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Low Pass Digital Filter Delay Compensation for Accurate Zero Cross Detection in Power Quality

Nuno M. Rodrigues[1], Fernando M. Janeiro[2], Pedro M. Ramos[3]

[1]Instituto de Telecomunicações, Instituto Superior Técnico, Universidade de Lisboa, Portugal, nuno.medeiros.rodrigues@tecnico.ulisboa.pt
[2]Instituto de Telecomunicações, Universidade de Évora, Portugal, fmtj@uevora.pt
[3]Instituto de Telecomunicações, Instituto Superior Técnico, Universidade de Lisboa, Portugal, pedro.m.ramos@tecnico.ulisboa.pt

Abstract **– Zero crossing detection with a low pass filter is a common method used to estimate a signal frequency or period when the signal is affected by noise, harmonics or other parasitic frequencies. This method is often used in power quality measurements due to the typical disturbances of the electrical power grid signals and is for example, suggested in IEC 61000-4-30 for power quality frequency estimation. Zero crossing is also needed to evaluate RMS events since RMS evaluation must be synchronized with the input signal zero crossings. However, the filter introduces a delay which affects the accuracy of the RMS evaluation timestamp.**
High accuracy power quality measurement systems are expensive but their usage has significantly increased in recent years. To create low cost power quality analysers, a solution based on a digital low pass filter to detect zero crossings and measure signal characteristics such as the RMS value or distortions with accurate timestamps, is analysed in this paper.

Keywords – Zero Crossing Detection, Power Quality, Signal Acquisition.

I. INTRODUCTION

Power quality (PQ) events are increasing due to new technologies used in power generation and electronic devices that are connected to the electrical grid. Electrical companies must ensure that the events that occur in the electrical grid are in accordance with standard limits that define, for instance, limits to the power grid frequency, maximum and minimum voltage, voltage fluctuations, interruptions duration and noise. This is done with PQ analysers that are either accurate, bulky and very expensive or portable ones with worse measurement capabilities/characteristics. Zero crossing (ZC) detection is not trivial due to the power grid noise or transients that can occur near ZCs. The use of a low pass filter is common to estimate signal frequency but the filter delay causes a phase shift that affects timestamps which are required to characterize Root-Mean-Square (RMS) PQ events. To accurately timestamp an electrical grid anomaly, the low pass filter delay must be compensated. The purpose of this paper is to study the use of a digital low pass filter to estimate ZCs and, by compensating the filter delay, develop a system capable of accurately determining when a RMS PQ event occurred.

II. RELATED RESULTS IN THE LITERATURE

Different techniques are used in software or hardware for ZC determination [1]. These include for example using a Phase Locked Loop (PLL) [2], interpolation [3] or pre-detection low pass filters. Zero crossing detection instants are useful to determine the frequency or period of an electrical grid signal and to estimate other signal characteristics such as RMS values. RMS must be evaluated every half period starting at every zero crossing. To do that, it is important to accurately detect when the zero transition occurred. The Institute of Electrical and Electronics Engineers (IEEE) published two standards related to monitoring electric PQ: IEEE 1159 [4] and IEEE 1159.3 [5]. The International Electrotechnical Commission (IEC) also has multiple standards related with power quality in the IEC 61000-4 testing and measurement techniques series [6]-[9].

III. METHOD DESCRIPTION

Electrical power grid measurements are difficult due to signal noise and distortions. Noise and distortions can cause false zero transitions and compromise measurements that depend on those transitions. This problem is usually solved using a digital low pass filter. However, to accurately timestamp when a RMS PQ event occurs, the low pass filter delay needs to be compensated. Also, the frequency response of the filter should cause a delay that is, as much as possible, frequency independent.

An eighth order low pass Butterworth digital IIR filter with four biquad sections is used in the results presented in this paper. The filter was designed using the MATLAB Filter Design and Analysis Tool (FDATool) with a cutoff frequency of 125 Hz and a sampling frequency of 12.5 kHz . Its frequency response is shown in Fig. 1. The inset figure shows the filter frequency response near the 50 Hz nominal frequency. Its amplitude response is significantly flat and the phase response is very linear.

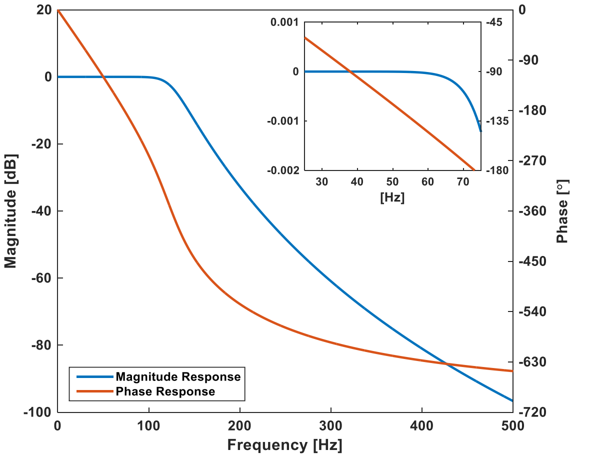

Fig. 1. 8th order lowpass Butterworth digital IIR filter frequency response with a sampling frequency of 12.5 kHz and a cut-off frequency of 125 Hz.

Multiple stimulus were used to estimate the filter delay. The filter average delay is 6.65 ms. In a first approach, this is the compensated value that the acquisition system uses to timestamp when a RMS PQ event occurred.

IV. RESULTS AND DISCUSSIONS

To validate the proposed method, simulations based on simulated signals that could occur in electrical power grid were performed.

Case 1 – Ideal input signal

The filter causes a delay at its output, so the first test case is to compensate the filter delay with the average value previously determined and verify if the ZCs matches with a signal without distortions.

The simulated input signal is

$$y(t) = \sqrt{2}\,\sin(\omega t) \quad (1)$$

where $\omega = 2\pi f$ and $f = 50\,\text{Hz}$. Fig. 2(a) shows the delay between the filter input and output signals while Fig. 2(b) shows the result of the delay compensation.

The objective is to design a low pass filter with a similar delay for the possible frequency range of the electrical power grid. Fig. 3 shows the relative zero crossing error for a frequency range from 45 to 55 Hz after a fixed compensation of 6.65 ms. Notice that the ZC error never exceeds 0.2% of the signal period.

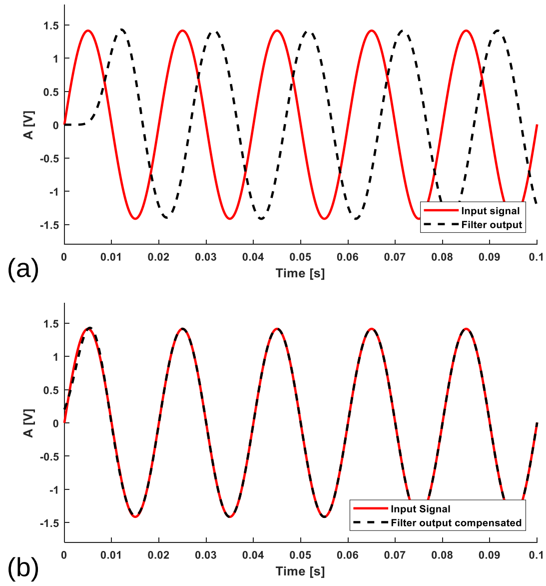

Fig. 2.Comparison between a 50 Hz input signal and the filter output before delay compensation (a) and after a fixed delay compensation (b).

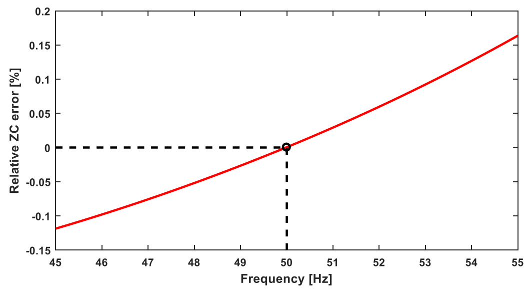

Fig. 3.Relative ZC error (normalized to the input signal period) after the filter compensation for signal frequencies from 45 Hz to 55 Hz.

In this simulation, the compensation delay is the fixed value obtained for the 50 Hz signal which results in a residual ZC error of 0.007%. For each frequency, the signal delay is compensated with the 50 Hz delay value and normalized with its period. The maximum ZC error is obtained for the 55 Hz signal.

Case 2 – Input signal with random noise

A power electrical signal has noise and it is important to test the filter response and the delay compensation with a noisy signal. Fig. 4(a) shows a simulated signal with 0.05 V RMS noise and its low pass filter output with delay. Fig. 4(b) shows the same signals but with the 6.65 ms delay compensation.

Without filtering, zero cross detection will *estimate* false crossings. Fig. 5(a) shows the relative ZC error as a function of the noise level after filtering with the proposed delay compensation. Fig. 5(b) shows the relative ZC error when no filter is applied with different levels of additive Gaussian noise. The error bars correspond to ±σ intervals of the multiple simulations.

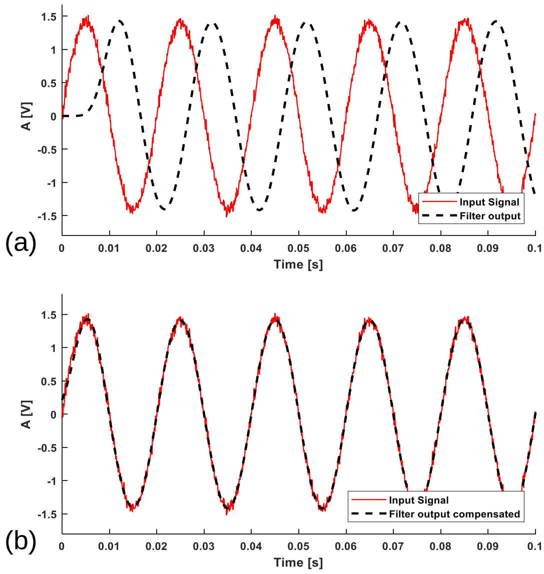

Fig. 4.Comparison between a 50 Hz input signal with 0.05 V RMS noise and the filter output before delay compensation (a) and after the fixed delay compensation (b).

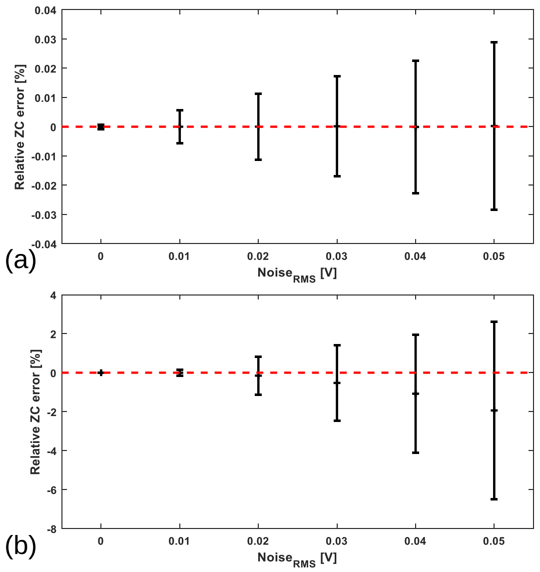

Fig. 5. Mean and standard deviation ZC error bars with 10000 repetitions of a 50 Hz input signal with different RMS noise levels with the filter and delay compensation (a) and without the filter (b). The input signal has a RMS value of 1 V.

As expected, if the noise increases the interference in zero cross detection is higher. But if a filter is used and its delay is compensated, the mean value is near zero and the standard deviations are lower. Without a filter, not only the standard deviations are significantly higher but the mean value or the estimated delay is consistently negative which corresponds to earlier than desired zero crossing detections. For example, for 0.05 V RMS noise, the standard deviation of the filter and delay compensation is near 0.03% of the nominal 50 Hz period while without filter it is 4.5% with an average error of -1.95%.

Case 3 – Input signal with harmonics

Independently of the signal harmonics, the filter delay must be able to match the zero cross of the input signal. In this case, a generic simulated signal is considered

$$y(t) = A_1 \sin(\omega t + \Phi_1) + A_3 \sin(3\omega t + \Phi_3) + A_5 \sin(5\omega t + \Phi_5) \quad (2)$$

where A_n is the n^{th} harmonic amplitude and Φ_n is the phase of harmonic n.

Signal harmonics influence the electrical power grid and cause problems in zero cross detections with the increase of its amplitude as is shown for example with the 3rd harmonic in Fig. 6. The relative phase of the third harmonic also influences the zero crossing time instant estimations.

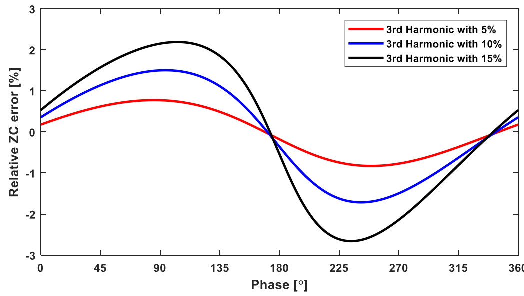

Fig. 6. Relative ZC error for a signal including the 3rd harmonic with different amplitudes and phases.

Fig. 7 shows the simulation results with the 5th harmonic, with $A_1 = \sqrt{2}$, $A_3 = 0.05A_1$ and $A_5 = 0.06A_1$ with $\Phi_{3,5} = 90°$. For this situation, ZC error is -0.02%.

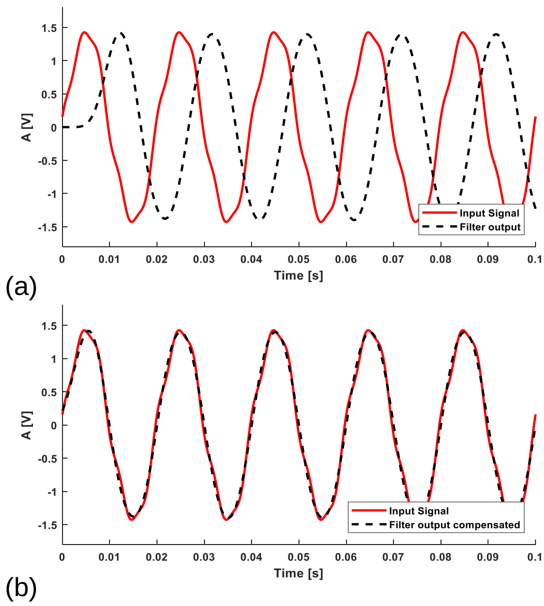

Fig. 7. Graphical comparison between a 50 Hz input signal with harmonics out of phase and the filter output before delay compensation (a) and after a delay compensation (b).

Case 4 – Input signal with pulses

Harmonic transients are one of the PQ events that can occur in the electrical power grid. When these transients occur near the zero crossings, they can have a significant effect on the performance of the ZC based frequency and RMS estimation. To simulate harmonic transients, periodic pulses in zero crossings with 0.2 V amplitude, occurring at 0 ms and 10 ms with a width of 100 µs are considered as shown in Fig. 8.

In the PLL based system proposed in [2], these harmonic transients could cause a phase shift of 180° which would, in turn, cause a timestamp error of half period. With the low pass filter the ZC error is identical to the situation without pulses. For example, in the situation depicted in Fig. 8, the ZC error is -0.07%.

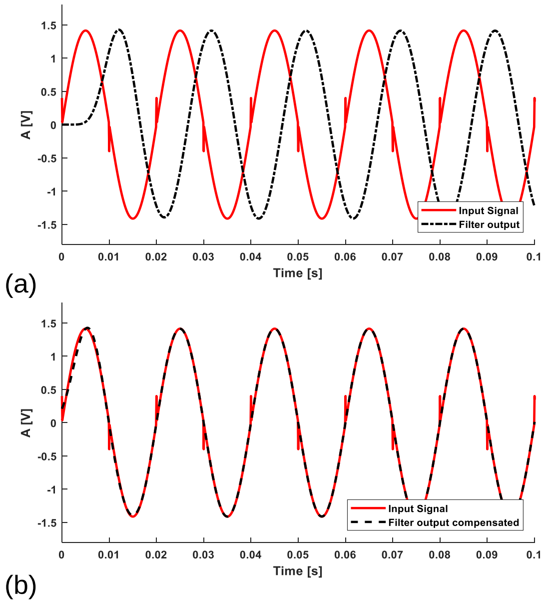

Fig. 8. Comparison between a 50 Hz input signal with transients on zero crossings and the filter output before delay compensation (a) and after a delay compensation (b).

V. CONCLUSIONS

Low pass filtering is a known technique used in PQ for zero crossing in frequency estimation. It is not as widely used in other signal measurements, such as RMS value, due to the delay introduced by the filter that significantly impacts the accuracy of the necessary RMS timestamp.

The study presented in this paper shows that a filter with a linear phase, for a target range of frequencies, causes a known delay for that range of frequencies. With this delay, it is possible to accurately estimate the ZC of the filter input signal. This is used for example, in the RMS calculation that must be synchronized with the power grid ZC.

Simulations show that harmonics could cause a higher error in the delay compensation as shown in Fig. 6 with an error of nearly 3% of the signal period but for a third harmonic with 15% amplitude of the fundamental.

VI. ACKNOWLEDGMENT

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