COMPUTATION OF POWER QUALITY SYMMETRICAL COMPONENTS USING FUZZY LOGIC BASED LINEAR COMBINERS

P.K. Dash, B. Mishra
Centre for Intelligent Systems
Regional Engineering College
Rourkela-769008, India.

S.K. Panda, M.M.A. Salama
Department of Electrical Engineering
National University of Singapore
Singapore.

Abstract

This paper presents a new approach to estimate the symmetrical and α - β components of the voltage and current signals of a power distribution network using Fourier Linear Combiners. The learning parameter for updating the weights of the combiner is adapted using a fuzzy logic based algorithm obtained from the error covariances. The new algorithm is tested using the recorded data from an industrial load bus supplying power elctronically controlled induction furnace loads. The estimation results are compared with a 19^{th} order Kalman filter approach to highlight the accuracy and fast tracking capabilities of the new approach. The linear combiner, however, presents a simple and implementable algorithm in comparison to the well known Kalman filter approach.

1. Introduction

Power quality is a term that is directed at a wide variety of variations in the electric power supplied to utility customers. These variations can originate and/or manifest themselves at various places in the power network. Many of these power quality concerns are associated with the operation and design of customer facilities, concerns associated with wiring and grounding problems, switching transients, load variations, and harmonic generations, etc.

The proliferation of power electronic devices and computer loads are directly linked to the increasing number of power quality related problems. Not only these types of loads are a source of additional harmonics, but they also have a high sensitivity to non-sinusoidal waveforms. As a result, the use of power quality analysis methodologies and measurement tools is becoming commonplace in power industry. Estimation of harmonic components in a power or distribution network supplying nonlinear loads and solid state switching devices is a standard approach for the assessment of the quality of delivered power. The identification of harmonics is important where harmonic standards are to be adopted. It may be used to allocate loads that exceeds specified harmonic current limits. Furthermore, it is an important requirement for designing harmonic filters.

Most frequency domain harmonic analysis techniques [1,2] use discrete Fourier transform (DFT) or fast Fourier transform (FFT) to obtain harmonic estimates of distorted signals. In applying FFT, the phenomena of aliasing, leakage and picketfence effects may lead to in accurate estimates of harmonic magnitudes. The DFT suffers from inaccuracies due to the presence of random noise usual in the measurement process and tracking of signals with time varying amplitude and phase involves large error. The application of Kalman filters, and recursive LMS and RLS filters [3,4,5] have been reported in the literature for tracking time varying signals embedded in random noise and

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decaying dc components. Both these filters suffer from large computational overhead and suitable values of covariance matrices and real-time implementation of these filters posses difficult problems.

This paper presents a new approach for the estimation of symmetrical components for the both the fundamental and harmonics of a power distribution network using Fourier linear combiner. The inputs to the Fourier linear combiner are the exponential complex functions pertaining to fundamental and harmonic components . The linear combiner has a set of adjustable weights which are updated using a nonlinear weight adjustment algorithm . Further the learning parameter of the linear combiner is computed using a fuzzy logic based algorithm based on the recursive error co-variance formulation .

The linear combiner provides a fast and a very simple technique for computing the amplitude of time varying signals embedded with noise . Further for a three-phase power and distribution network , the symmetrical components play an important role in classifying the types of power quality disturbances on the network . From the amplitude and phase of the individual phases of the 3-phase network , symmetrical components are calculated at each sampling instant for the fundamental and harmonics. Computer simulation results for real-time data from a distribution network are presented in this paper to highlight the efficacy of this approach.

2. Fourier linear combiner

The voltage or current of a power network is expressed in the form

$$y(t)= \sum_{i=1}^{N} A_i Sin(iw_0 t + \phi_i) \qquad (1)$$

where A_i and ϕ_i represent the peak amplitude and phase angle , respectively , of the fundamental and harmonic components ; w_0 is the angular frequency of voltage or current signal and is to be known apriori . The discrete version of the above signal is given by

$$y(k)= \sum_{i=1}^{N} A_i Sin(iw_0 k\Delta T + \phi_i) \qquad (2)$$

ΔT=sampling interval
k = iteration count or the sampling instant
The fourier coefficients of the above model can be computed using Fourier linear combiner (Fig.1) , which has a input sequence of the form (including a constant dc component)
$x(k)$=

$$\left[1 \quad e^{jw_0 k\Delta T} \quad e^{2jw_0 k\Delta T} \quad \ldots\ldots\ldots \quad e^{2jNw_0 k\Delta T}\right]^T \qquad (3)$$

The output of the linear combiner is the estimated signal

$$\hat{y}(k) = \left[x(k).W(k)\right] \qquad (4)$$

where W(k) is a weight vector of the form

$$W(k) = \left[A_{dc} \quad A_1 e^{j\phi_1} \quad A_2 e^{j\phi_2} \ldots\ldots A_N e^{j\phi_N}\right] \qquad (5)$$

From the weight vector , amplitude and phase are obtained by some simple manipulations .

The weight vector is updated recursively as

$$W(k+1) = W(k) + \frac{\alpha(k).e(k).x(k)}{\lambda + x^T(k).x(k)} \qquad (6)$$

$\alpha(k)$= learning rate
e(k) = error at kth time step

$$= y(k) - Im(\hat{y}(k)) \qquad (7)$$

λ = a small integer to avoid division by zero .

The learning parameter is made complex to yield complex weight updation and is of the form

$$\alpha(k) = |\alpha(k)|.(1 + j) \qquad (8)$$

The magnitude of $|\alpha(k)|$ lies between 0 to 1.414 for providing good convergence and better noise rejection property.The learning parameter $\alpha(k)$ is made adaptive by choosing the variation in the form

$$\alpha(k) = \mu \cdot \alpha(k) + \gamma \cdot e^2(k) \tag{9}$$

where $0 < \mu < 1$ and $\gamma > 0$ and $0 < \alpha < 2$.
The convergence of LMS algorithm depends on the proper choice of the step size α and a higher α results faster convergence and better tracking capability at the cost of misadjustment. A smaller value of α yields lower misadjustment and low convergence speed of the algorithm and hence may not be able to track non-stationary signals. The fuzzy logic based algorithm uses the error covariance to estimate the step size of the learning parameter α. The learning parameter is rewritten as

$$\alpha(k) = \mu\alpha(k) + \Delta\alpha(k) \tag{10}$$

where $\Delta\alpha(k)$ is obtain as

$$\Delta\alpha(k) = FL(e(k), e(k-1)) \tag{11}$$

The function FL is obtained by using a fuzzy logic based inferencing procedure. An error covariance factor ec(k) is obtained as

$$ec(k+1) = \beta\, ec(k) + (1-\beta)e(k).e(k-1) \tag{12}$$

The value of β is usually chosen as 0.8 or 0.9. A fuzzy logic rule base to obtain $\Delta\alpha(k)$ is obtained as

R1 : If ec(k) is ZE then $\Delta\alpha(k)$ is ZE.
R2 : If ec(k) is VS then $\Delta\alpha(k)$ is VS.
R3 : If ec(k) is S then $\Delta\alpha(k)$ is S.
R4 : If ec(k) is M then $\Delta\alpha(k)$ is M.
R5 : If ec(k) is L then $\Delta\alpha(k)$ is L.
R6 : If ec(k) is VL then $\Delta\alpha(k)$ is VL.

The linguistic variables ZE, VS, S, M, L, and VL represent the fuzzy subsets zero, very small, small, medium, large, and very large, respectively. The membership functions of the fuzzy linguistic variables ZE, VS, S, M, L, VL are shown in Fig.2.

A simple fuzzy inferencing mechanism is used to yield the output as

$$\Delta\alpha(k) = \frac{\sum_{i=1}^{6} \mu_i \Delta\alpha_i}{\sum_{i=1}^{6} \mu_i} \tag{13}$$

where μ_i is the firing level of the fuzzy rule and $\Delta\alpha_i$ is the Centre of gravity of the output fuzzy subset of the ith rule. This approach requires only two multiplications and one division and hence is suitable for real-time implementation. A slight variation of the above defuzzification procedure is

$$\Delta\alpha(k) = \frac{\sum_{i=1}^{6} \rho_i \mu_i \Delta\alpha_i}{\sum_{i=1}^{6} \rho_i \mu_i} \tag{14}$$

where $\rho_i = 1 - \frac{S_i}{S}$ and S is total area under the membership functions of all the output fuzzy subsets and S_i is the area under the function corresponding to the output fuzzy subset of the ith linguistic rule.

The weight vector of the linear combiner yields the amplitude and phase angle of the signal. For example

$$W_1 = A_1 e^{j\phi_1} \tag{15}$$

for the fundamental

and $W_N = A_N e^{j\phi_N}$ (16)

for the Nth harmonic.

3. Sequence Components Calculations

From the sampled values of the voltage and current data, the linear combiner produces the amplitude and phase angle of the fundamental and harmonic components at each sampling instant k. In a 3-phase system, let the weights of the combiner for the fundamental component are denoted by

$W_{1a}(k)$, $W_{1b}(k)$, $W_{1c}(k)$, respectively. Hence the zero -, positive -, and negative – sequence components of the voltage or current signals are obtained as

$$\begin{bmatrix} V_0(k) \\ V_1(k) \\ V_2(k) \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} W_{1a}(k) \\ W_{1b}(k) \\ W_{1c}(k) \end{bmatrix} \qquad (17)$$

where $a = e^{j\frac{2\pi}{3}} = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$

$$a^2 = e^{j\frac{4\pi}{3}} = -\frac{1}{2} - j\frac{\sqrt{3}}{2}$$

For the Nth harmonic the values of a and a^2 are
$a = e^{j\frac{2\pi}{3}N}$, $a^2 = e^{j\frac{4\pi}{3}N}$

The sequence components are required to detect the power quality problems involving unbalanced operation (both steady state and outages). Also the detection of high impedance faults on distribution feeders can be reasised from the estimation of sequence components for 3rd and 5th harmonic fault currents.

The α - β components are also useful in fully describing the three phase instantaneous voltages and currents. It is well know that the positive and negative sequence components can be separated faster in α - β components then in other forms. Thus for the fundamental

$$\begin{bmatrix} V_\alpha(k) \\ V_\beta(k) \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} W_{1a}(k) \\ W_{1b}(k) \\ W_{1c}(k) \end{bmatrix} \qquad (18)$$

4. Digital Simulation Results

The severity of power quality problems at an industrial load bus. The load consists mainly of power electronic devices to convert ac to dc and then to high frequency ac for induction heating.

The fuzzy logic based Fourier linear combiner approach is used to monitor on sample to sample basis the instantaneous peak amplitude and phase angle. The frequency of the supply is known apriori or can be monitored, if required. A sampling rate of 64 samples per cycle (based on 50Hz waveform) is used for the estimation. A MATLAB software package is used for the purpose. Fig.3 shows the actual 3-phase voltage and current waveforms of the industrial load.

The voltage and current samples are used to produce the positive, negative and zero sequence components of the fundamental and harmonic components. As the fifth harmonic component is substantial in the waveform of the recorded data, the symmetrical components of the 5th harmonic voltages and currents are calculated. Figs.4(a) and 4(b) shows the amplitudes of the fundament and 5th harmonic components with time, showing clearly the efficacy of this algorithm. Fig.5 shows the amplitudes of the 7th harmonic voltage and current components. Reference values are also shown in the figure to provide a meaningful comparison. A Kalman filter approach with suitably tuned covariance matrics is also used. The Kalman filter provides almost identical reasults in the case of Fourier linear combiner. However, the cost of computational overhead for a 19th harmonic Kalman filter model is excessive.

5. Conclusions

The paper presents a new approach for the computation of symmetrical and α - β components for an unbalanced power distribution network using Fourier Linear Combiners. The convergence speed and noise rejection efficacy is suitably enhanced by using a fuzzy logic based learning parameter computation based on error covariances. The fuzzy logic approach is simple and yields a robust tracking of the noisy signal. Further due to the simplicity of this model in comparison to the well known Kalman filter, this approach is suitable for real-time implementation.

6. References

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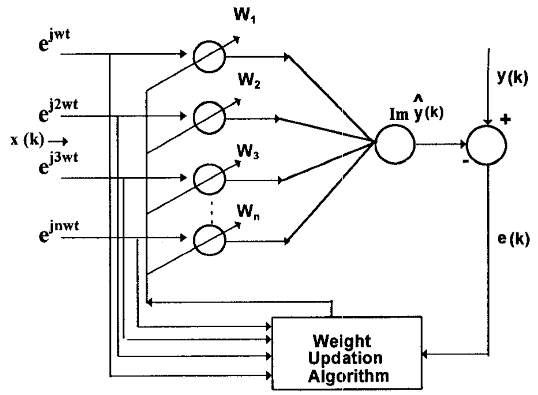
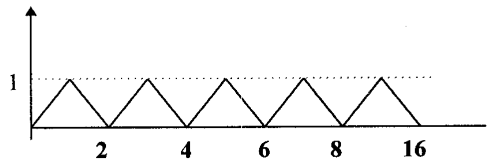
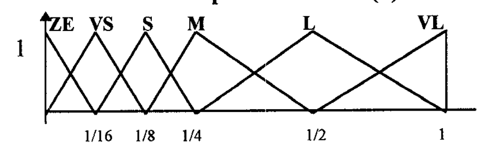


Fig.1 Fourier linear combiner with complex inputs

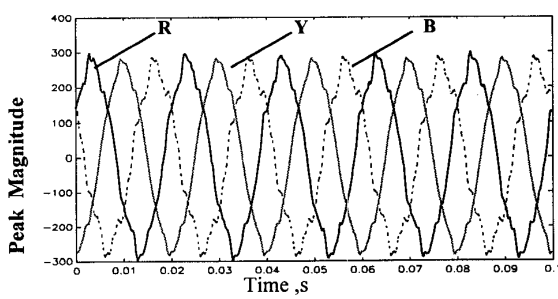


Membership function of U(k)

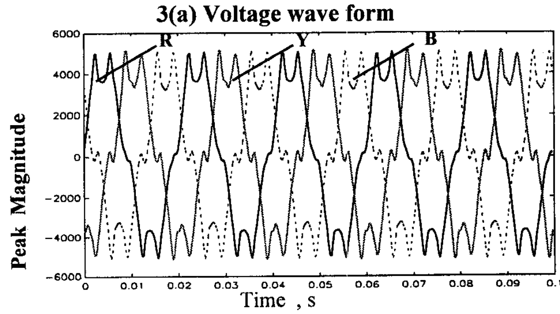


Membership function of $\Delta\alpha(n)$

Fig.2 Fuzzy membership functions

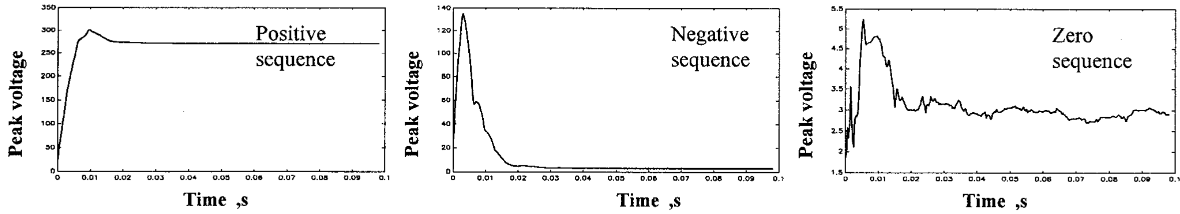


3(a) Voltage wave form

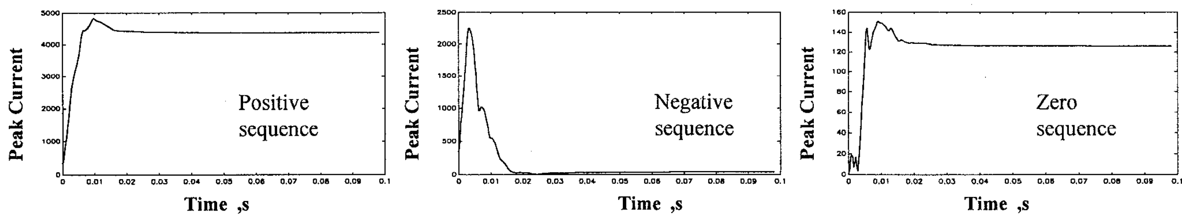


3(b) Current wave form

Fig.3 3-phase voltage and current waveforms

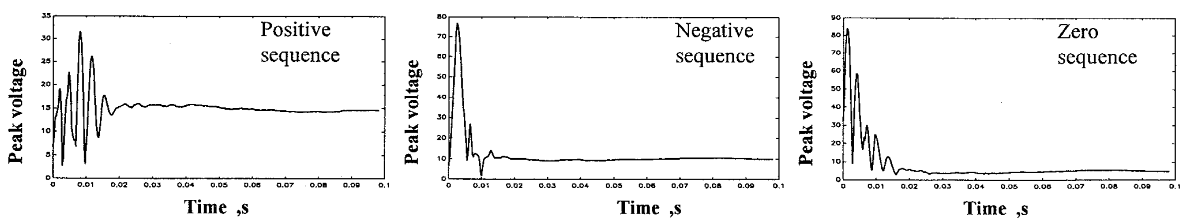


(i) Fundamental voltage components

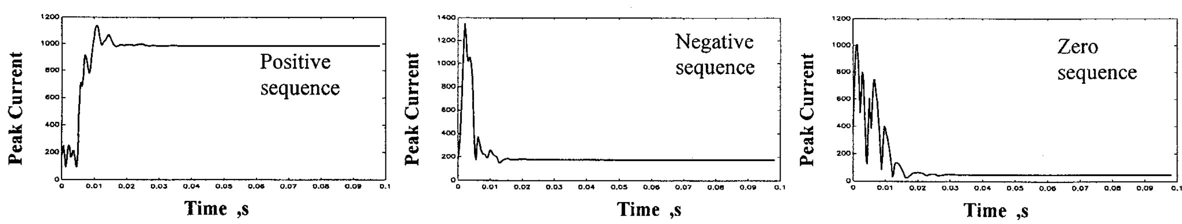


(ii) Fundamental current components

Fig.4(a) Amplitude of fundamental voltage and current

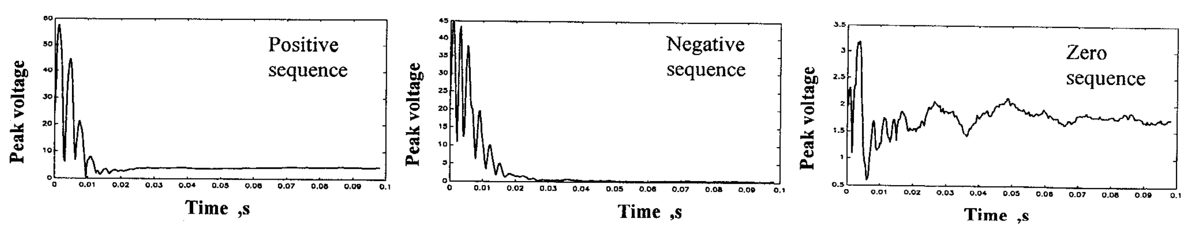


(i) 5th harmonic voltage components

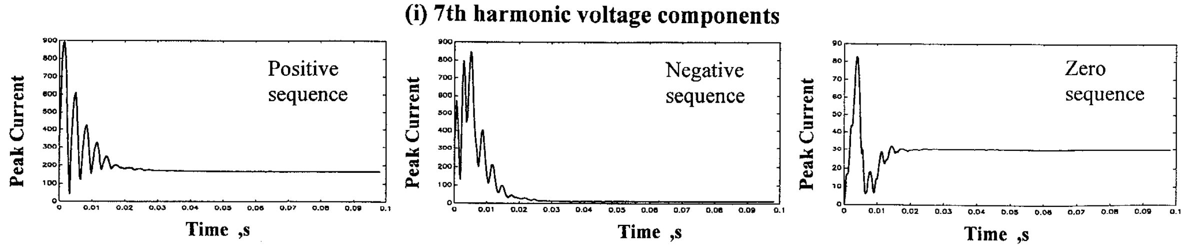


(ii) 5th harmonic current components

Fig.4(b) Amplitude of 5th harmonic voltage and current



(i) 7th harmonic voltage components



(ii) 7th harmonic current components

Fig.5 Amplitude of 7th harmonic voltage and current