Revisiting Zero-Crossing Methods for Frequency Estimation in Protection Relays

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***Abstract*— Protection relays require fast, reliable frequency estimation, yet modern grids with high penetrations of inverter-based resources and evolving network dynamics challenge classical estimators. In this paper, zero-crossing-based methods are revisited, their behavior under non-ideal conditions is analyzed, and a practical, protection-oriented implementation is presented. Four variants are formalized and compared; performance is evaluated in the presence of DC offsets, harmonics, noise, phase-step events, power swings, and rapid frequency ramps, and computational complexity is profiled. The effects of calculation-window length, post-processing security checks, processing burden, rate-of-change-of-frequency (RoCoF) estimation, sampling frequency, ADC resolution, and prefiltering are also discussed. The results show that robust performance can be achieved by zero-crossing-based algorithms in grids with high IBR penetration; however, with few modifications.**

Keywords*— *Power system protection, frequency estimation, signal processing, protection relay design

I. Introduction

Frequency can be broadly defined as the number of repetitions of an event in a specific time period. For power systems, frequency represents the number of fundamental cycles repeated in 1 second or the inverse of the time period of one fundamental cycle (i.e. f=1/T, where f represents the frequency, T represents the time period of the fundamental cycle). It can thus be seen that the time window over which a frequency is measured, is generally arbitrary and can be selected based on the use case. For example, if the frequency is constant with respect to time, then the time window length does not matter. Frequency measured over a short window will match exactly with the frequency measured over a long window of time. If, however, the frequency is changing with respect to time then frequency measured over a short window could be significantly different than that calculated over the longer window.

In the conventional power systems of yesteryears, the power source was almost always a synchronous generator. The synchronous generators along with turbines have very large rotating inertia associated with them, which ensured that frequency could not change drastically (almost constant). Therefore, the frequency value measured over a shorter window such as sub-cycle to few cycles of fundamental would be very close to the frequency value measured over longer windows such as few hundred milliseconds to a second.

Generally, the protective relays measure frequency over a window of few fundamental cycles to obtain a steady frequency value. It is worth noting that the measured frequency is not only important for the frequency relaying (over/under frequency, rate of change of frequency, V/Hz etc.) but its accuracy is also imperative for the accuracy of the estimated phasors. Reliable frequency enables underfrequency load shedding to arrest frequency decline [1], islanding detection and microgrid anti-islanding, fast ROCOF-based load shedding before the frequency nadir, loss-of-infeed detection and system separation, and V/Hz-based overflux protection of transformers, generators, and shunt reactors during overvoltage or low-frequency conditions.

As the grid is increasingly becoming IBR-dominated, the frequency of the grid is impacted by the limited inertia of IBRs and the proprietary control systems of the IBRs. Generally, the controls systems of the IBRs measure frequency using very short window methods such as phase locked loops (PLLs) and accordingly inject the current as per their control strategy. The inconsistency of the control design between different vendors and different types of IBRs results in unexpected waveforms [2]. The limited inertia of the IBR-dominated grid exacerbates this problem. In such grids, the frequency measurement can change relatively quickly [3]. The approach of measuring frequency over few cycles risks the outcome that the frequency is already ‘old’ and does not reflect the ‘current’ frequency of the system by the time it is measured.

II. Frequency Measurement: Zero-crossing Methods

Various frequency measurement techniques such as zero-crossing, PLL-based [4], signal demodulation [5] etc. are found in literature. However, the zero-crossing techniques are the most widely used because of their simplicity and robustness. Zero crossing method measures the time period between the zero-crossings and frequency is estimated by taking inverse of the measured time period. Depending upon the zero-crossing pairs used (refer to Fig.1), the frequency can be estimated from:

- Consecutive zero crossing (CZC): Frequency is estimated from consecutive zero-crossings pairs, i.e., ZC_1-ZC_2, ZC_3-ZC_4. This method provides a frequency measurement value every half fundamental cycle.
- Same-sign zero crossing (SSZC): Frequency is estimated either from negative to positive zero crossing only or from positive to negative zero crossings only, i.e., exclusively only one pair from ZC_1-ZC_3 or ZC_2-ZC_4 is used. This method provides a frequency measurement value after a full fundamental cycle.

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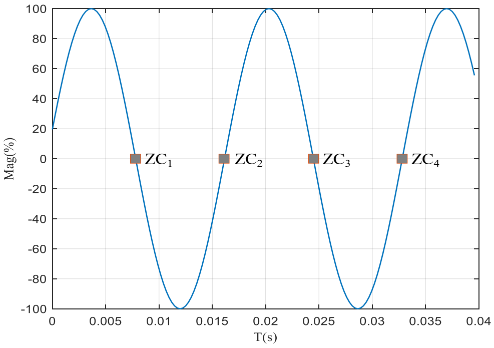

Fig. 1. Zero-crossing based frequency estimation: different combinations

- Dual-sign zero crossing (DSZC): The frequency is estimated from negative to positive and positive to negative zero-crossings zero crossings simultaneously, i.e., both pairs ZC_1-ZC_3 and ZC_2-ZC_4 are used. This method yields 2 frequency measurements over a fundamental cycle with each measurement estimated over a full fundamental cycle.
- Hexa-dual-sign zero crossing (HDSZC) in three phase systems: In this method, the Dual-sign method is applied to the each of the three-phases of the power system. This method yields 6 frequency measurements within a fundamental cycle with each measurement measured over a full fundamental cycle.

III. Performance Evaluation

In the following subsections, the performance of the algorithms in dealing with power-system phenomena will be analyzed. In the simulations, the nominal frequency is 60 Hz and the SNR is 40 (dB). The sampling rate is 64 samples per cycle. As a signal conditioning stage, a 31-tap low-pass filter is applied to all signals in the algorithm to remove high-frequency components. The HDSZC method uses the filtered voltage and current signals directly, while the other three methods apply the Clarke transformation to the filtered signals and then use it as the input to the algorithm. Fig.2 shows the four algorithms in this scenario and illustrates their characteristics under base case which is constant nominal frequency conditions.

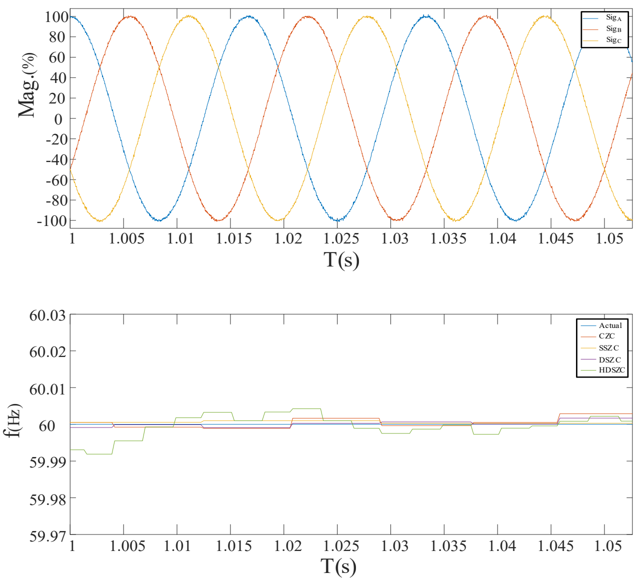

Fig. 2. Base case: Nominal frequency with SNR=40 (db)

A. DC presence

Zero-crossing-based methods use the time difference between sign-change moments. When the signal includes a DC component (or a decaying DC component), the algorithm exhibits particular characteristics. Fig.3 shows the frequency-estimation output of different methods with a constant 5% DC component on Phase A. As shown, the consecutive-sample-based method displays unacceptable oscillations. Note that when the DC component is larger than the AC component, the signal will not have zero crossings, which leads to algorithm instability. Such cases occur rarely, typically for fault currents near generation units, where the signal contains both decaying AC and decaying DC components.

B. High order Harmonic presence

In this section, the impact of higher-order harmonics on the algorithms is analyzed. In the sample cases, the signal includes 10% of the 2nd, 3rd, 5th, and 7th harmonics (each). As shown in Fig.4, all algorithms except the CZC method exhibit similar behavior, while the CZC method shows oscillations. This suggests that when the actual frequency is approximately constant, algorithms which uses same-sign zero-crossing period do not face significant challenges.

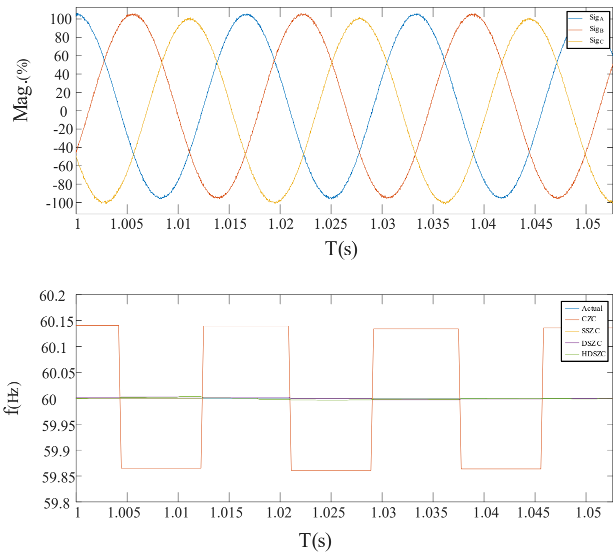

Fig. 3. Impact of constant 5% DC offset in Phase-A on frequency measurement

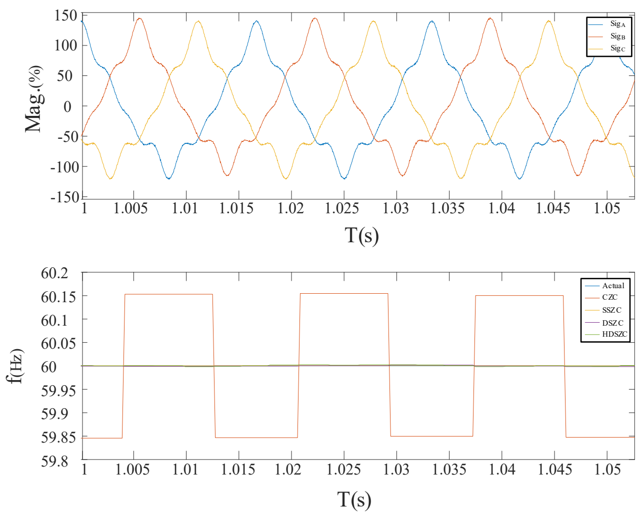

Fig. 4. Impact of presence of high order harmonics in the signal (10% of 2^{nd}, 3^{rd}, 5^{th}, 7^{th} each) and frequency measurement

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C. *Power swing condition*

Fig.5 shows the signals during a severe power swing at 5 Hz with 30% magnitude. As shown, although the actual frequency is fixed at 60 Hz, all of the algorithms exhibit oscillations in their outputs. The oscillation amplitudes are similar, and their frequency is the same as the power-swing frequency. Differences in update rates introduce apparent lead–lag effects in the algorithm outputs. Thus, this case shows that zero-crossing algorithms perform poorly under power swings, although band-pass filtering can improve stability. A discussion of such band-pass filtering is outside the scope of this paper.

D. *Noise*

Fig.6 shows the signal with different noise levels, SNR = 20 dB, comparing to the base one which is SNR = 40 dB (Fig.2). As the noise level increases, all algorithms exhibit oscillations in their outputs; however, the oscillation amplitude is small and largely negligible. Although the presence of an anti-aliasing filter and prefiltering was expected to yield accurate frequency estimates, even these small oscillations can impair the accuracy of RoCoF calculations.

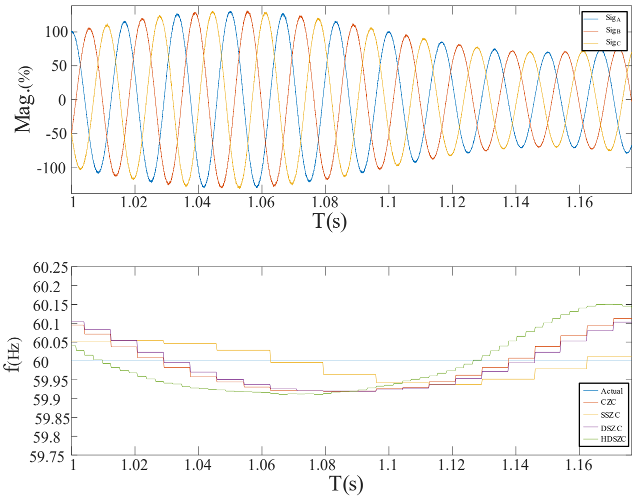

Fig. 5. Impact of power swing on frequency measurement

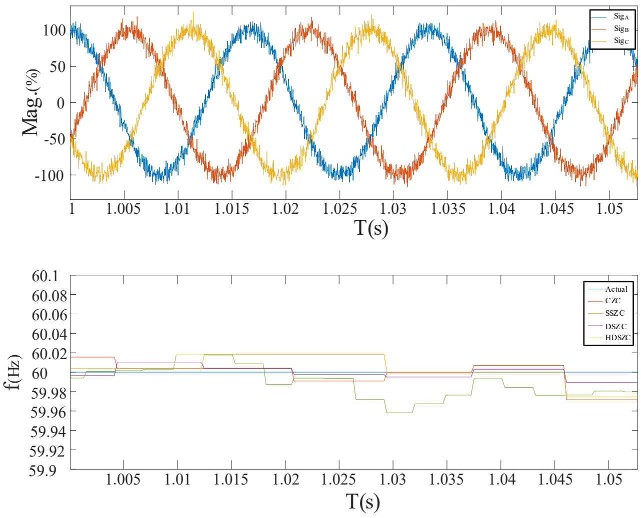

Fig. 6. Impact of noisy signals (SNR=20dB) on frequency measurement

E. *Angle jump*

Sudden angle jumps used to be rare in power systems dominated by synchronous generators. With the increasing penetration of inverter-based resources (IBRs), such phenomena are now observed more frequently. Ideally, frequency-estimation methods should be immune to angle jumps; however, because zero-crossing-based algorithms rely on waveform crossings, they are susceptible to them. Fig.7 shows angle jumps of −35°, +35°, and 0° in phases A, B, and C, respectively. As shown, the HDSZC algorithm settles much faster than the other algorithms. Another notable observation is that the HDSZC output exhibits oscillations, whereas the others show non-oscillatory errors with longer duration. These observations suggest that an averaging filter could improve the HDSZC output, while it has almost no impact on the others. The fast dynamics of the HDSZC algorithm demonstrate superior performance when the system has high IBR penetration.

F. *Fast frequency variation*

One of the key scenarios in which a frequency-estimation method must perform well is during continuous frequency variations. In conventional systems, such variations had low dynamics, whereas in systems with high IBR penetration the rates of change are higher. Therefore, the algorithm needs to be both faster and more accurate.

Fig.8 shows the frequency estimation for a case where the frequency begins increasing at a constant rate of 5 Hz/s. As shown, the actual frequency starts to increase at t = 1.02 s. The algorithms begin to respond with some delay; among them, HDSZC has the best performance, while the SSZC algorithm performs the worst. In terms of error, HDSZC also has the smallest error compared to the others, whereas the SSZC algorithm has the largest error.

These errors were present in conventional systems as well; however, because error magnitude is related to the rate of change, and synchronous-generator-dominated systems had very low rates, the errors were negligible. In newer systems, where higher rates are possible, algorithms like SSZC are not sufficiently effective.

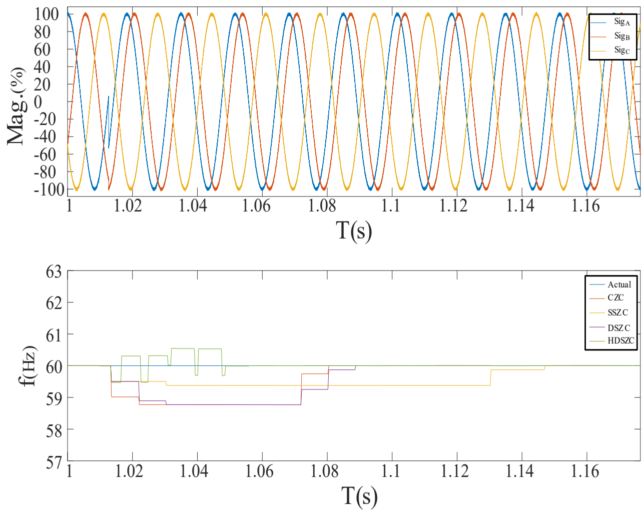

Fig. 7. Impact of angle jumps (phase A= −35°, phase B=+35°) on frequency measurement

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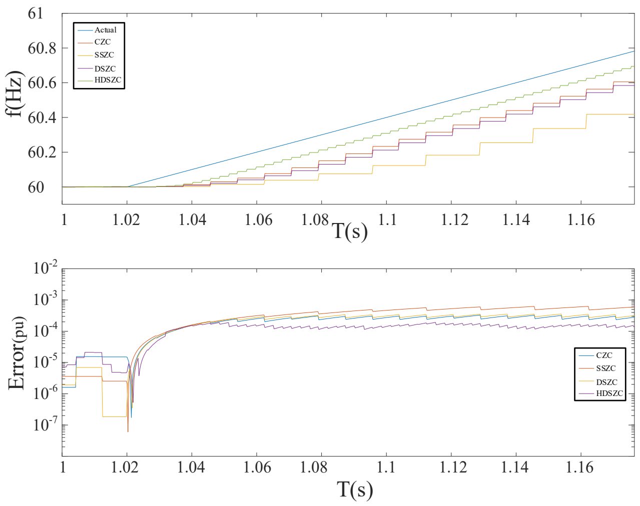

Fig. 8. Fast frequency variation and performance of different zero crossing based methods

Fig.8 (b) shows the per-unit error for two cases in which the rate of change of frequency is +5 Hz/s and +0.5 Hz/s. As shown, when the frequency rate is 10 times higher, the error is approximately 10 times larger, making it non-negligible.

IV. Discussion

A. *Prefiltering*

Normally, the voltage is the preferred signal for the frequency measurement, and voltages in conventional systems remain largely sinusoidal even during faults and disturbances. However, in weaker system and especially those with connected to IBRs, there could be higher harmonic and noise content in the voltage signals. In applications such as differential relays, there is a possibility that voltage signal might not be available. For such cases the frequency will be measured from current signals which are more likely to have harmonics and noise contamination.

The harmonics and noise could result in 'false' or 'shift' in the zero-crossing, thus, impacting the accuracy of estimated frequency. The low-pass prefiltering of the signals attenuates the harmonics and noise components, and provides higher accuracy of frequency estimation.

Fig. 9 shows an extreme case in which the signals contain 10% of the 2nd, 3rd, 5th, and 7th harmonics, and are also highly noisy, with a SNR of 20 dB. As shown, the 31st-order low-pass filter effectively eliminates both noise and harmonic components. Figures 9(a) and 9(b) present the absolute per-unit error values for the frequency estimation algorithm using the filtered and unfiltered signals, respectively. As expected, the error obtained with the filtered signal is significantly lower, at the cost of an inherent time delay.

B. *Calculation window length*

The estimated frequency is normally averaged over a window of time or measurements to remove the potential jitter in the measurements. Limited A/D resolution, error in zero-crossing instance approximations are few of the potential causes of the jitter. It should be noted that averaging attenuates the jitter but it also introduces the delay. Thus, the calculation window should be carefully selected so that it provides necessary balance between jitter performance and measurement delays. Generally, the HDSZC and DSZC methods would require shorter calculation window length as compared to CZC and SSZC methods due to their higher reporting rates. The ability to operate with shorter window lengths gives these algorithms an advantage in quickly tracking high-rate changes.

C. *Post processing Security checks*

The post security checks could be applied to the 'raw' measured frequency values to reject the unreliable/unreasonable measurements. The checks such as minimum and maximum permissible frequency values, maximum permissible difference successive frequency measurements, maximum permissible jitter etc. are few examples of the post processing security checks. The basis for the post processing security checks is the fact that frequency in power system applications should lie within a specific frequency band (e.g., within 2Hz to 120Hz). The other security check addressed the rate of change of frequency, based on the assumption that frequency would not change drastically in conventional power systems due to high inertia. However, these security checks need to be revisited, as higher frequency-change rates are possible in power grids with high IBR penetration.

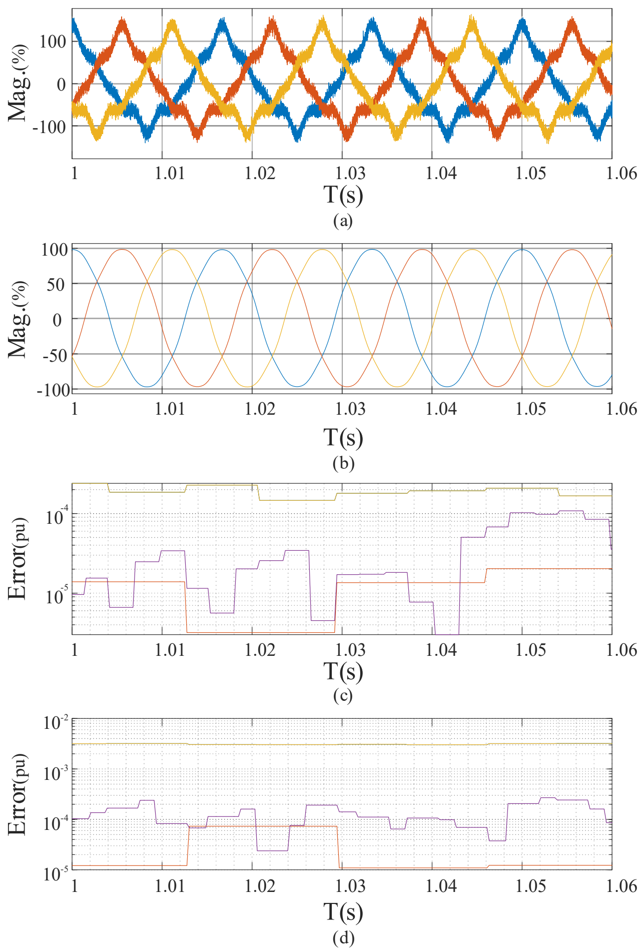

Fig. 9. Prefiltering Impact on the accuracy of frequency measurement (a) Three phase noisy signals (SNR=20db) with presence of high order harmonics in the signal (10% of 2^{nd}, 3^{rd}, 5^{th}, 7^{th} each). (b) Three phase signals after applying 31-tap filter. (c) Error of frequency estimation methods with prefiltering (d) Error of frequency estimation methods without prefiltering

Maximum effectiveness of post processing security checks is expected in HDSZC method. In this method if frequency measurement from a particular phase is failing the check, then frequency from other phases can be used. If frequency measurements from all phases is failing, then it implies that indeed there was a non-linearity in the system.

Care should be taken while designing post processing checks that it should not reject 'true' frequency measurements. This requirement becomes more stringent as the grid becomes IBR-dominated.

D. Processing burden

The processing burden of the zero-crossing methods increases as the reporting rate of the frequency increases. As an example, for a rotating machine application, the system operating at 75Hz will have higher processing burden as compared to when the system is operating at 45Hz.

This fact also holds true when different zero-crossing methods are compared against each other. For the same system frequency, the method which has higher reporting rate such as HDSZC method has higher processing burden than the method with lower reporting rate such as same-sign method. The processing burden was one of the primary limitations to the use of frequency estimation algorithms. Moving forward, this constraint will cease to be a major challenge as the computational throughput and algorithmic efficiency of contemporary digital systems have increased substantially and will continue to increase in the future, primarily due to advances in semiconductor fabrication and parallel processing architectures.

E. Rate of Change of Frequency (RoCoF) calculation performance

RoCoF element provides critical information about balance of power between power generation and consumption. RoCoF as the name suggests is the time derivative of the frequency. As the derivative operator is very sensitive to noise/jitter, therefore the noise should be attenuated as much as possible from frequency measurements before calculating RoCoF value. Care should be taken as attenuation of jitter/noise introduces the delay in frequency measurement and 'too much' delay might cause RoCoF value to be an 'old value'.

In modern systems with a high penetration of inverter-interfaced loads and generators, this block requires deeper analysis, as the signals are more susceptible to noise and harmonics. Balancing high accuracy and fast response with obustness to these disturbances is the main challenge, but a full treatment is beyond this paper's scope due to space constraints.

F. Impact of sampling frequency and Analog to Digital converter (ADC) resolution

Higher sampling frequency results in smaller time difference between the successive samples, while higher ADC resolution implies higher precision of the samples. Both factors make linear interpolation of zero crossing more accurate, and hence frequency measurement. Normally, sampling rates between 2-5kHz are sufficient to achieve a high level of accuracy for frequency measurement in power systems.

V. Conclusion

In this paper, zero-crossing frequency estimation was revisited with an emphasis on protection-grade performance under modern grid conditions. A unified treatment of four variants was presented: consecutive zero crossing (CZC), same-sign zero crossing (SSZC), dual-sign zero crossing (DSZC), and hexa-dual-sign zero crossing (HDSZC). In addition, a practical 64-samples-per-cycle implementation augmented by a 31-tap prefilter was developed. The performance of all four methods was characterized under DC offset, higher-order harmonics, noise, phase steps, power swings, and rapid frequency ramps.

The simulations show that CZC has the poorest accuracy in the presence of DC offset and high harmonics, indicating that it is not suitable for implementation in relays. Under power swing conditions, all four methods exhibit similar oscillatory behavior. A high-noise condition (SNR = 20 dB) was also investigated. Although the presence of an anti-aliasing filter and prefiltering yields acceptable frequency estimates, the analysis shows that RoCoF calculation requires additional treatment under such unfavorable conditions. Angle jumps, a phenomenon increasingly observed in power grids due to the presence of inverters, also cause oscillations in the algorithms, with HDSZC exhibiting the best performance among the variants. High frequency variation, one of the most challenging conditions for control and protection in modern grids, was also investigated. The results demonstrate that only HDSZC provides an acceptable response in terms of accuracy and speed, reinforcing the need to revisit existing zero-crossing-based methods. An insightful discussion of aspects, including calculation-window length, post-processing security checks, processing burden, rate-of-change-of-frequency (RoCoF) estimation, sampling frequency, ADC resolution, and prefiltering, is also presented.

Overall, the simulations indicate that zero-crossing-based methods remain suitable for use in protection relays. However, given recent changes in grid behavior, it is worthwhile to revisit these methods in lieu of the 'extra' information available in three-phase signals and to ensure fast and accurate performance.

VI. References

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