DETECTION OF VOLTAGE FLICKER IN NOISY SIGNALS

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ABSTRACT
The fluctuation of voltage is one of the important power quality events. Different methods have been proposed for estimating the voltage envelope, but the presence of noise is, in general, not considered. A method for estimating the envelope in presence of noise, based on the Hilbert transform and a low-pass filter, is presented. The results obtained from a real signal measured from an arc furnace are shown.

Keywords: *Hilbert transform, flicker, voltage fluctuation.*

1. INTRODUCTION

Voltage fluctuations can be described as systematic variations or random variations in the voltage envelope. The fluctuation of voltage is one of the important power quality events due to the effects of electronic and control systems, and in the light flicker. There are several sources of voltage flickers as arc furnaces, fans, pumps, lifts, switching of powers factor capacitors, large motors [1, 2].
Different methods have been proposed for estimating the magnitude and frequency of flicker. The IEC [3] and IEEE [4] standards recommend the square demodulation, a method used in demodulation of AM signals, which consists in tracking the flicker envelope by squaring the input voltage signal. Other methods proposed are Fast Fourier Transform [5], Least Absolute Value [6], Kalman filters [7], Wavelet transform [8], Teager Energy Operator [9]. Hilbert transform is also used [10-13], and, in particular, using Prony analysis and Hilbert Transform [14].
Recently, the performance of several flicker detecting methods were compared [15]. The core of flicker analysis is to track the envelope of voltage signal, that is, the instantaneous amplitude. Then, an important characteristic of the algorithms proposed is their on-line behavior; the faster is the estimation of the voltage envelope values, the better is the on-line behavior.
Another aspect of the problem is the presence of noise. In [16] this problem is pointed out and solved using the Hilbert transform for estimating the flicker envelope and the wavelet transform for extracting other noises contained on simulated data. Here we propose a different method to remove the noise which combines the actions of the Hilbert transform and a low-pass filter. The effectiveness of our approach is shown on a signal obtained from real measures.
This paper is organized as follows: the use of the Hilbert transform for an efficient estimation of the voltage envelope is explained in Section 2, in Section 3 we describe the signal used to test the method, and finally Section 4 presents the numerical results.

2. ENVELOPE ESTIMATION USING THE HILBERT TRANSFORM

2.1 Estimating the envelope

In this section we review some results concerning the estimation of the envelope of a discrete signal.

The Hilbert transform is used in signal processing to derive the analytic representation of a signal $x[n]$. The analytic representation of a signal is well known for continuous-time signals [17] and it is also defined for discrete signals as

$$z[n] = x[n] + iHx[n],$$

where $Hx[n]$ denotes the discrete Hilbert transform of the sequence $x[n]$ [18]. This representation allows a straightforward identification of the envelope of an amplitude modulated signal. An amplitude modulated signal is modeled by:

$$x[n] = a[n]\cos(\omega n), \quad (1)$$

where the frequency content of $a[n]$ has an upperbound less than ω. In this conditions, Bedrosian theorem for discrete signals [18] states that:

$$Hx[n] = a[n]H\cos(\omega n),$$

which turns into $Hx[n] = a[n]\sin(\omega n)$. Now, the analytic representation of the signal takes the simple form

$$z[n] = a[n]e^{i\omega n},$$

and the amplitude (or the envelope) $a[n]$ is easily obtained from $a[n] = |z[n]|$.

For the sake of completeness, we include Bedrosian theorem as stated in [18]:

Theorem 1 *Suppose that* $z_1[n]$ *and* $z_2[n]$ *are complex sequences with discrete-time Fourier transforms* $Z_1(e^{i\omega})$ *and* $Z_2(e^{i\omega})$. *Then*

$$H(z_1 z_2)[n] = z_1[n]H(z_2)[n]$$

if there exists a nonnegative number $\sigma < \pi$ such that

$$Z_1(e^{i\omega}) = 0, \text{for } 0 < \sigma < |\omega| < \pi, \text{and } Z_2(e^{i\mu}) = 0, \text{for } 0 < |\mu| \le \sigma < \pi.$$

2.2 Hilbert filter

In this section we describe the Hilbert filter in more detail. The discrete Hilbert transform $Hx[n]$ of the sequence $x[n]$ is defined in the frequency domain as [19]

$$(F\{Hx\})(\omega) = -i\,\mathrm{sgn}(\omega)X(\omega), \tag{2}$$

where $X(\omega)$ is the discrete Fourier transform of x:

$$X(\omega) = (Fx)(\omega) = \sum_{n=-\infty}^{\infty} x[n]e^{-i\omega n}.$$

From equation (2), the transfer function of the Hilbert transform for discrete signals is

$$H(\omega) = \begin{cases} -i, & 0 < \omega < \pi \\ 0, & |\omega| = \pi \\ i, & -\pi < \omega < 0. \end{cases}$$

The transfer function may also be expressed as

$$H(\omega) = -i\,\mathrm{sgn}[\sin(\omega)] = G(\omega)e^{i\frac{\pi}{2}},$$

with $G(\omega) = -\mathrm{sgn}[\sin(\omega)]$. The discrete time representation of the Hilbert filter is easily obtained from this expression. In fact, $G(\omega)$ is an odd function whose Fourier transform reads

$$G(\omega) = \frac{4}{\pi}\sum_{m=0}^{\infty}\frac{1}{2m+1}\sin[(2m+1)\omega].$$

Denoting $h(k) = F^{-1}[H(\omega)]$ the inverse Fourier transform of $H(\omega)$, we have

$$h(k) = \frac{2}{\pi k}\sin k\frac{\pi}{2}, k \ge 0, \text{and } h(-k) = -h(k).$$

Figure 1 shows the impulse response $h[k]$ of a Hilbert filter of order 38 and Figure 2 shows the magnitude response $|H(\omega)|$.

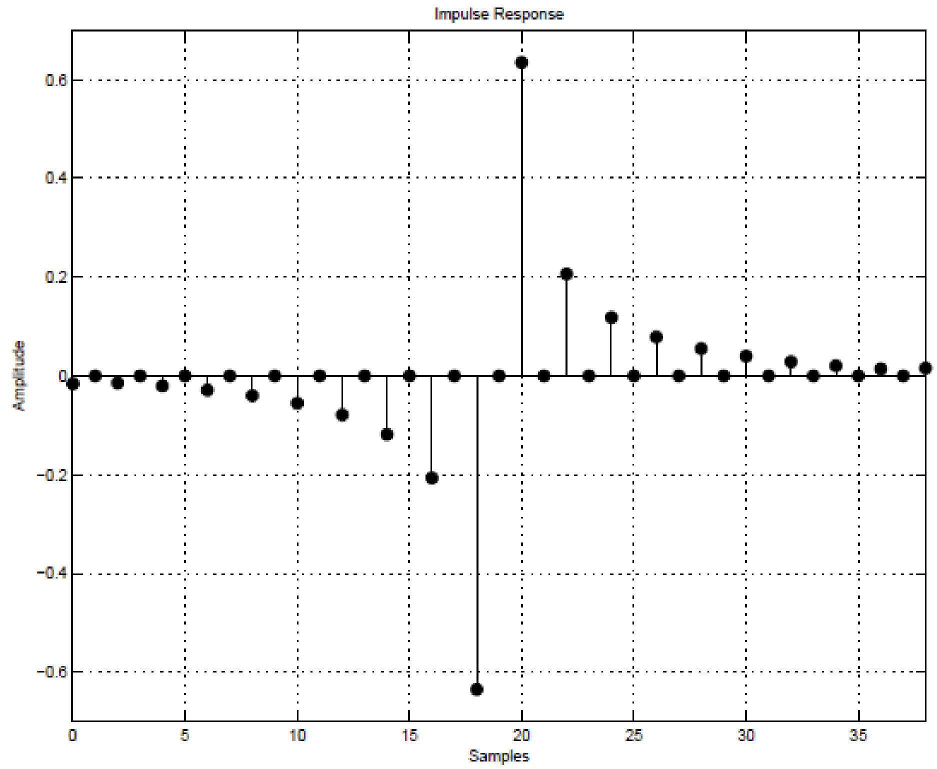

Figure 1. Impulse response.

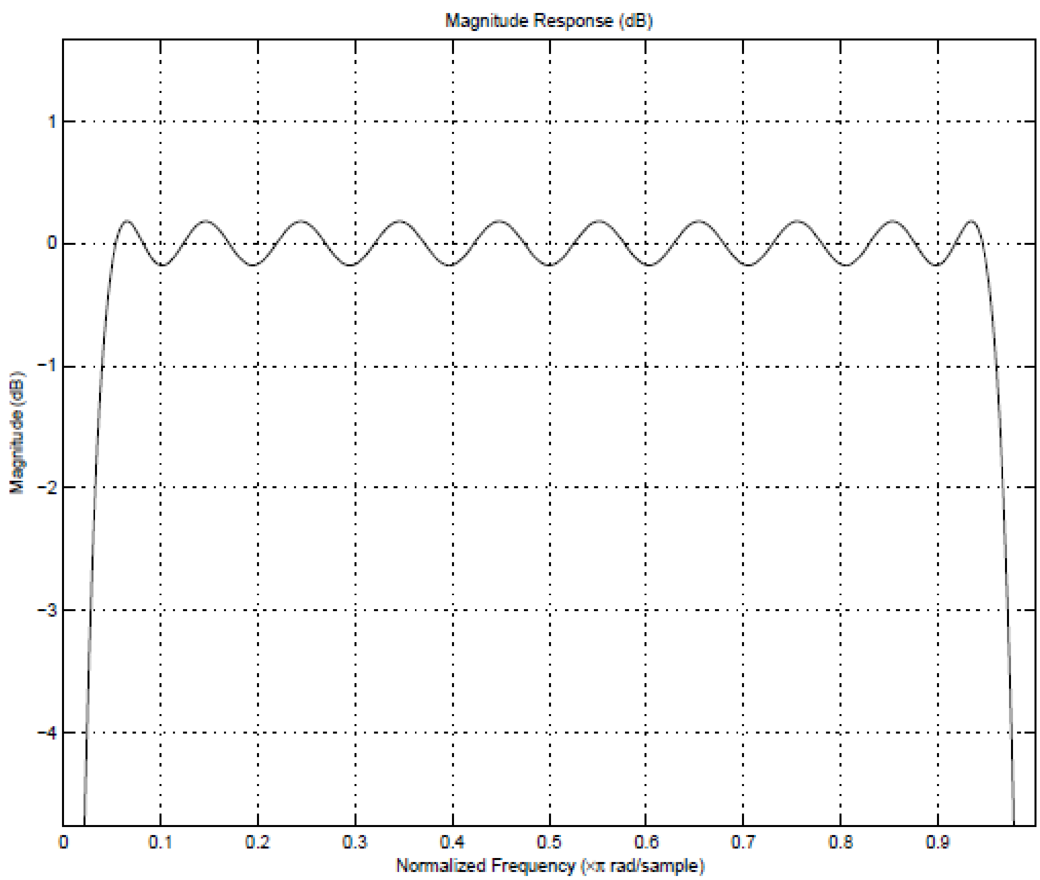

Figure 2. Magnitude response.

2.3 Implementation of the Hilbert filter

The Hilbert transform can be easily implemented in the discrete domain by an FIR filter. This kind of discrete filter allows obtaining constant group delay and constant phase over the entire bandwidth. Moreover, the nature of the filter makes unnecessary the stability analysis.

Moreover, if the filter order is even, it behaves as a band pass filter which has zeros at 0 Hz and at the Nyquist frequency. So that its impulse response is similar to that shown in Figure 1, in which the odd coefficients are zero. However, if the filter order is odd, the zero in the Nyquist frequency disappears and the odd coefficients are no longer zero. For this reason, the Hilbert filter of even order is easier to implement than the filter of odd order. This is because the zero coefficients can be omitted. Therefore fewer multiplications and additions are required (see figure 3).

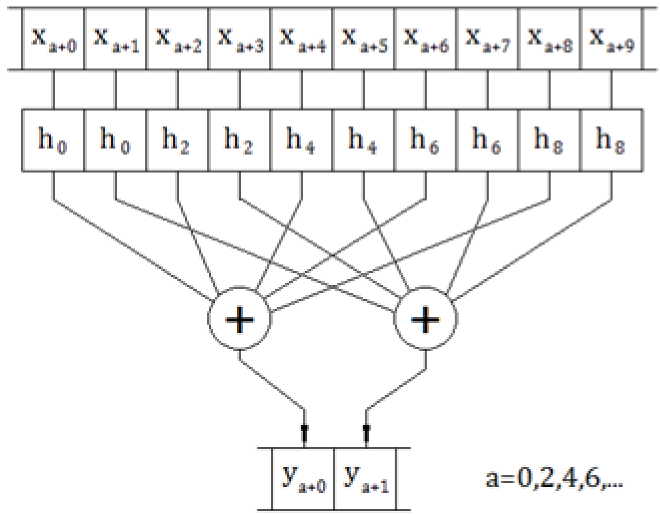

Figure 3. Convolution strategy.

In this paper, the calculation of the coefficients is performed with the "Filter Design & Analysis Tool" in MATLAB.

3. A SIGNAL FROM AN ARC FURNACE

In this paper, the performance of the proposed model on tracking the voltage flicker signal envelope is examined with a signal coming from real measurements. It is a typical AC arc furnace application in a steel plant. This arc furnace is served from a 13.8 kV bus. The measured signal is one of the phase voltages and it was sampled at a sampling frequency of 1000 Hz.

Since this signal is distorted by noise that comes from making physical measurements, a serious issue is the robustness of the method for estimating flicker. Previous works hardly consider this problem.

As an example, we make some comments on Prony algorithm which has been used in this problematic [14]. Prony algorithm is good at system identification provided that the available samples come from a signal completely predictable and free of any randomness. Under these conditions, it is a good alternative for obtaining mathematical models in the form of damped complex exponentials from a small number of samples. This type of representation allows a straightforward calculation of the Hilbert transform of the signal [14]. However, when the signals have some degree of randomness like signals immersed in noise, Prony algorithm is very unstable and it requires a large amount of samples to achieve an acceptable approximation. This method has some other drawbacks: it is very difficult to estimate the optimal number of exponentials to use in the approximation, the calculation involves two pseudo-inverse matrices whose systems are poorly conditioned, which increases the instability, and finally it has a high computational cost.

4. NUMERICAL RESULTS

We present numerical results on the estimation of voltage envelope of the signal from an arc furnace which was described in the previous section.

The method is implemented in Simulink from Matlab (see Figure 4).

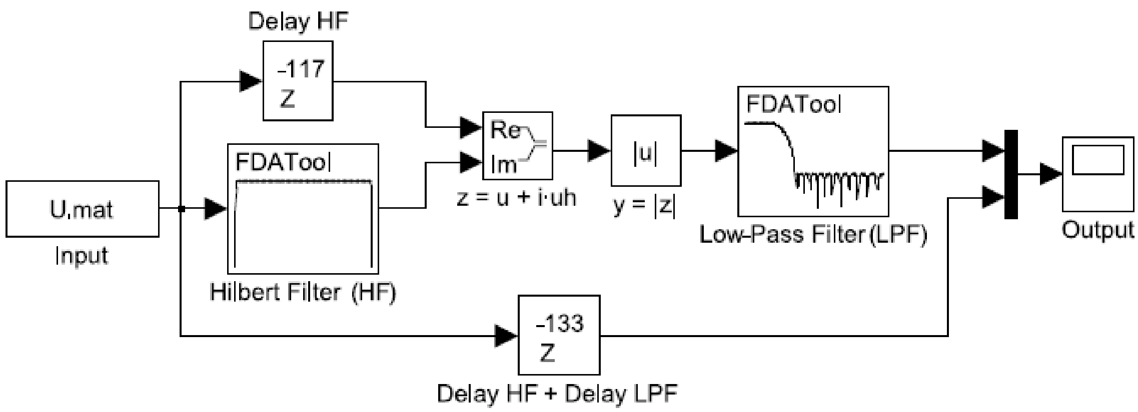

Figure 4. Block diagram fo the estimator.

From the block diagram Figure 4 we can make the following analysis:

1. The Hilbert filter is a FIR, all zeros filter of order 234, linear phase, whose magnitude response is shown in Figure 5.

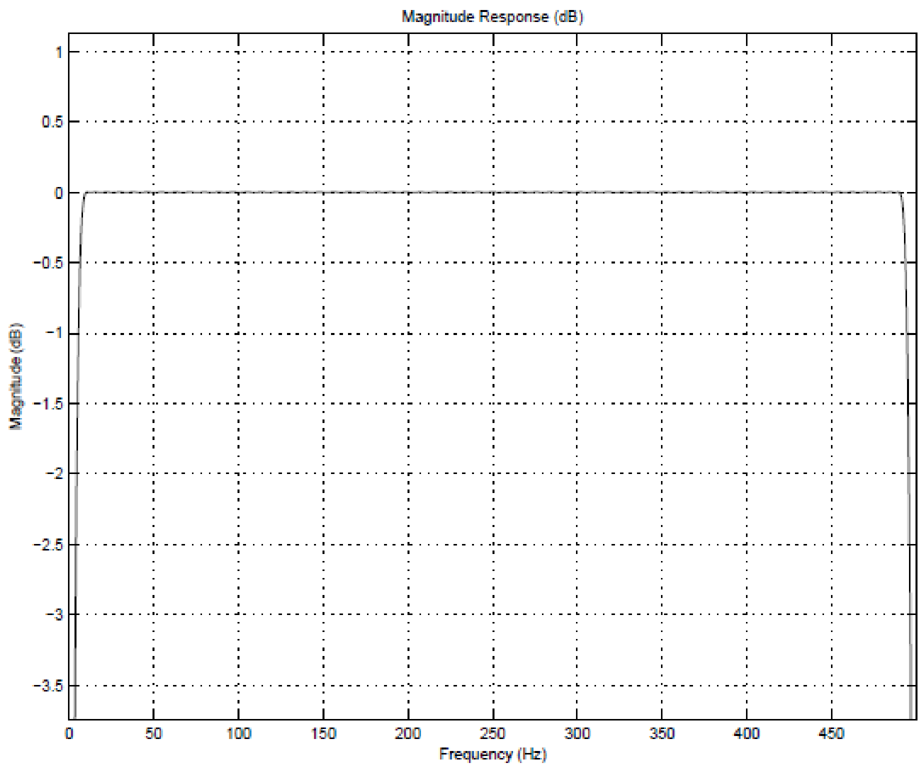

Figure 5. Magnitude response of the Hilbert filter.

2. The envelope is estimated, then a low-pass filter is applied to minimize the influence of noise. This is a FIR equiripple filter of order 32, with cutoff frequency 120 Hz.

3. Because of the fact that the signal passes through two FIR filters there is a delay time in the tracking processes. However, as the two filters have a linear phase response, they have a constant group delay response. Therefore, this time delay is constant for all frequencies and it can be calculated. In this case, it resulted in a total delay of 133 samples, and it represents 0.133 sec at a sampling frequency of 1000Hz. It represents approximately 8 cycles of the fundamental frequency (60Hz).

Figures 6 shows estimations of the voltage envelope corresponding to the diagram of Figure 4 using the measurement of the arc furnace voltage. There are two intervals of 0.5 sec: [18.5,19] and [19,19.5].

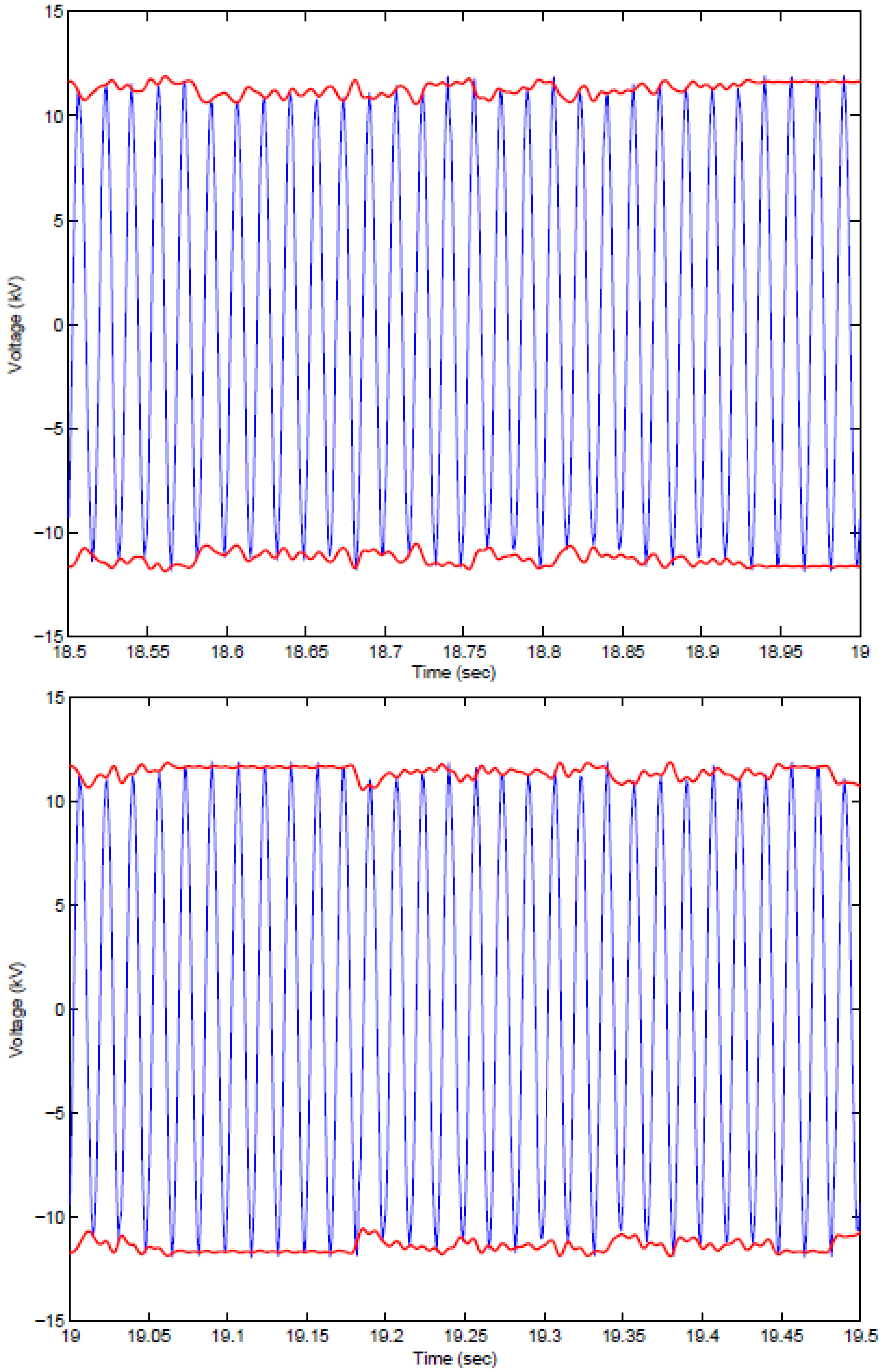

Figure 6. Estimated voltage envelope of an arc furnace signal

5. CONCLUSIONS

We have presented a method for estimating signal flicker in presence of noise using the Hilbert transform. The characteristics of both filters (the Hilbert filter and the low pass filter) are described in Section 4. The proposed algorithm was implemented in a DSP Blackfin EZ-537. We tested this technique on a real world signal produced by an arc-furnace. In contrast to the method presented in (Feilat 2006), this algorithm does not have instabilities, as was analyzed in section 4.

ACKNOWLEDGMENTS
We thank Alberto Del Rosso for providing us the measurement of the arc furnace voltage.

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