

Performance of Power-Line-Signaling Based Detection Algorithms for Islanding Protection of Distributed Generators in Interharmonic Polluted Systems

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Abstract. Recently, a new islanding detection scheme based on power electronic signaling technology has been proposed in the literature. By broadcasting a signal on the distribution feeders from the substation to the down-stream DGs, the absence of the signal at the DG site will be a sign of islanding. The scheme is more reliable than regular local detection techniques while it costs much less than transfer trip schemes. As the checking of the signal continuity is done via signal detectors, performance analysis of implemented detection algorithms is one of the main concerns. Since, the scheme relies on distortion broadcasting, our purpose is to answer the first question arises i.e., `` Is it a reliable scheme for DGs located at industrial areas that are rich in harmonics and interharmonics? ". Results show that for spectral based detection algorithms, more selective thresholds must be set in case of excessive interharmonic pollutions.

Key words

Distributed Generation, islanding detection, power frequency communication, power line signaling, interharmonics.

1. Introduction

Creating small, controllable disturbances on power system voltage and current waveforms, to represent distinguishable information-oriented power-electronicbased signals, was first introduced in the early 1970s. Now, after years of development, one of the applications of this so-called *Power Electronics Signaling Technology* is the power frequency communication scheme. In this scheme power lines are used for transmitting the signals. The outbound two-way automatic communication system (TWACS) reviewed in [1,2] manipulates a shunt type signal creation method (zero-crossing distortion technique) as a simple signal creation method with reasonable speed. The distortion injection is at distribution substation bus and the response is detected at the remote site of the network. This PLC technology is much simpler and robust than other widely used PLC techniques, specially the one that uses a hight frequency waveform superimposed on the 60 Hz or 50 Hz carrier waveforms. The new power electronic based created

signal is transient oscillatory in nature and has a different signal propagation characteristic than the regular signals transmitted in PLC technologies. W. Xu et al. in [3] developed an islanding detection method using a similar signaling technology to the outbound TWACS. The followings are some advantages of this method: it doesn't need any telecommunication coverage, theoretically it can be used regardless of the power imbalance in an island and for different DG types. The cost of the signal generator can be shared among all downstream DGs. Switching of any openable device can be detected automatically. In order to spread the cost of signal generator over multiple applications or in case of signal interference with AMR signal transmitters, the meter reading signal generator can be used for both islanding protection and AMR, deploying different signaling channels [4,5].

Furthermore, the proposed scheme in [3] was improved in [6] by adding the feature of main supply disconnection detection to the signal generator. This detection is done by examining the dc component of the upstream transient current created during the signaling process. This feature adds flexibility and adaptability to the previous scheme, i.e. the signal generator can now be installed between the substation and DG sites.

Although the signal extraction method used in the aforementioned schemes is proved to be immune to the power system integer harmonics but the fact that noninteger harmonics (interharmonics) are quite often generated in the system, inquired us into assessing the performance of the detection algorithms deployed in signal detectors. The main interharmonic sources are adjustable speed drives (ASDs) with P_1 pulse rectifier and P_2 pulse inverter and periodically varying loads such as arc furnaces. Their generated interharmonics depend on P_1 , P_2 , the drive operating frequency and the load varying frequency, respectively [7]. Accordingly, we have injected reasonable interharmonic pollutions to the detection channel waveforms to perform our study.

This paper is structured as follows. Section II presents the Scheme configuration. Section III talks about the signal generator. Section IV introduces the characteristics of the signal as its the prerequisite for proposing the detection algorithms in the next sections. Section V discusses the signal detector and detection techniques. Section VI deals with basics of performance analysis of the signal detection techniques. Section VII presents the simulation results and discussion. The last section concludes this paper.

2. Scheme Set-up

A power-line-signaling (PLS) communication system is composed of two devices, a signal generator (SG) and a signal detector (SD). In regular set-ups (non-scalable ones) the SG is placed at the substation bus. In case of islanding conditions, opening of switching devices between SG and SD or substation outage, the downstream DG units will trip. Furthermore, the SG can have auxiliary inputs which give flexibility to the system operators when they need the DGs to be shut down. As the signal carrier is the power line itself, the formation of an island can be detected automatically since the signal can't be detected anymore. Fig.1 illustrates the scheme.



Fig. 1. Power line signaling islanding detection scheme.

3. Generating the Signal

With reference to [3] a *waveform distortion* technique is selected as the power electronic signaling method. The rule is that as the thyristor is fired, precisely controlled current pulses are drawn from the point of the installation. The firing is done at a preset angle before the voltage zero crossing point. The momentary short circuit current is limited by the step down transformer used for supplying the thyristors. Such a limited voltage distortion doesn't exceed the power quality limits as it only can be detected using special signal detection techniques after being propagated through the transmission lines.

Particular signaling patterns can be carried out by firing the thyristor within different intervals and through certain channels (phase to phase or phase to ground). In order to reduce the heat stress on the thyristor, while providing a reasonable response time from the islanding initiation time, a 4 cycle interval between two subsequent firing events has been assigned. Also according to [3], a phase to phase signaling is chosen since it has higher signal strength (ratio of signal peak to its carrier peak). Although anti-parallel thyristors can be used to fire at either rising or falling edge of the voltage to facilitate more signaling patterns, we use a single thyristor (for falling edge firing).

4. Characteristics of the Signal

The switchings that create the distortion signal start at an angle, say 20 degrees, before the voltage zero-crossing and end at the first zero current. From circuit theory, superposition principle demonstrates that this is equivalent to injection of a negative voltage source in the signaling channel. Therefore, the signal received at the DG site v_{signal} is considered to be response of the system to the virtual voltage source. The oscilatory nature of the recieved signal is mathematically proved in [3]. According to [2] these transient oscillations are actually damped resonance phenomena of a distribution system due to the injected perturbation.

5. Signal Detection

Checking the presence of the broadcast signal at the signal detector position is the key to the islanding protection. The detection process includes signal extraction and a subsequent signal processing method.

A. Signal Extraction

A phase to ground channel (B-G) is selected as the detection channel. In order to extract the signal from this voltage waveform, subtraction of two consecutive cycles is used. Mathematically we can describe this subtraction by:

$$v_{simal}(t) = V_B(t) - V_B(t-T) \tag{1}$$

Where T is the period of fundamental frequency, 60 Hz, waveform. For the dc component, the first harmonic and the other integer harmonics (for which, T will be an integer multiple of their own period) the previous equation will become:

$$a_h \sin(h\omega(t)) - a_h \sin(h\omega(t-T)) = 0$$
⁽²⁾

Hence, in consequence of the executed extraction method, the detector filters out the integer harmonics which are common in power systems as a result of transformer and electromechanical devices operation, but as the distortion only exists in one of two consecutive cycles it would be extracted. Fig. 2 depicts (1) considering the fact that, in order to avoid data repetition, each cycle of the detection channel waveform occurs only one time in the subtraction process.



Fig. 2 Subtraction Pattern for signal Extraction [3]

The authors in [2] have claimed that field experiments show that the natural frequencies of the signal are between 200 Hz and 600 Hz, we will use this fact for the detection algorithm criterion. In the subsequent sections we will illustrate how immune are common detection algorithms that are followed the subtraction pattern mentioned in (1).

B. Detection Algorithms

W. Xu *et al.* in [3] introduce three detection algorithms. The first algorithm uses the RMS value of v_{signal} for signal detection. It's not a well developed method and therefore as the aforementioned authors have mentioned in their paper, it doesn't perform reliably in actual fields with high noise. The two remaining algorithms, namely spectral based and template based algorithms, will be introduced.

1) Spectral Based Detection Algorithm

According to Fig. 2, the subtraction results in 2 cycles for every 4 cycles of the detection channel voltage. Although we do not know that the generated signal is in which of these two cycles (it depends on the signal generator operation time), when the firing angle is less than 30°, the signal can only be in the window shown in Fig. 3 for each cycle. We refer to this window as the signal segment of the extracted signal cycles.



Fig. 3. Signal Segment [3]

The principle is to use the FFT analysis for the signal segment and the remainder segments of each extracted cycle.

As it have been stated in [3], in practice the signal frequency is system dependent, moreover it may reside between two harmonics and also has a transient nature. These facts and the frequency range stated in section A, make us conclude that the proper index for detection is a composite RMS of a group of harmonics. Moreover, the signal window in Fig. 3 has a width of 180° therefore only even harmonics of the fundamental frequency, 60 Hz, will have considerable magnitudes. Consequently the index is defined as:

$$RMS_{h} = \sqrt{M_{4}^{2} + M_{6}^{2} + M_{8}^{2} + M_{10}^{2}}$$
(3)

A threshold will be selected two assess the presence of the signal. Since the signaling is done every 4 cycle of the carrier, in normal conditions only one out of the four segments in extracted 2 cycle waveform satisfies the threshold. In abnormal situations more than one segment satisfies this principle while in islanding cases non of the segments contains the signal. For the sake of reliability the final decision depends on whether the same concluded case happens for 4 consecutive signaling periods. This results in discrimination between real islanding events and local faults/cap-bank switchings.

2) Template Based Detection Algorithm

A correlation index between the v_{signal} and a windowed sinusoidal waveform aligned to the thyristor firing instant will be used as the detection index. Similar to the rationale behind using the harmonic group in the spectra algorithm, here we need to use a group of templates. In accordance with the natural frequency range in section A, and the index in [3] the detection principle equations can be summarized as:

$$RMS_t = \sqrt{CR_5^2 + CR_6^2 + CR_7^2 + CR_8^2 + CR_9^2}$$
(4)
Where:

$$CR_{h} = \left| \sum_{i} v_{signal} v_{template-h_{i}} \right|$$
(5)

Which is cross-correlation of the signal and the template at current time. Equation 4 can be expressed in percentage, if we refine 5 as the absolute value of equation 6.

$$CR_{h} = \frac{\sum_{i} v_{signal_{i}} v_{tem plate - h_{i}}}{\sum_{i} v_{tem plate - h_{i}}^{2}}$$
(6)

3) Algorithm Comparison

Using the field test results reported in [4,8] we know that: * Since the signal frequency doesn't experience any momentous variations, both detection RMS indexes are reliable and robust.

* The more difference between detection index value of v_{signal} segments, the better the detection performance.

* Performance of the template based algorithm highly relies on the accuracy of the template.

* Statistical analysis of signal to noise ratio of the algorithms show that the template based method has the highest average signal-to-noise ratio (S/N) but its S/N is distributed in a wider range, with a minimum close to spectral method minimum S/N (Signal-Noise-Ratio is defined as the ratio of the detection index of the so-called with-signal cycle to the detection index of the non-signal cycle).

6. Detection Performance in Presence of Interharmonics

We can define the extracted v_{signal} as the result of the following convolution:

$$v_{signal} = D(t) * V_B(t) = \sum_{n=0}^{N} c_n \delta(t - nT) * V_B(t)$$
 (7)

In the implemented extraction pattern used in [3], N = 1 and $c_0 = 1, c_1 = -1$. From (7) we have:

$$D(j\omega) = c_0 + c_1 e^{-j\omega T} + \dots + c_N e^{-jN\omega T}$$
(8)

Authors of [2] refer to D as the detection vector and demonstrate that they are in fact finite impulse response

filters (FIRs). The extraction procedure is the convolution of the filter with detection channel voltage containing the generated distortion. Fig. 4 illustrates the fact that unlike the integer harmonics, any background distortion of the interharmonic type can not be filtered out.



Fig. 4. Extraction Pattern Result in Presence of Interharmonics

From [8] we realize that the detection process immunity to interharmonics depends on the subtraction pattern used for signal extraction, i.e. whether they provide sufficient attenuation of interharmonics–see Fig. 5 in which, filter (a) is defined as $\delta(t)-\delta(t-T)$ (the common extraction pattern used in power line signaling islanding detection) and filter (b) illustrates how other extraction methods can filter out different background distortions.



Fig. 5. Magnitude of Frequency Response of Different Extraction Patterns

7. Simulation Results

Fig. 6 depicts the simulated system in PSCAD, note that for the signal detector and the signal generator separate component pages have been created. The detection channel signal is processed using the programs developed in MATLAB.



Fig. 6. Single line diagram of the simulated system

Parameters of the system could be found in [3].

A. Regular System with no Interharmonics

Fig. 7 depicts the v_{signal} waveform which is processed by the aforementioned detection techniques.



Fig. 7. Extracted Waveform

1) Spectral Based Detection

Fig. 8 shows the results for 5 consecutive signaling periods (all normal events, i.e. DG is connected to the utility), the signal is in the signal segment of the first cycle of the extracted waveform for each signaling period (i.e. the second segment), as it can be seen the signal is successfully detected using the threshold assigned in [4] (1.2 V). Additionally, we opened the breaker in order to see the algorithm results in case of islanded event, the evaluated RMSh values were all similar to non-signal segments of Fig. 8 confirming the proper detection of the islanded event.



Fig. 8. RMSh for 5 Consecutive Normal Events

2) Template Based Detection

Fig. 9 shows the results of template based detection for with signal and without signal cycles of each signaling period extracted waveform. Simulation results are similar to the ones in [4], therefore we have selected the same threshold (15%). Note that unlike the spectral based method, non-signal segments of the cycles are not processed since we have assigned zero value for the template outside the signal window. Similar to the spectral based method after opening of the breaker, RMSt for all the segments was of no-signal value.



Fig. 9. RMSt for 5 Consecutive Normal Events

B. Detection Channel Polluted by Interharmonics

According to [7], interharmonics always appear in pairs with the summation or difference of 2 times of the fundamental frequency. We have selected 2 pairs of interharmonics measured in [7] (264-384 Hz and 228-348 Hz). We add 0.2% of these interharmonics to our detection channel signal in order to study the performance of the detection process in case of pollutions limited to IEC 1000-2-4 standard values. Moreover, we have also simulated the case for excessive pollutions to find out at which condition does each of the algorithms fail. Note that although the order of the interharmonics has impact on the detection performance but our simulations showed that generally the reaction of the methods can be assessed using some sample orders. Fig. 10 depicts the extracted signal (detection algorithms input signal).



Fig. 10. Extracted Signal After Interharmonic Injection

1) Spectral Based Detection

Fig. 11 illustrates the spectral based detection method in presence of interharmonics of 0.2% and 0.3%.



Fig. 11. RMSh for 5 Consecutive Normal Events–Interharmoic Polluted Channel

As it can be seen in the figure, the algorithm fails to detect the signal in all of the signaling periods when the detection channel is polluted with 0.3% interharmonic.

2)Template Based Detection

Fig. 12 illustrates the spectral based detection method in presence of interharmonics.



Fig. 12. RMSt for 5 Consecutive Normal Events–Interharmoic Polluted Channel

From the figure we can conclude that for pollutions more than 0.7% the signal detector can not perform reliably, since for the 0.7% case it fails to detect the signal in the fifth signaling period.

8. Conclusion

The effort, presented in this paper, to assess the performance of the common power line signaling islanding detection scheme, can answer to the mostly arose question for the engineers that are not familiar with this scheme i.e., its performance in harmonic and interharmonic polluted industrial areas.

The signal extraction stage, which forms the input to the detection techniques, plays the major rule in filtering the background distortions. It is demonstrated that although the common extracting method in the anti-islanding scheme successfully filters out the dc, fundamental and integer harmonics, but it can not filter out the interharmonics. Therefore, studying the detection results

when there are interharmonic sources in the area is needed. The simulation results show that although both of algorithms perform well in case of maximum standard interharmonic limit; for the spectral based algorithm a more selective threshold must be assigned when detection channels are polluted with excessive interharmonics. But, the template based method can still discern the signal in channels with excessive pollution using its default threshold.

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