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Performance of Frequency Anti-Islanding Protection Considering Different Frequency Estimation Methods

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Abstract: Frequency anti-islanding protections use frequency measures to determine an islanding condition, which are usually filtered to eliminate high frequency components. Digital relays can use different frequency estimation methods, which could lead to different results between different methods and filter lengths. This paper compares three frequency estimation methods found in digital relays against noise, harmonics, DC decays, steps and slopes of frequency, showing their intrinsic differences. Islanding events are simulated to show the importance of investigating frequency measurement methods and filter lengths before performing any protection study.

***Keywords*: Frequency estimation methods, Anti-Islanding Protection, Zero-Crossing, Clarke Transform, Rate of Change of Phase Angle.**

1. INTRODUCTION

In power systems, correct frequency estimation is essential for power system stability and the proper working of control and protection systems, as reflects the load/generation balance. An error in frequency estimation might lead to malfunctioning of these systems, leading to load shedding and loss of grids. (Begovic *et al.*, 1993; De La Ree *et al.*, 2010; Sorrentino and Carvalho, 2010; Carcelen-Flores *et al.*, 2012). Different methods have been developed to measure frequency. The simplest method consists of detecting consecutive zero-crossings of system voltage signals, identifying the period of the wave, and, consequently, its frequency. Although simple, the zero-crossing method is sensitive to noise, harmonics, and DC decays (Begovic *et al.*, 1993; Sorrentino and Carvalho, 2010). The Discrete Fourier Transform (DFT) can also be used to measure frequency through phasor angle variation (Phadke, Thorp and Adamiak, 1983; Sorrentino and Carvalho, 2010; Sanca, Souza and Costa, 2016), and through direct calculation using the first derivative (Moore, Carranza and Johns, 1994) and second derivative (Seo and Kang, 2017) of the real and imaginary parts of the estimated phasor, with better immunity to harmonics and DC decays. Least-error squares algorithms to estimate frequency have been presented in Sidhu and Sachdev (1998) and Das and Sidhu (2013). Other approaches, such as Prony’s method (Lobos and Rezmer, 1997), Newton algorithms (Terzija, Djuric and Kovacevic, 1994) and Adjustment Points of a Sine Wave (APSW) (Agha Zadeh *et al.*, 2010; Sorrentino and Carvalho, 2010; Sanca, Souza and Costa, 2016) can also be found in specialized literature.

The anti-islanding protection is intended to disconnect (or change the operation mode) of the distributed generation (DG) in the case of a loss of grid. Passive anti-islanding protections are cheaper and do not introduce distortions to the grid, and thus, are the most used technique. Frequency protection is a passive anti-islanding technique that measures grid frequency to monitor the load/generation balance. In the case of islanding, the balance condition is disturbed, leading to frequency excursions, which are detected by the frequency protection, which decides, through the protection setting, whether the disturb is considered an islanding or not (Redfern and Fielding, 1993; Mahat, Chen and Bak-Jensen, 2008).

As seen in the technical literature, different frequency estimation might result in different frequency estimates. Additionally, digital relays filter the input and output signals to reduce the influence of distortions, which might cause signal attenuation or time delay (Sorrentino and Carvalho, 2010; Sanca, Souza and Costa, 2016; Grebla, Yellajosula and Hoidalen, 2018).

Thus, frequency protections using different estimation methods can produce different results. This paper investigates the influence of frequency estimation methods and their filtering in the performance of anti-islanding protection, through graphical and tripping time comparisons. Section 2 presents the studied methods of frequency estimations presenting a comparison through test signals simulated. Section 3 presents briefly the system used for simulating islanding cases and the parameters of the performed tests.

Section 4 presents the simulation results with discussion and Section 5 presents the study conclusions.

2. FREQUENCY ESTIMATION METHODS

In this section, three frequency estimations methods are presented. Those methods were chosen based on the algorithms found in industrial relays.

2.1 Zero-crossing technique (ZC)

This technique is based on counting the time between two instants of time in which the monitored signal crosses level zero, as depicted in Fig. 1. This time interval is representative of the system frequency, which can be obtained by calculating the inverse of the period calculated. The measures of time can be of two consecutive zero-crossings, as in Fig. 1, or consecutive increasing or decreasing zero-crossings. The last two take into account the slope of the monitored signal (Begovic *et al.*, 1993; Sorrentino and Carvalho, 2010).

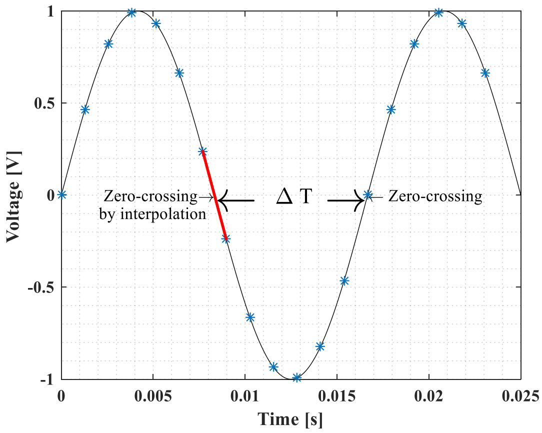

Fig. 1 Graphical representation of zero-crossing technique.

In digital relays, where the monitored signal is sampled, the exact sample in which the monitored signal crosses zero might not be available, and interpolation may be necessary to estimate the zero-crossing time, as depicted in Fig. 1 (Sorrentino and Carvalho, 2010).

Despite simple, the zero-crossing technique is sensitive to noise, harmonics and DC decays, that can be attenuated through filtering of the monitored signals and the estimated frequency (Begovic *et al.*, 1993; Sorrentino and Carvalho, 2010).

2.2 Zero-crossing technique with Clarke Transform (ZCCT)

The zero-crossing technique is often employed in each phase voltage of the system (SEL, 2012b), which might lead to a discrepancy in the frequency estimated between different phases.

Thus, the zero-crossing technique with Clarke Transform associates the information of all phases instantaneously through the Clarke Transform and applies the zero-crossing technique to the alpha component (SEL, 2012a). The alpha quantity is calculated as follows:

$$V_{alpha} = V_a - 0{,}5(V_b + V_c) \tag{1}$$

with V_a, V_b, and V_c the instantaneous voltages in phases *a*, *b*, and *c*, respectively.

2.3 Rate of change of phase angle (RoC)

The method, in this paper, called “rate of change of phase angle” (RoC) is a DFT-based method, first proposed by Phadke, Thorp and Adamiak (1983).

The DFT separates the monitored signal in real and imaginary parts, and its algorithm can be recursive or non-recursive. If the monitored signal is estimated with the non-recursive method, the estimated phasor, composed by the real and imaginary parts, rotates in the counterclockwise with the system frequency. Alternatively, with the recursive method, the estimated phasor keeps stationary, drifting if the system frequency also drifts (Phadke, Thorp and Adamiak, 1983; Phadke and Thorp, 2008).

Independent of the algorithm used, the DFT can be used for frequency estimation using the phase angle given by the arctangent of the ratio of the real and imaginary parts of the monitored signal (Phadke, Thorp and Adamiak, 1983; Sorrentino and Carvalho, 2010; Hwang and Markham, 2014; Sanca, Souza and Costa, 2016).

In this paper it was used the non-recursive approach. Thus, the frequency estimated by the variation of phase angle represents the system frequency. Given a series of phase angle estimations δ_k, the system frequency can be estimated through (2), where ΔT is the time interval to calculate the frequency:

$$f = \frac{1}{2\pi}\frac{\delta_k - \delta_{k-1}}{\Delta T} \tag{2}$$

A value for ΔT encountered in industrial relays is 50 ms. This time interval ΔT, in which the samples of phase angle δ_k are taken, filters the estimated frequency (Sorrentino and Carvalho, 2010).

The RoC method, as a direct consequence of the use of DFT, is immune to noise, harmonics and DC decays but presents oscillations when system frequency presents large deviations from the nominal value (Phadke, Thorp and Adamiak, 1983; Sorrentino and Carvalho, 2010; SEL, 2012b).

3. TEST SYSTEM AND SIMULATION PARAMETERS

The frequency measurement methods are modeled in the software Alternative Transients Program (ATP). The frequency estimation methods are tested using 60 Hz as nominal frequency with the injection of synthetic signals with known parameters. Table 1 contains a summary of all the tests performed with a brief description. Those tests are intended to show the differences between the frequency estimation methods as well as the importance of filtering the estimated frequency. The filtering of the frequency estimations is accomplished through averaging filter. The frequency estimations are filtered through averaging filter over a complete system cycle (60 Hz). The tests parameters are described in Table 1.

Table 1. Frequency estimation models tests.

Test	Action
Noise	Injection of a sinusoidal wave with a Signal-to-Noise Ratio (SNR) of 10,000. The SNR of 10,000 represents that the amplitude of the noise signal is only 1% of the amplitude of the fundamental frequency signal.
Harmonics and DC decays	Injection of a sinusoidal wave with the presence of second and third harmonics with amplitudes of 3.5% of the fundamental frequency and a DC decay with an amplitude of 18% of the fundamental frequency.
Changes in frequency	Injection of two steps of frequency (2 Hz and -4 Hz and two slopes of frequency (5 Hz/s and -10 Hz/s).

After testing the frequency estimation models, islanding events are simulated using the test system presented in Motter and Vieira (2018), without the synchronous generator connected to bus 824. The system is depicted in Fig. 2, and it is based on the IEEE 34-bus system, containing two distributed generators: a synchronous generator, connected at the bus 848, and an inverter-based source at the bus 840.

The frequency estimation methods are compared with different averaging filters length. Table 2 presents the simulated islanding cases. The islanding events are simulated by opening the switch identified by “SW1” in Fig. 2 (only the synchronous generator is islanded). The synchronous generator power dispatch and the adjacent load “LGD1” are varied to obtain islanding cases that generate considerable overfrequency and underfrequency events. Other system loads were kept at 1 pu. The column denoted by “Load Condition (pu)” presents the load condition of the islanded system caused by variations in the load “LGD1”. For example, the first row indicates that the overfrequency simulation was accomplished by setting the generator dispatch at 0.98 pu, the adjacent load LGD1 in 0.33 pu, which caused a load condition, for the islanded system, of 0.83 pu. The power base of the system is equal to the generator rated power 1112 kW.

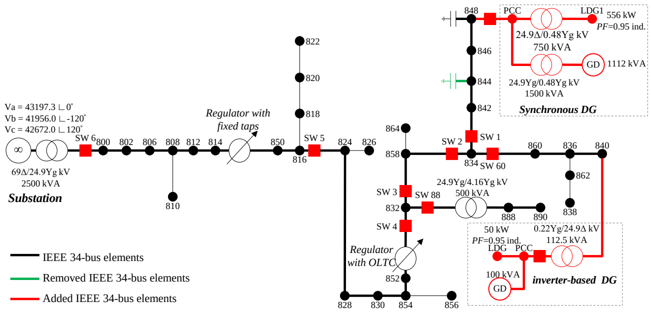

Fig. 2 Test system based on IEEE 34-bus.

Table 2. Islanding cases simulated.

Case	Generator dispatch (pu)	LGD1 (pu)	Load condition (pu)	ΔP (kW)
Overfrequency	0.98	0.33	0.83	-162
Underfrequency	0.75	0.50	0.98	260

4. RESULTS AND DISCUSSION

This section presents the results obtainaed by testing the frequency estimation methods through the injection of signals and simulation of islanding events.

4.1 *Noise test*

A signal with SNR of 10,000 was generated, and the frequency estimation obtained by each of the studied methods are shown next. Fig. 3 shows the frequency estimation results for each method without averaging filter, while Fig. 4 shows the filtered frequency.

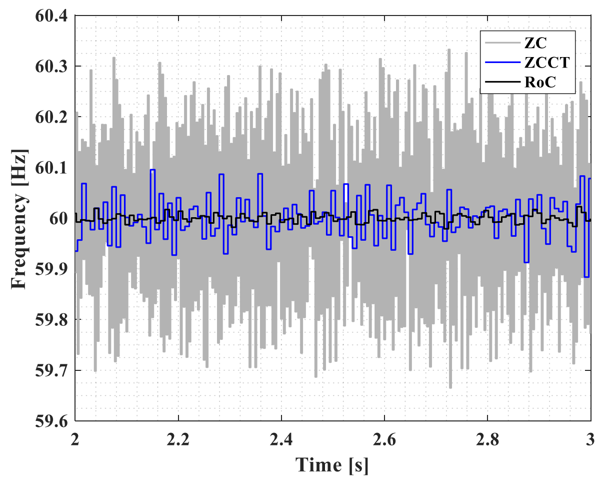

Fig. 3 Frequency estimation from noisy signal. No filtering.

Observing Fig. 3 and Fig.4, it is possible to identify that the methods of ZC and ZCCT techniques are more susceptible to suffer from noise influence. This behavior is understandable since the noise distorts the signal wave and might cause the zero-crossings to occur earlier or later than expected, while the RoC, due to the DFT process, filters the noise component. Filtering the estimations reduces the excursions but not the oscillations of the signal, as can be observed in Fig. 4.

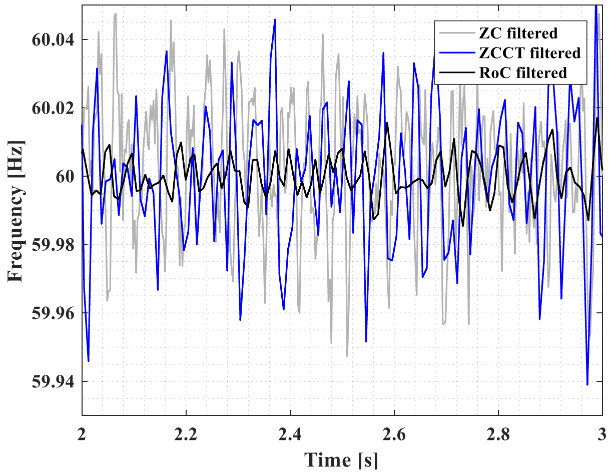

Fig. 4 Frequency estimation from noisy signal. Filtered signals.

4.2 Harmonics and DC decays

The experiment with harmonics and DC decays was accomplished by injecting a pure sinusoidal wave and adding harmonic components and the DC decay at specific points of the simulation. The second harmonic is inserted into the signal used for frequency measurement at 0.5 s while the third harmonic is inserted at 1.0 s. The DC decay is inserted at 1.5 s. Fig. 5 and Fig. 6 show the result of the experiment, and the levels of each added components are presented in Table 1.

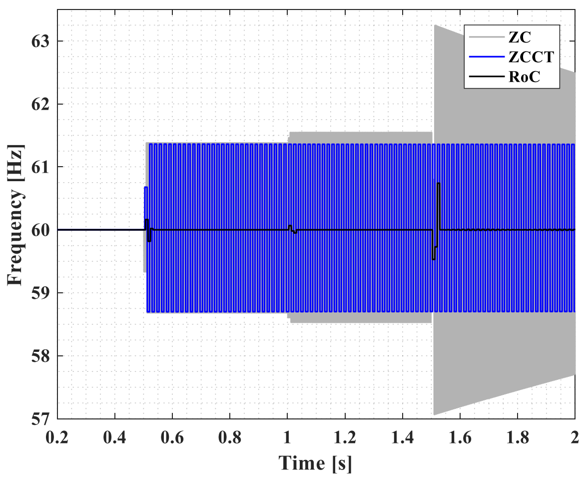

Fig. 5 Frequency estimation of signal with harmonics and DC decay. No filtering.

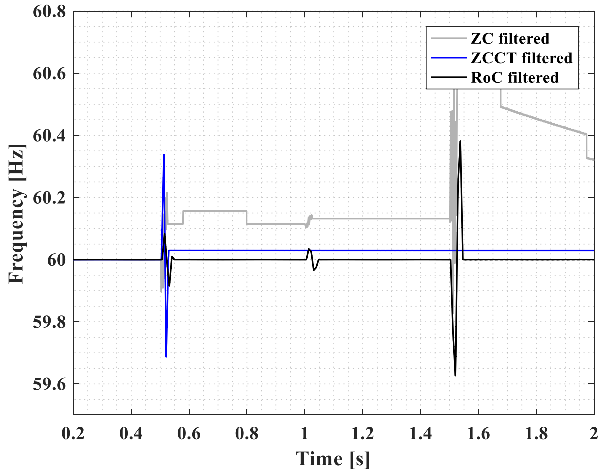

Fig. 6 Frequency estimation of signal with harmonics and DC decay. Filtered signals.

As can be observed in Fig. 5 and Fig. 6, the RoC estimation method does not suffer from the influence of harmonics and DC decays, because of the filtering process accomplished by the DFT estimation of angle, which separates the signal into the harmonics and also filters the DC component. Both ZCCT and ZC estimation suffer from the presence of harmonics, which is explained by the distortion of the signal wave caused by the presence of harmonics. Although sensitive to harmonics, the ZCCT is not sensitive to DC decays due to the Clarke Transform, which splits the signal into orthogonal parts and the γ-quantity.

4.3 Changes in Frequency

The results obtained by the simulation described in Table 1 are depicted in Fig. 7.

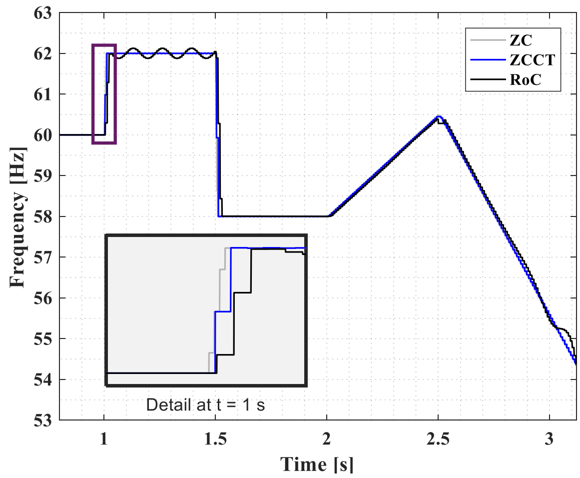

Fig. 7 Frequency estimation test. Step and slope. Filtered signals.

The presented signals are not filtered since the frequency estimations are all correct. However, some details can be observed as the difference in the transient response of these methods. By their nature, the ZC is the fastest, while the RoC is the slowest. It indicates that there might be differences in the performance of anti-islanding protection when applying different methods. Moreover, the RoC method presents oscillating behavior when the system frequency deviation is significant due to the leakage effect.

4.4 Islanding events

The simulated islanding events, according to Table 2, intend to point out the importance of knowing the frequency estimation algorithm and the filter length of digital relays used. The results of the simulated islanding cases are shown in Fig. 8 and Fig. 9, where the regions of most interest are highlighted. They show the exact point where frequency crosses the levels of 62 Hz and 56.5 Hz, respectively. Other settings are analyzed and are represented in Fig. 8 and Fig. 9 by the dotted straights. Besides considering different estimation methods, the current analysis also considers different filter lengths.

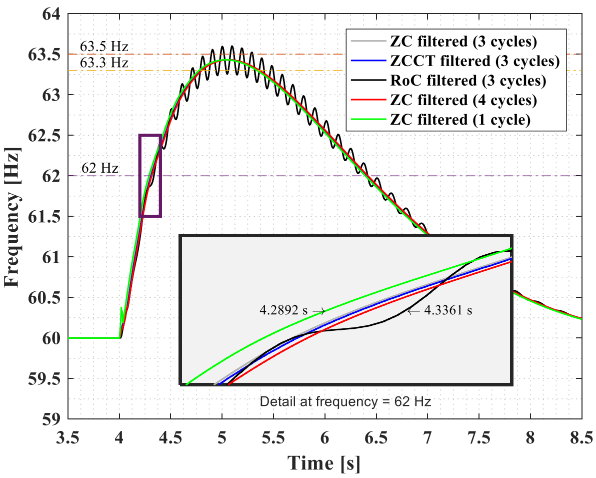

Fig. 8 Frequency estimations of islanding event causing overfrequency.

The highlighted regions in Fig. 8 and Fig. 9 indicate differences when considering different frequency estimation methods and filter lengths. For those events, the maximum differences observed in the tripping time are 47 ms and 25 ms for the overfrequency and the underfrequency events, respectively.

Additionally, as can be observed in Fig. 10, which presents a more detailed view of the event depicted in Fig. 8, only the RoC method would trip the protection if an instantaneous setting of 63.5 Hz were applied. Furthermore, the RoC method would be the only method not able to trip the protection if a setting of 63.3 Hz with temporization higher than 34 ms was applied due to the oscillatory behavior, which would reset the counting of time. Similar behavior can be observed for the event of islanding, causing underfrequency, depicted in Fig. 9, for the settings of 54.2 Hz and 54.5 Hz with a maximum temporization of 50 ms. It is important to highlight the settings are based on the ride-through requirements presented in IEEE 1547-2018 (IEEE, 2018).

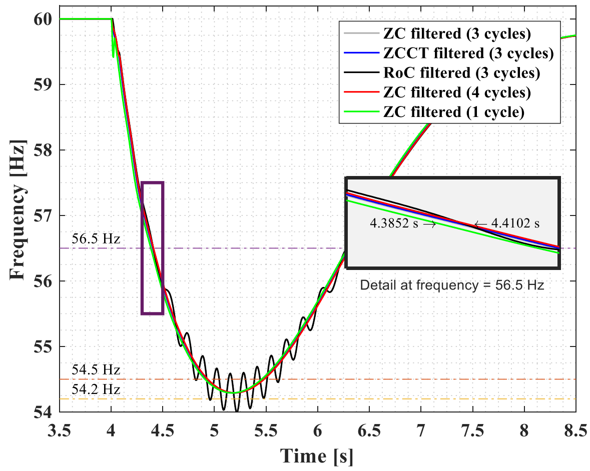

Fig. 9 Frequency estimations of islanding event causing underfrequency.

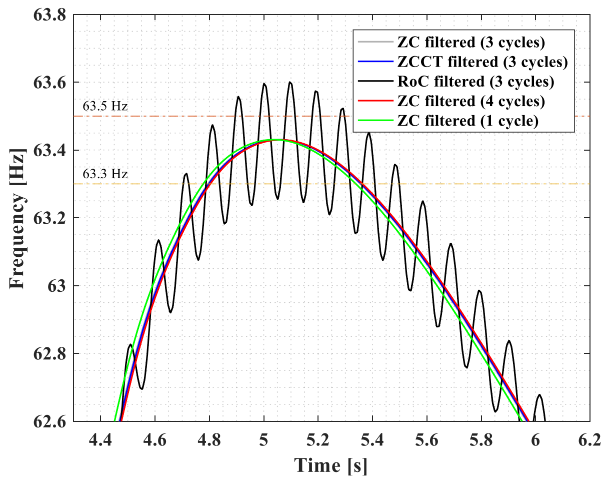

Fig. 10 Highlight on the oscillography of overfrequency event.

5. CONCLUSIONS

Power system frequency estimation is essential to the proper working of control and protection systems. Different frequency estimation methods have been proposed in technical literature and manuals of different digital relays employ different frequency estimation methods. This paper has analyzed three methods found in digital relays manuals. All three methods analyzed presented different behaviors in the presence of noise, harmonics, DC decays, and changes in frequency, which brings doubt that different frequency estimation methods, considering filtering, present the same performance against the same event. Two islanding events were simulated, causing overfrequency and underfrequency. The frequency estimations obtained show that, in general, the time difference might be insignificant. However, for specific cases and settings, certain estimations methods may not be able to trip the anti-islanding frequency protections, pointing out the importance of a thorough study of the estimation method and filters employed in the digital relay before any protection study.

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