LOSS-OF-MAINS DETECTION BY INTERNET BASED DIFFERENTIAL ROCOF

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Abstract

This paper considers the enhancement of loss-of-mains detection by use of a differential rate-of-change-of-frequency relay to reduce nuisance tripping and improve sensitivity to small excursions in frequency. The telecommunications media which might carry the differential ROCOF signal are reviewed with a focus on channel latency, bandwidth and security.

1 Introduction

Embedded generation has traditionally accounted for a relatively insignificant capacity on the UK's electrical system. 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.

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 [1], which advocates two technologies for the detector. These are Rate-of-Change-of-Frequency (ROCOF) and Vector Shift (VS).

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.

In this paper a telecommunications based solution is proposed to exploit the benefits of a differential ROCOF system suggested in [2] at a price which competes with existing loss-of-mains protection devices. The telecommunications media under consideration is the public Internet.

2 Differential ROCOF

Bright suggests a differential ROCOF scheme dubbed Comparison of Rate of Change of Frequency, COROCOF [2]. The general principal is that the COROCOF relay at a generator set (receiving relay) can distinguish between a local disturbance in frequency (indicating loss-of-mains) and a system wide disturbance through use of a 'blocking' signal sent by a COROCOF sending relay. The blocking signal indicates to the receiving relay that it should not trip.

A more generalised form of this system would, instead of a blocking signal, continually broadcast the ROCOF observed at a sending site to all the area's receiving sites, Figure 1. The decision to trip can then be made at the generator set's relay with all the available information.

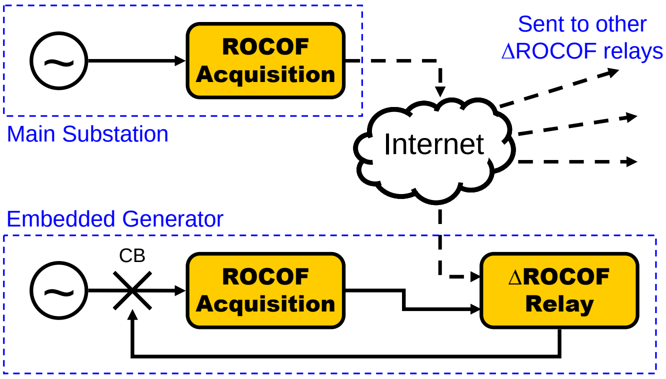

Figure 1: Generalised differential ROCOF system.

The sending relay would be installed in a location where power islanding is unlikely, such as a medium to large substation. If the telecommunications media is the Internet, the sending site would require a good, high bit-rate, low latency link, probably with a back-up channel.

3 Telecommunications media

The level of investment in the telecommunications media, which is a part of the protection system, must be proportional to the probability of a disturbance and the cost of failing to protect against that disturbance. While transmission level protection may necessitate the expense of dedicated fibre optic telecommunications systems, distribution level protection must typically rely on existing modes of communication.

Distribution protection telecommunications may be grouped into four categories. These are fixed telephone, mobile telephone, Professional Mobile Radio and Internet Protocol.

3.1 Fixed telephone communications

Fixed telephone systems have traditionally been dominated by leased lines where, depending on the exact nature of the installation, the propagation time of the signal determines the latency. Modern systems will, to some extent, have their traffic switched by some electronic device, adding to the delay.

In the UK the primary fixed telecommunications provider, British Telecom, has made it an objective to almost fully switch their network to Internet Protocol by the year 2012, the network to be named the "21st Century Network", or 21CN. This is because BT have stated their belief that the future of telecoms lies in data [9], which will be dominated by the Internet. For this reason BT is migrating their current products to emulated services over IP on the 21CN system.

The exact affect 21CN will have on latency for communications within the BT / telephone network is unclear, but it is speculated that it will be similar to that observed today for regular Internet traffic. Furthermore, BT is required to observe a maximum delay time of 150 ms [7] with a recommendation for less than 25 ms [8].

3.2 Mobile telephone communications

Mobile telephone communications are often cited as a means of easily connecting remote electronic devices without the need to install new cabling or other apparatus (antennae) or invest in external infrastructure (private base stations). Mobile telephone companies also try to adhere to the 150 ms delay time specified in [7].

From a power system protection perspective, however, mobile telephone networks can be rejected due to the long call setup time and, more importantly, the lack of a guarantee of service. Anyone trying to use a mobile telephone at a large public gathering will be familiar with the inability of the network to service the large number of calls. In the same way, the mobile telephone network cannot be relied upon to handle the large volume of traffic which can arise from a power system disturbance.

3.3 Professional Mobile Radio

Professional Mobile Radio (PMR) systems are dedicated mobile communications systems designed to be used by a specific organisation or company. These can range from the emergency services (police, fire and ambulance) dispatch, command and control systems to commercial systems operated by utility companies. A typical characteristic of some, but by no means all, PMR systems is that they are designed to continue operating even if public telecommunications networks fail.

Terrestrial Trunked Radio, TETRA is becoming the standard PMR system in Europe and beyond, with widespread adoption by emergency services and a gradual take-up by utilities, including power system operators.

TETRA is designed primarily as a voice communicator, something similar to a "walkie-talkie", but also has the ability to carry data. Work began on the system in 1990 and lead to a standard based around TDMA (time division multiple access) with a data rate of 4.8 kbps. This was perfectly adequate for mobile data systems of the time, but has been completely leapfrogged in terms of throughput by newer commercial alternatives. TETRA transceivers are also expensive compared to GSM equivalents due to the reduced economies of scale which GSM products enjoy.

Where TETRA does offer an advantage is that it guarantees access to the channel with short call setup times. If the low bit-rate and high costs of the transceivers could be tolerated, TETRA might offer a reasonable solution.

3.4 Internet Protocol based communications

The title 'Internet Protocol based communications' should refer to all methods of communication via the public packet switched data network known as the Internet. A detailed analysis is beyond the scope of this current paper but the authors have previously reported upon an experimental analysis of Internet Protocol delays in [6].

It was shown in [6] that current Internet services offered over ADSL (by telephone line) achieve delay times less than 40 ms, while emerging services offered by WiMax (microwave link) would take 340 ms. More recent analysis has shown a marked improvement in the WiMax service, with delays now reduced to 150 ms and below.

The bit-rate of these services ranges between 512 kbps to 24 Mbps for ADSL and 512 kbps to 300 Mbps for WiMax, depending on limiting technical factors and the level of subscription paid. For both, a typical speed of several Mbps is considered normal.

For the end user, Internet Protocol based systems offer a very low cost solution versus the latency and throughput available. This is due to the massive, global economies of scale in using the worldwide Internet Protocol standard.

3.5 Telecommunications security

One of the most common concerns is prohibiting unauthorised access to the communications network. It is possible to achieve such security by using a Virtual Private Network (VPN). A VPN creates a logical connection between a number of computers allowing data to be sent and received much like any other network. However, the VPN's advantage is that before any data enters a public network, it is encrypted. Without knowledge of the passwords to gain access to the network, a malicious attacker would be unable to read any data on the network, or to falsify data or spoof data into the network.

On the Internet, Denial of Services (DoS) style attacks could remain a concern, since such attacks rely on overwhelming the capacity of the telecommunications channels. However, with the assistance of a reliable Internet Service Provider (ISP), such an attack should have very limited effect.

3.5 Telecommunications conclusions

In terms of performances versus cost, Internet Protocol based products appear to offer the best solution. With gradual introduction of Local Loop Unbundling (LLU) and construction of a private WiMax network, utilities could enhance its performance further and eventual operate a private IP network.

4 Time Stamping

The preferred technique in the power system community to align data taken at multiple locations is to stamp the data with a real-world time. In this technique, each packet or frame of data is sent along with a time code which indicates the time at which the measurement was taken. Typically the time code indicates the number of seconds (and fractions thereof) passed since some agreed date.

Universal Time Co-ordinated (UTC) gives the time elapsed since midnight 1st January 1970 (00:00 01/01/1970). This would be the most commonly used time standard in the world, although it is important to note that it is not the only one. The GPS satellite system gives time since 01/01/1980, although most receivers adjust this time to UTC.

Within the Phasor Measurement Unit industry, use of the USA's Global Positioning System (GPS) is standard practice. This is likely due to its global presence and the low cost of embedded GPS receiver modules. However, it is important to remember that the GPS system is not primarily intended for civilian use. Facilities have been built in to GPS to disrupt the signal on command over specific areas of the globe to assist with military operations. For this reason, it is important that any protection system relying on time synchronisation must not rely solely on the GPS system.

Russia currently operates a partial satellite navigation system known as GLONASS. The system is hoped to be restored to full operation by 2009.

The European Union and ESA are in the process of funding the 'Galileo' Global Positioning System, which currently has one experimental satellite in orbit. The project is aimed to be completed by 2010. It is likely that after Galileo is established there will be receivers on the market capable of using all three systems; GPS, GLONASS and Galileo.
Alternatives to satellite time keeping include broadcast terrestrial time references, such as the MSF signal (formerly Radio Rugby clock) broadcast by the National Physics Laboratory (NPL) in the UK or DCF77 in Germany, besides several others. To use such terrestrial broadcasts, it is necessary to know the position of the receiver with respect to the transmitter so that the propagation delay of the signal may be computed and corrected for (this is done automatically by global positioning receivers). As long as the receiver doesn't move from site to site often, this shouldn't be a problem.

Given the variety of technologies it would be expected that a differential ROCOF relay would have the facility to synchronise to the 1-Pulse-Per-Second (1PPS) signal provided by many time sources in addition to any embedded time reception technology.

5 Frequency Measurement

There are many methods of estimating power system frequency; these include:

- Zero Crossing Detection
- Spectral Leakage
- Phase Locked Loops

While each method is capable of producing an accurate estimation of frequency in the steady state, the transient response of each technique is different.

The zero crossing technique calculates the period of the incoming signal using a microprocessor based counter triggered whenever the sign of the waveform crosses from positive to negative, or vice versa. Noise around the zero crossing can distort the estimation. Usually several cycles will be measured, alleviating the affect of the noise by averaging. This technique requires very simple hardware and its low cost has made it popular in ROCOF relays.

Frequency estimation by spectral leakage utilises a by-product of the windowing applied when processing Fast Fourier Transforms. It can be observed after an FFT is applied that small frequency components appear that do not exist in the original signal. The transfer function for this phenomenon may be calculated and by application of the inverse transfer function, the original frequency may be determined. This technique is hampered when the incoming signal is polluted by harmonics and random noise, which is the case on most power systems. Narrowband filters are used to enhance this technique's performance.

Phase locked loops (PLL) offer a fast estimation of frequency. A local oscillator's frequency is continually adjusted so as to match the instantaneous phase of the incoming signal. The magnitude of the control signal indicates the system frequency. Harmonics on the measured signal will cause ripple on the control signal and thus affect the estimation. A low pass filter may be used on the control signal to alleviate the effect of noise and harmonics at the expense of slowing the tracking speed of the PLL, thereby damping any transients.

It is important that once a frequency estimation technique is selected for differential ROCOF that a specification be drawn up defining the response of the estimator to transients. Using devices with different responses will unnecessarily reduce the sensitivity of the system and may cause nuisance tripping.

6 Simulated Differential ROCOF with a variable latency communications link

A model of a Differential ROCOF system was developed in MATLAB in order to develop an appreciation for suitable techniques which may latter be applied to a physical demonstrator. The model is summarised in Figure 2.

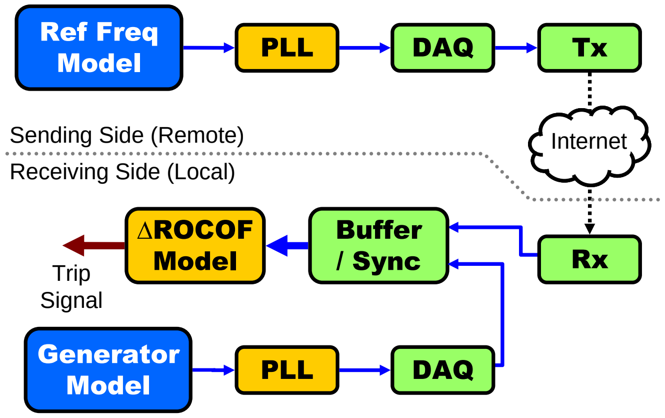

Figure 2: Block diagram of Differential ROCOF model.

The reference frequency model produces a sinusoidal waveform at a nominal frequency of 50Hz with a programmable rate of change and/or disturbances. This sinusoid is passed to a PLL which produces a voltage proportional to the detected frequency. A data acquisition (DAQ) block simulates the sampling of a PC and time stamps the data before the signal is transmitted through a variable transport delay.

The Internet connection is simulated using a fixed transport delay of 40 ms and a varying random delay between 0 and 40 ms, giving a coarse approximation to inter-arrival delay / jitter and out of sequence arrival.

Once this signal is received, the time stamps on the received data are used to buffer and synchronise the data with a signal derived in a similar way from the local genset relay.

Finally, a differential ROCOF relay is modelled. If the difference in ROCOF between the two sites exceeds a defined threshold, a trip signal is sent.

The simulation is run with a variable step side to allow for accurate modelling of the analogue sections. Since phase-locked-loops are estimating the frequency, the DAQs are set to sample the frequency and ROCOF at 200 Hz (i.e. four times every cycle at a nominal frequency of 50 Hz).

As a benchmark operating time, a standard ROCOF relay will usually take 80 ms to detect a fault. This arises since a ROCOF relay calculates frequency based on a sliding window of 3-cycles, and requires 2 consecutive calculations to confirm the disturbance is permanent [3]. This is 4-cycles, which at 50 Hz equates to 80 ms.

In the UK, ROCOF relay settings typically lie between 0.1 Hz/s and 1 Hz/s with the vast majority at the lower end of the scale [4]. In Northern Ireland and the Republic of Ireland, ROCOF relay settings are generally greater than 0.4 Hz/s [5] for diesel generators and it has been suggested to use 0.55 Hz/s for wind generators. Due to the smaller size and inertia of the electricity grid in Ireland, disturbances cause frequency transients of greater magnitude than a similar disturbance would cause on the UK or continental systems.

6.1 Relay simulation without noise (ideal)

The differential ROCOF relay model was found to trip appropriately for disturbances in frequency of between 0.1 Hz/s and 0.5 Hz/s. What was of greater interest was to determine the relay's response to a) system wide disturbances and b) small local disturbances.

The first scenario applied a disturbance of 0.5 Hz/s at both the mains reference frequency and at the generator. This deviation should trip a standard ROCOF relay. The model was found to respond correctly, with no nuisance tripping to this system wide event.

The second scenario applied a very small frequency deviation to the generator only. This was 0.02 Hz/s, well under the detection threshold of a standard ROCOF relay. The differential ROCOF relay correctly identified the discrepancy and tripped after 47 ms. Virtually all of this time delay is caused by the telecoms delay (40+ ms). During this time the generator frequency only decreased by 1.74 mHz, which would be considered normal operation.

6.2 Relay simulation with noise (practical)

On repeating the above simulations using a model which now includes a random error in ROCOF estimation of ± 0.5%, it was found that the idealised differential ROCOF relay caused many nuisance trips. This arises since the sensitivity of the relay was set to detect all ROCOF excursions (i.e. if the difference between local and remote ROCOF is non-zero). The small errors in frequency estimation were considered to be actual discrepancies in ROCOF.

To overcome this problem it was necessary to include a dead band in the relay model, that is to say a threshold in the difference between ROCOF signals below which the relay will not operate. By tuning the dead band, it was found that nuisance tripping could be prevented at the expense of delaying the response of the relay to valid events.

With the modification, detection of the 0.02 Hz/s excursion now requires 127 ms, while a more typical 0.10 Hz/s event requires 92 ms detection time as seen in Figure 3. At the moment of the trip, the telecoms delay was 70 ms, with the previous two samples both delayed by 50 ms. The fault was detected on the samples 40 ms and 45 ms after the fault begins. The remainder of the trip time can be accounted for my telecoms delay.

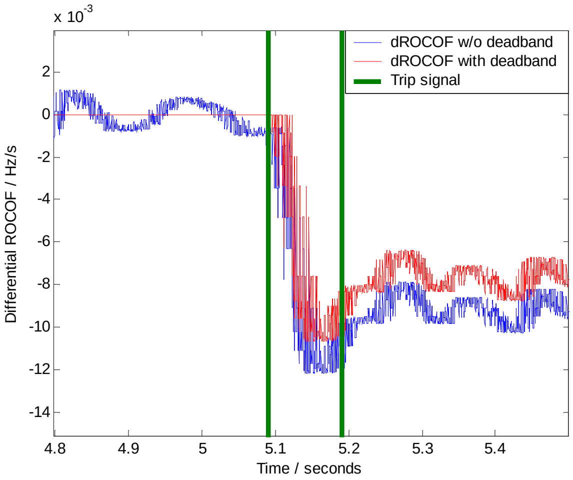

Figure 3: Differential ROCOF relay with dead band responding to a 0.1 Hz/s step in ROCOF.

6.3 Conclusions from simulations

Differential ROCOF's does reduce nuisance tripping and increase the sensitivity of ROCOF at the expense of a longer trip acquisition time due to the necessity to communicate a reference signal to the local relay.

The effects of noise and measurement error could be reduced with an improved correlation technique, and combining differential ROCOF with a differential frequency and phase system could yet further stabilise the system.

With the present interest in micro-grids and synchronous islanding, a method of networking individual relay protection systems into a local area protection and control scheme seems a logical step forward.

7 Experimental evaluation of differential genset protection schemes

In order to evaluate the susceptibility of a differential ROCOF relaying scheme, among other methods, to the characteristics of variable latency telecommunications systems, a demonstrator has been constructed at Queen's University Belfast.

The demonstrator consists of a 5 kVA alternator (DC motor prime mover) which may be synchronised to the mains supply of the building, a load bank, a reference supply with no generation connected, two phasor measurement units (PMU) capable of measuring frequency as well as phase, and an Internet Protocol 'repeater' on the other side of Belfast city. An illustration is given in Figure 4.

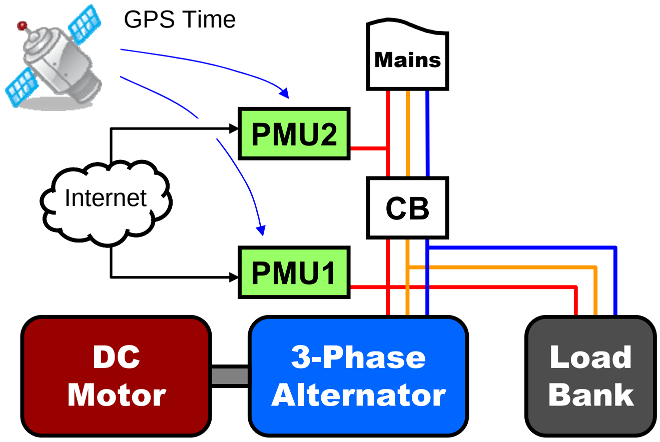

Figure 4: Illustration of Differential ROCOF demonstrator.

The demonstrator allows for various software emulated relays, such as differential ROCOF, to be applied in real-time on real hardware. The response of the relay to various mismatches between synchronised and islanded load may be observed, allowing the model to be evaluated.

It is intended to use this demonstrator as the basis of a phase control system for application to a 50 kVA diesel generator as part of a strategy to enable synchronous island operation.

8 Conclusions

Through simulation it has been demonstrated that differential ROCOF offers benefit to reducing nuisance tripping, at the expense of a longer trip time. Furthermore, it has a much improved sensitivity to low discrepancies in ROCOF. While in the ideal case trip times are very low and approach those of a standard ROCOF relay, the application of noise which would be seen in a practical environment diminishes the performance.

Future work will consider improved noise reduction techniques and correlation methods, use of differential phase rather than frequency, and operation of a practical demonstrator of the technology to allow model relays to be tested on real-time real-world data.

Acknowledgements

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