A Nonlinear Adaptive Filter for Improved Power System Operation and Protection

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Abstract-- Fundamental voltage, current and phase magnitude estimates are required for a wide variety of power system applications. In this paper, a review of a novel non-linear adaptive filtering algorithm for power system applications is presented. The algorithm has the ability to track and estimate the parameters of a sinusoid in real-time. This makes it suitable for a wide range of applications in electrical engineering. It is compared to other methods of tracking power signals such as the Fourier and Wavelet analysis. Suitability of the algorithm for application in power quality, voltage and frequency control and under frequency relaying has been identified.

***Index Terms*—nonlinear filter, power quality, dips, harmonics, active filter, frequency control**

I. Introduction

The ideal power system consists of sinusoidal voltages and currents at a constant frequency. Power system loads and system faults affect the shape and frequency of the current and voltage waveforms. The deviation of the waveform from a pure sinusoid can cause maloperation of sensitive equipment and even downtime. The problem has been aggravated with the increasing use of power electronic loads. The problem becomes one of identification and classification of power system disturbances. This paper explores the practical application of of the nonlinear adaptive filter proposed by Ziarani and Konrad [1] for improved power systems operation and protection. The algorithm may be used for utility power systems as well as finite inertia shipboard power systems, which may experience significant frequency shifts.

II. Tracking and Processing of Power Signals

Current and voltage transducers located at various points in the power system, send proportional signals to measurement and protection equipment. These continuous signals are converted at an appropriate sampling rate into discrete form by analogue to digital converters (ADC) of micro controllers or digital signal processors (DSP). The data is then processed at different levels to derive useful information [2].

[3] defines power quality as: "Any power problem manifested in voltage, current, or frequency deviations that result in failure or misoperation of customer equipment." Power quality phenomena can therefore be categorized mainly in terms of voltage and frequency deviations.

III. Extraction of Fundamental Frequency Current and Voltage

Fundamental voltage, current and phase magnitude estimates are required for a wide variety of power system applications. Examples are active filtering, detection of voltage peaks for VAR compensation and the need to extract the fundamental frequency component for transient stability assessment. An algorithm capable of extracting and estimating a specified single sinusoidal component of its input and tracking the variations of amplitude, phase, and frequency of such a sinusoid can be useful for numerous applications. The potential exists for also tracking multiple frequencies, which may exist in cases of instability.

A. Formulation of the Algorithm

A complete mathematical proof is presented in [1]. The governing set of equations for the algorithm is

$$\dot{A} = \mu_1 e \sin\phi \quad (1)$$

$$\dot{\omega} = \mu_2 e A \cos\phi \quad (2)$$

$$\dot{\phi} = \mu_3 e A \cos\phi + \omega \quad (3)$$

$$y(t) = A \sin\phi \quad (4)$$

$$e(t) = u(t) - y(t) \quad (5)$$

in which $u(t)$ and $y(t)$ are the input and output signals to the core algorithm, respectively. State variables A, ϕ and ω directly provide estimates of amplitude, phase, and frequency of $u(t)$. Parameters μ_1, μ_2, and μ_3 are positive numbers that determine the behavior of the algorithm in terms of convergence speed and accuracy. Specifically, parameter μ_1 controls the speed of the transient response of the algorithm with respect to variations in the amplitude of the interfering signal. Parameters μ_2 and μ_3 mutually control the speed of the transient response of the algorithm with respect to variations in the frequency of the interfering signal [1].

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IV. Comparison of Methods for Tracking Power Signals

A. *Voltage Deviation*

Disturbances

a) Voltage Dips and Swells

RMS and peak voltage methods are used to calculate voltage dips. Both of these methods use a windowing technique to calculate the dip depth and duration. The algorithm can be used to track voltage dips in real time without using a windowing technique. The amplitude A predicts the peak magnitude of the voltage or current waveform. Figure 1 shows the ability of the algorithm to track voltage dips.

A forty percent dip is simulated after nine cycles. The algorithm has the ability to track the dip. It is not known how the algorithm will respond in a noisy environment. Further research will address methods for minimizing the errors.

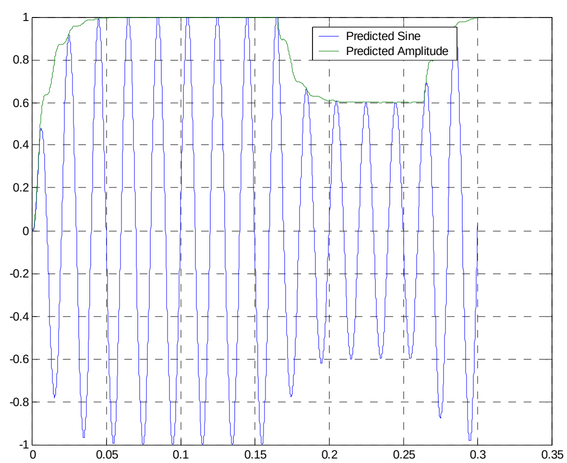

Figure 1: Tracking a voltage dip in real time

b) Transients

Transients can be categorized as either impulsive or oscillatory. Oscillatory transients can be classified into three subclasses coinciding with the common types of switching in power systems.

- High-frequency
- Medium-frequency
- Low-frequency
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(1) Wavelet

The wavelet transform has been used successfully in diagnosing transient events [9,10].

(2) Algorithm

The limited convergence speed of the algorithm poses problems in the processing of short duration intervals such as transients. In [11], the algorithm is used prior to the application of the wavelet transform to successfully detect broken rotor bars in induction motors. This approach needs to be investigated for improvement in diagnosing and characterizing power quality transients.

c) Waveform Distortion

(1) Fourier Transform

The Fourier Transform (FT) has several disadvantages such as aliasing and spectral leakage [2].

(2) Algorithm

The core algorithm is intended to extract one single sinusoidal component from its input signal. A multiplicity of core units may be employed in parallel, or alternatively cascaded to decompose a multi-component input signal into its constituent sinusoidal components as shown in figure 2 below.

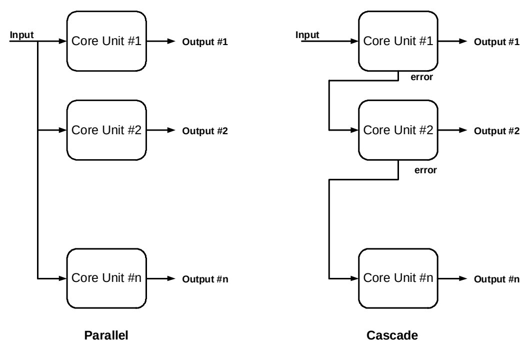

Figure 2: Two ways of decomposing an input signal into a multiplicity of core units

Frequency Deviation

For power system control and protection, it is important to carry out real time calculations of the supply frequency and track its variations [4]. Variations in the supply frequency from the steady state value can be indicative of unexpected power system disturbances for which corrective action needs to be taken.

As frequency estimates are normally required in real time, processing time is critical and hence computationally expensive algorithms and time delays due to pre and post filtering to remove distortion are undesirable [2]. The zero-crossing methods and DFT techniques often used assume sinusoidal waveforms of one frequency and are unreliable in the presence of distortion.

A sharp notch filter is capable of separating and extracting a desired sinusoidal component of a given signal if the frequency of the signal remains constant. However, when a transient occurs on the power system, the frequency may vary with time. Therefore, for changes in the frequency of the input signal, errors using a notch filter may be large.

One of the strongest features demonstrated by the algorithm in the literature, is the estimation of frequency [5,6,7,8]. Large variations of the frequency around the center frequency can be measured. Reference [1] compares different methods of frequency deviation with the algorithm. The algorithm displays a high degree of noise immunity and directly provides an estimate of the amplitude and phase of the extracted sinusoid. Implementation of the algorithm for under-frequency relaying and frequency control needs to be researched.

V. Advantages of The Algorithm

- Phase lock loop (PLL) techniques are not required for the extraction of sinusoidal signals having a time varying phase. PLL's have a limited frequency lock in range within which the variations of the desired signal are tolerated.
- It has a simple structure and is easy to implement.
- No windowing of data is required.
- Less processing power is required as compared to FFT and Wavelets.

VI. Disadvantages of the Algorithm

- The limited convergence speed of the algorithm poses problems in the processing of short duration intervals.
- The coefficients of the algorithm have to be optimized for a particular application.
- The errors associated with the algorithm are not known and needs to be investigated and quantified.

VII. Potential applications in power systems

- Generator frequency control.
- Under-frequency relaying
- Dip identification and mitigation.
- Early detection of sags implies quicker response time for sag mitigation devices. An example is a UPS.
- Harmonics and active filtering.
- Flicker quantification.
- Noise elimination for power line communication.
- Demand and power factor control.
- Power line communication

VIII. Conclusion

The algorithm has been compared to several standard methods of identifying power quality phenomena. Potential applications have been identified for use in power systems. The ability of the algorithm to track a sag in real time was demonstrated. This work forms the basis for further research in the identification of power quality events and the subsequent improved protection and operation.

IX. References

[1] A.K. Ziarani, "Extraction of Nonstationary Sinusoids", *PhD Thesis*, University of Toronto, Canada, 2002

[2] Arrilaga, J., Watson, N.R., Chen, S., *Power System Quality Assessment*, Wiley, England, 2001

[3] McGranaghan, M.F., Dugan, R.C., Beaty, H.W., Santoso, S., "Electric Power Systems Quality", McGraw-Hill, 2002

[4] Kundur, P., *Power System Stability and Control*, McGraw-Hill, New York, 1994

[5] A. K. Ziarani and A. Konrad, "A method of elimination of interferences of quasi-periodic nature," Proceedings of the 44th IEEE Midwest Symposium on Circuits and Systems, Fairborn, Ohio, 14-17 August 2001, pp. 363-366.

[6] A.K Ziarani, A. Konrad, "A nonlinear adaptive method of elimination of power line interference in ECG signals," IEEE Trans. Biomedical Engineering, Vol. 49, No. 6, June 2002.

[7] A.K. Ziarani, A. Konrad, "A nonlinear method of frequency estimation in noise," Proceedings of 2002 IEEE International Midwest Symposium on Circuits and Systems, Vol. 3, Tulsa, Oklahoma, 4-7 August 2002, pp. 316-319.

[8] A. K. Ziarani, I. M. Blumenfeld, A. Konrad, "Experimental verification of a novel method of extraction of nonstationary sinusoids," Proceedings of 2002 IEEE International Midwest Symposium on Circuits and Systems, Vol. 1, Tulsa, Oklahoma, 4-7 August 2002, pp. 455-458.

[9] P. Pillay, A. Bhattacharjee, "Application of wavelets to model short-term power system disturbances", IEEE Trans. Power Systems, Vol. 11, November 1996.

[10] S. Santoso, P. Hoffman, "Power quality assessment via wavelet transform analysis", IEEE Trans. Power Delivery, Vol. 11, No. 2, April 1996.

[11] P. Pillay, H. Douglas, A.K. Ziarani, A., "Detection of broken rotor bars in induction motors using wavelet analysis" Electric Machines and Drives Conference, 2003. IEMDC'03. Volume: 2, 1-4 June 2003

X. Biographies

Raj Naidoo has a BSc and Msc in Electrical Engineering from the University of Natal and Witwatersrand respectively. He is currently working towards a PhD degree at the University of Cape Town. His interests include power quality, power system planning and power system stability. He is a registered professional engineer in South Africa. His working experience includes six years at Eskom.

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