordinated Universal Time (UTC).

The measurement convention for synchrophasors is to define the observed waveform with respect to its cosine; that is to say that the reported phase is the angular difference between the instant of the reporting time and the instant the waveform is at its peak. This is illustrated in Fig. 1.

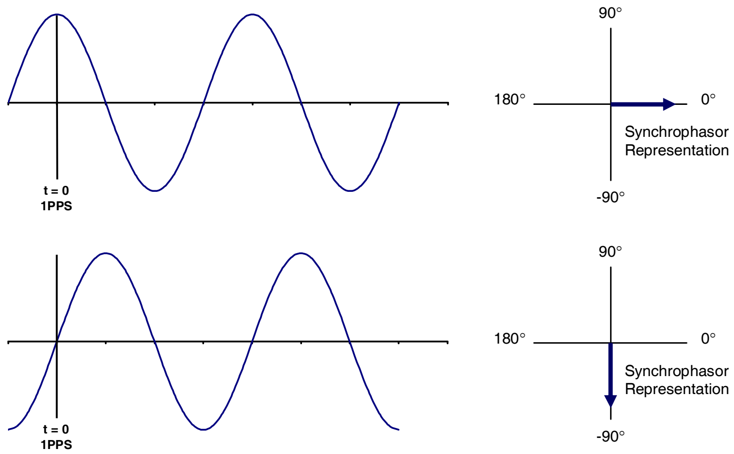

Fig. 1. Synchrophasor representation with respect to waveform and time.

IEEE Standard C37.118 [7] sets out operating guidelines for the synchrophasor measurement system, including format of time tag and time synchronization, communication format and data structure, reporting rates and accuracy limits. In this prototype the measurement standards of C37.118 are observed but a simplified communications protocol is used.

3. WIMAX TELECOMMUNICATIONS

Following the successful adoption of Wi-Fi (802.11 a/b/g) on the Local Area Network (LAN), it became clear to equipment vendors and standards bodies of the demand for a similar standard for Wide Area Networks (WAN). The IEEE standards board established the IEEE 802.16 working group in August 1998 to develop standards appropriate to fixed broadband wireless access (BWA or FWA). IEEE 802.16 would become known as WiMax.

A report on the feasibility of operating a WiMax telecommunications network on existing utility UHF SCADA sites was prepared by the authors [8]. The simulated propagation results proved unfavourable due to geographical factors. However, there exists a commercially operated WiMax network in Northern Ireland with widespread coverage. This uses more suitable hilltop locations, Fig. 2. The prototype Loss-of-Mains system makes use of this network. Virtual Private Networking (VPN) encrypts the data to prevent unauthorized access to, or manipulation of, the signals.

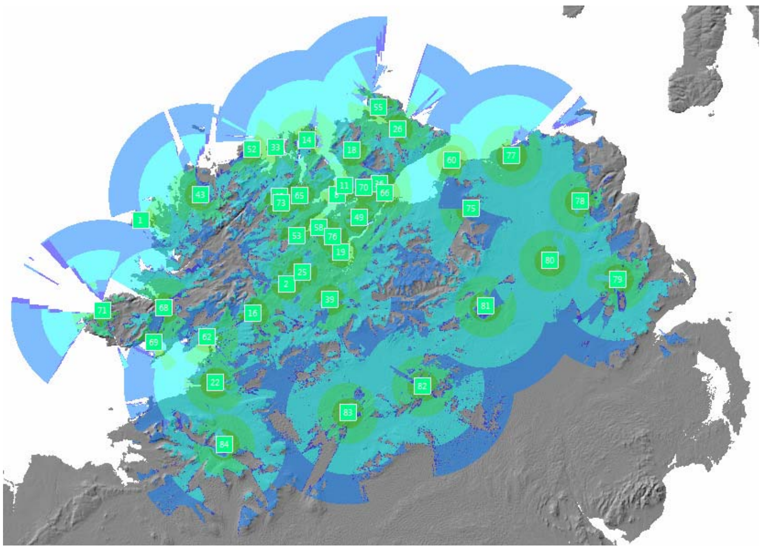

Fig. 2. WiMax coverage in the north of the island of Ireland.

4. OUT-OF-SYNCHRONISM RECLOSURE

In [9] it is demonstrated experimentally that performing an out-of-synchronism reclosure of approximately ±60° on a synchronous alternator is equivalent to a three-phase short circuit of the alternator, which it would be designed to withstand. Although, the alternator would not be designed to operate like so repeatedly.

Best et al. show that the short circuit currents and torque vary near linearly with phase angle between 0° and ±60°. This gives rise to the suggestion that out-of-synchronism reclosure might be regularly tolerated at up to ±30° out-of-sync, when the short circuit current and torque are approximately half the alternator's design limits. That is to say, that should the alternator be operating in an island, so long as it is within ±30° of the utility network, this could be considered acceptable. This shall be the limit used on the prototype detector. Different limits would be required depending on the nature of the prime mover.

5. LOSS-OF-MAINS DETECTOR

The schematic of the synchrophasor loss-of-mains detector is shown in Fig. 3. A PMU installed at a transmission substation broadcasts its phasor measurements via the Internet to loss-of-mains relays installed at embedded generator sites. Here, the received synchrophasor is compared to the local synchrophasor and the protection rule applied.

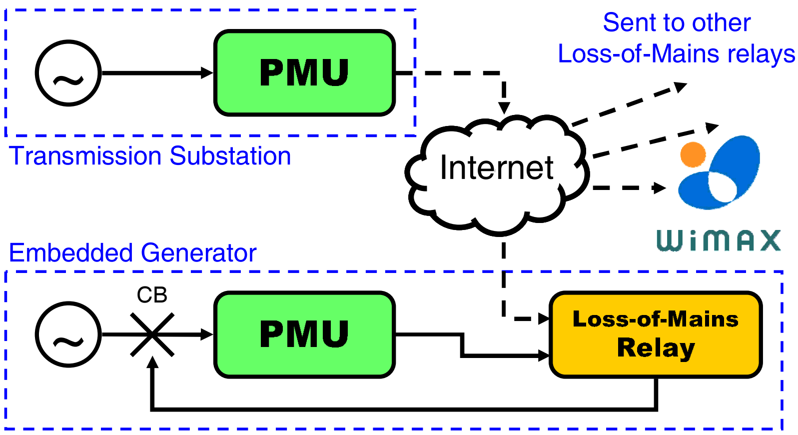

Fig. 3. Loss-of-Mains detector schematic.

The Loss-of-Mains detector software is prototyped in National Instruments' Labview development environment on Microsoft Windows XP. Labview utilises the Windows networking stack for Internet Protocol (IP) communications. This greatly simplifies the Labview program since Windows takes care of all the device drivers necessary to operate the Network Interface Card. The same machine can also run the Virtual Private Networking software, creating a logical 'LAN' across the Internet.

The detector user interface is shown in Fig. 4. The left hand charts plot the measured frequency and phase angle at both the local and remote sites with respect to time. The "Synchroscope" shows the instantaneous phase difference between the local and remote sites, and the lower text indicators display the received packets of data.

The Synchroscope can be configured with upper and lower limits of phase deviation which are considered the "healthy" state for the Loss-of-Mains detector. From section 4, these are set to ±30°.

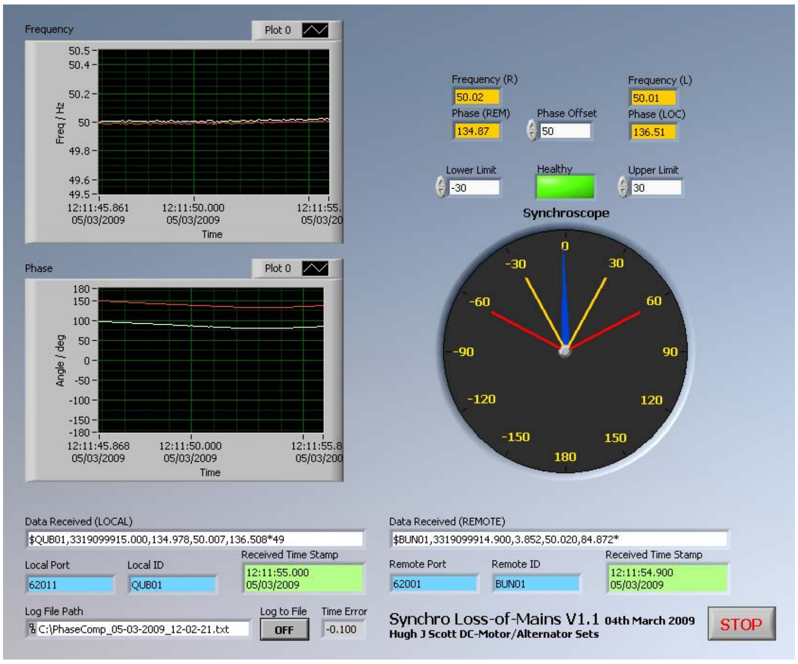

Fig. 4. Loss-of-Mains detector user interface.

The steady state phase offset between the local and remote signals needs to be continually updated. During normal operation the phase offset variation is very slow. The authors have shown that the daily range of phase angle variation between several sites rarely exceeds 13° [10], as shown in Table 1.

	Maximum	Minimum	Range	24-hour period
QUB	27.02°	17.09°	9.93°	5.64°
UCD	24.57°	9.52°	15.05°	11.11°
Wind Farm-1	-25.69°	-38.80°	13.11°	12.87°
Wind Farm-2	6.00°	-7.22°	13.22°	7.97°

Table 1. Phase angle variation observed at sites on the distribution network.

Since the phase variation itself is well below the threshold of the Loss-of-Mains detector, it is possible to average the offset value as a moving window spanning the course of tens of minutes to hours. The objective is that the phase deviation reported should tend to zero in all normal operating modes, yet the offset should vary slowly enough that out-of-synchronism islanding will be detected accurately. If the offset is calculated using too short an averaging window, it is possible that the detector will fail to detect islanding.

6. EXPERIMENTAL EVALUATION

An experiment was conducted to measure the phase difference in real-time between two locations on the island of Ireland. Site 1 is adjacent to a wind farm in Buncrana, Co. Donegal, Ireland. Site 2 is located in Queen's University Belfast, Northern Ireland. Both sites have PMUs connected to the distribution network. They are interconnected using a VPN over WiMax as discussed in Section 3.

Fig. 5 shows the phase difference between the sites with respect to time (blue, solid line). On the same graph is plotted the aggregate wind power output of the island of Ireland (red, dashed line). It is apparent, with the exception of the afternoon of day 1, that there is a close correlation between wind power output and phase angle. This is to be excepted since Buncrana is distant from nearby transmission substations. The aberration on the afternoon of day 1 is likely due to a variation in the local wind conditions, or curtailment of wind generation due to operational necessity given the weak electrical network in Co. Donegal.

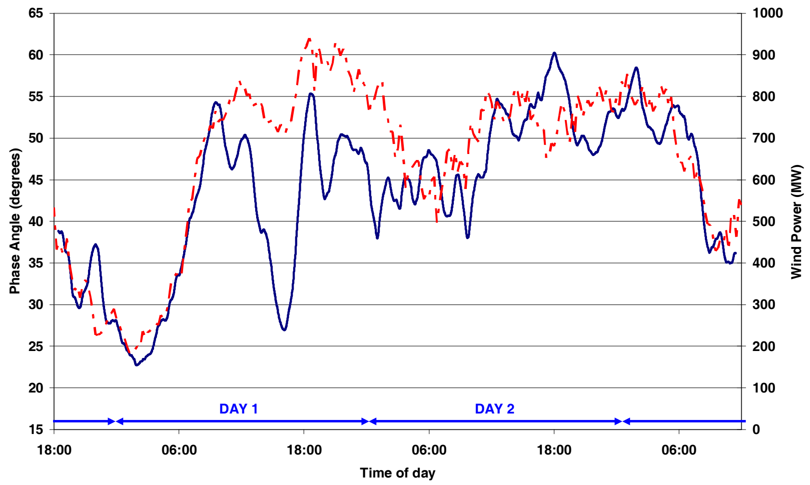

Fig. 5. Phase difference between Buncrana and Belfast (blue) and total Irish Wind Power output (red).

The phase difference was averaged continuously over an hourly window so as to approximate the steady state offset. This was then subtracted from the instantaneous phase difference. The result of this operation is shown in Fig. 6. It is apparent that for the most part the instantaneous phase difference oscillates between approximately ±5°, the notable exception being at 18:00 on day 1. This peak variation of −10° is most probably due to changes in wind farm operation (e.g. curtailment). The phase variation can be reduced by shortening the offset window, but this is at the expense of detector sensitivity.

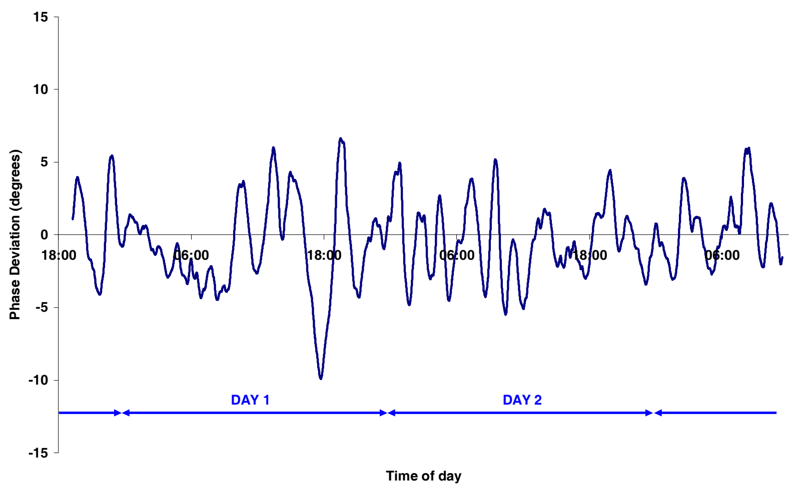

Fig. 6. Instantaneous Phase difference less hourly ‘steady-state’ average.

Given that the maximum phase variation is well below the detector threshold, an averaging window of 1 hour seems appropriate. The phase variations are greater than Table 1 as two distribution sites were used to gather data, as opposed to using a transmission site as a reference. Furthermore, Buncrana, Co. Donegal is more electrically distant (impedance) from QUB than points on the transmission network. This would indicate the need for several reference sources spread geographically on the network.

Of primary concern is the speed of response of the loss-of-mains detector. From [6], synchrophasor loss-of-mains detectors can detect an island with 1% imbalance in power import/export to the grid in 5 seconds. In this case, a much larger threshold of 120° was used instead of the ±30° proposed in this paper. Given that it is proposed that a generator operating within ±30° may ride through the fault, the determining factor in speed of response is the measurement speed of the PMUs and the latency of the telecommunications network. Fig. 7 shows the latency of a WiMax connection to a wind farm in Northern Ireland with respect to Queen's University Belfast measured over a week.

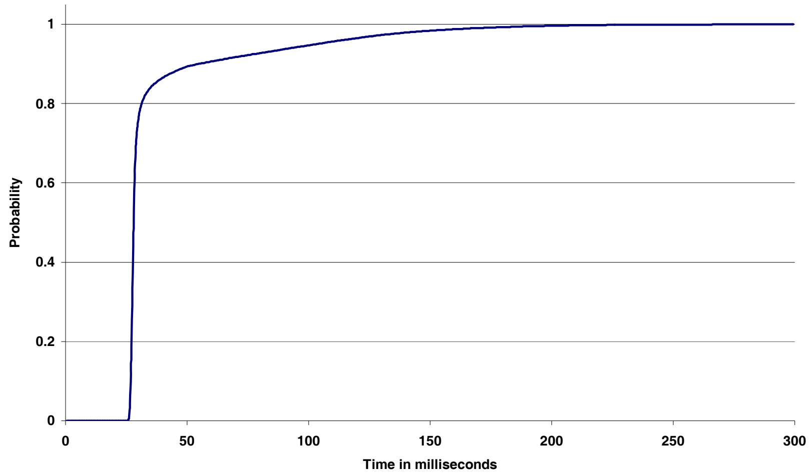

Fig. 7. Latency of WiMax network (one-way)

Of the packets of data transmitted to the wind farm, 80% of those arrive within 31 ms of transmission, 90% arrive within 55 ms and the remainder arrive within 200 ms. If the reporting rate of the PMUs is set to 10 Hz, the maximum response time of the loss-of-mains detector will be 300 ms, with typical response times being in the order of 150 ms. In the event of telecommunications failure, excess telecoms latency or packet loss, the detector is able to revert to standard ROCOF operating mode.

7. PROTOTYPE TRIALS

The prototype of this loss-of-mains detector is to be installed for trials against conventional ROCOF and VS detectors. These will be conducted on the Great Britain network with assistance from Scottish & Southern Electricity, and on the Northern Ireland network working with Northern Ireland Electricity.

8. CONCLUSIONS

An islanding detection and monitoring system has been designed and tested in the laboratory using real-time data captured from the Irish electrical power system. It has been proposed that the islanding detector can be used to allow generators to ride through faults on the network if they are able to remain within a specified phase deviation. It has been demonstrated that during normal operation the phase angle varies slowly enough to allow a long time constant for calculation of the steady-state phase offset at the site being monitored. This is in the presence of varying wind on a weak part of the network. Field trials are due to commence in the near future.

8. ACKNOWLEDGEMENTS

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BIBLIOGRAPHY

[1] K. Pandiaraj; B. Fox; D.J. Morrow; S. Persaud; J.P. Martin “Centralized control of diesel gen-sets for peak shaving and system support” (Proc. Inst. Elect. Eng. Gen., Transm., Distrib., vol. 149, no. 2, pp. 126–132, Mar. 2002.)

[2] ELECTRICITY ASSOCIATION: “Recommendations for the connection of embedded generating plant to the distribution system”, Engineering recommendation G59/1, Northern Ireland, (1993).

[3] R. Bugdał, A. Dyśko, G.M. Burt, J.R. McDonald, “Performance analysis of the ROCOF and Vector Shift methods using a dynamic protection modelling approach” (Power System Protection PSP 2006, pp. 139-144, 2006)

[4] C.G. Bright, "COROCOF: comparison of rate of change of frequency protection. A solution to the detection of loss of mains," (Developments in Power System Protection, 2001, Seventh International Conference on (IEE) , pp.70-73, 2001)

[5] D.M. Laverty; D.J. Morrow; T. Littler; P.A. Crossley, "Loss-of-Mains Detection by Internet Based ROCOF," (Developments in Power System Protection, 2008. DPSP 2008. IET 9th International Conference on , pp.263-268, 17-20 March 2008)

[6] A. Ishibashi; M. Imai; K. Omata; S. Sato; T. Takagi; Y. Nakachi; S. Ogawa, "New type of islanding detection system for distributed generation based on voltage angle difference between utility network and distributed generation site," (Developments in Power System Protection, 2004. Eighth IEE International Conference on , vol.2, no., pp. 542-545 Vol.2, 5-8 April 2004)

[7] *IEEE Standard for Synchrophasors for Power Systems*, IEEE Std. C37.118–2005 (Revision of IEEE Std. 1344–1995).

[8] D.M. Laverty; D.J. Morrow; J. O’Raw; P.A. Crossley, "Wireless Telecoms for Distribution Networks Based on WiMax," (CIRED 2009. Paper 0856, 8-11 June 2009)

[9] R.J. Best; D.J. Morrow; P.A. Crossley, "Out-of-Phase Synchronization of a Small Alternator," (Power Engineering Society General Meeting, 2007. IEEE , vol., no., pp.1-7, 24-28 June 2007)

[10] R.J. Best, "Synchronous Islanded Operation of Isolated Power System Areas," (PhD thesis, Queen’s University Belfast, Belfast, UK, 2008)