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A DEMODULATION TECHNIQUE FOR POWER SYSTEM LOCAL FREQUENCY AND VOLTAGE MEASUREMENTS

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ABSTRACT

The demodulation technique of two complex signals is used to estimate the power system local frequency and voltage phasor. The first complex signal is generated from the three-phase voltage waveform by using the $\alpha\beta$-transformation, while the second complex signal is assumed to have a one per unit amplitude and to rotate in a direction opposite to the original three-phase voltage signals with nominal frequency ω_o(negative sequence signal). Use of the demodulation technique does not introduce a double frequency component, which limits the speed of the frequency estimator especially, if the signal has a high signal to noise ratio. Two closed form formulae are derived based on the least error squares (LES) algorithm, for system frequency as well as its phase angle. It is shown that using such a technique, a very short data window size can be used to measure the power system frequency. To be specific, a minimum of two samples data window is enough for the noise free signals.

Keywords: Demodulation, frequency relaying, least error square estimation algorithm

I. INTRODUCTION

Power system voltage amplitude and local frequency are very important varaibles in power system protection for frequency relaying and load shedding. They are also important for the automatic voltage regulator (AVR) function [1]. Presently, power system networks are polluted with harmonics, due to the widespread use of power electronic devices of all types in generation, transmission and distribution. Moreover, the use of nonlinear loads in the distribution network injects harmonics of different order. Harmonics in power systems cause many operational problems such as signal interference with communication channels in the system, and malfunction of relays, particularly in solid-state and microprocessor controlled apparatus used to estimate frequency and its rate of change. As a result there is a need to find a fast and accurate algorithm for measuring system frequency and voltage signal in such an environment [1].

During the past two decades, various digital techniques have been developed and tested for frequency measurement. These include, change of angle for phasor measurement [2], Kalman filtering algorithm [3], zero crossing and its variants[4,5], demodulation with fixed and variable frequency [6-8]. During that period, static state estimation theory was applied for frequency measurement, these include the least error squares technique (LES), the recursive least error squares technique and the least absolute value technique [6-9,10,11]. All techniques were implemented off-line to measure the off nominal, near nominal, and nominal frequency as well as power system voltage amplitude and phase angle. They produce good estimates of the system variables for the cases considered. Ref.13 implemented an algorithm using the orthogonal sine and cosine filtering. The algorithm works with any relative phase of the input signal and produces a new frequency estimate for every new input sample. Ref.14 presented a method based on digital filtering and Prony's estimation. The discrete Fourier transform with a variable data window is used to filter out noise and harmonics associated with the signal.

The demodulation of two complex signals was applied in [15], by converting the three-phase voltage signal into a complex quantity. This complex signal is demodulated with a known complex phasor rotating in opposite direction to the input to avoid production of a double frequency signal. Orthogonal signal components obtained with the use of two orthogonal FIR filters were implemented in [16]. The essential property of the algorithm is its outstanding immunity to both signals orthogonal component magnitudes and FIR filter gain variations. This algorithm uses the per-phase digitized voltage samples.

In this paper the demodulation of two complex signals technique is used to measure the power system local frequency and voltage phasor. The first complex signal is generated from the three-phase voltage waveform by using the αβ-transformation, while the second complex signal is assumed to have a one p.u amplitude and rotates in the opposite direction to the original three-phase voltage signals with nominal frequency ω_o(negative sequence signal). Using the demodulation technique does not introduce a double frequency component, which limits the speed of the frequency estimator especially, if the signal has a high signal to noise ratio. Two closed formulas are derived based on least error squares (LES) algorithm, for the system frequency as well as its phase angle. It has been shown that using such a technique, a very short data window size can be used to measure the power system frequency. For a noise free signals a minimum of two samples data window size is needed

II. VOLTAGE SIGNAL MODELING

The αβ-Transformation is used in the analysis of electrical machines. It has a little application in the power system analysis. In this section we use this transformation to transform the three-phase voltage signals to a complex phasor having the same frequency and phase angle of the original three-phase voltage signals. The three-phase voltage signals of a power system can be written, at any sample interval k, as:

$$\begin{aligned} v_a(k) &= V_{ma}\sin(\omega k\Delta T + \varphi_a) + \varepsilon_a(k) \\ v_b(k) &= V_{mb}\sin(\omega k\Delta T + \varphi_b - 120) + \varepsilon_b(k) \\ v_c(k) &= V_{mc}\sin(\omega k\Delta T + \varphi_c + 120) + \varepsilon_c(k) \end{aligned} \tag{1}$$

Where, V_m is the signal amplitude, ω is the fundamental frequency, ΔT is the sampling time = $1/F_s$, Fs is the sampling frequency in Hz, k is the sampling step, $k=1,m\ldots$; m total available number of samples, and φ is the voltage phase angle. Furthermore, $\varepsilon_a(k)$, $\varepsilon_b(k)$ and $\varepsilon_c(k)$ are the noise terms, which may contain harmonics.
The well-known αβ- transformation is obtained as:

$$\begin{bmatrix} v_\alpha(k) \\ v_\beta(k) \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_a(k) \\ v_b(k) \\ v_c(k) \end{bmatrix} \tag{2}$$

$$v_\alpha(k) = \sqrt{\frac{2}{3}}\left(v_a(k) - 0.5v_b(k) - 0.5v_c(k)\right) \tag{3}$$

$$v_\beta(k) = \sqrt{\frac{2}{3}}\left(\sqrt{3}/2\, v_b(k) - \sqrt{3}/2\, v_c(k)\right) \tag{4}$$

For m samples of the three-phase signals,m samples for $v_\alpha(k)$ and $v_\beta(k)$ are obtained. By using this transformation, harmonics of order three and their multiples are suppressed.The complex voltage formed from these two voltages, and having the same frequency ω and phase angle ϕ as the original three phase voltages is:

$$v(k) = v_\alpha(k) + jv_\beta(k) \tag{4}$$

which can be written in phasor form as:

$$v(k) = V(k)e^{j(\omega t+\phi)} \tag{5}$$

where the amplitude $V(k)$ of the complex phasor can be found as:

$$V(k) = \left[v_\alpha^2(k) + v_\beta^2\right]^{\frac{1}{2}} \tag{6}$$

and phase angle θ(k) is given as:

$$\theta(k) = \tan^{-1}\frac{v_\beta(k)}{v_\alpha(k)} = \omega k\Delta T + \varphi \tag{7}$$

If the complex signal of equation (5) is demodulated by a signal having a one per unit amplitude and the nominal frequency ω_o and rotates in the opposite direction to the complex phasor (negative sequence signal) as shown in Figure 1,

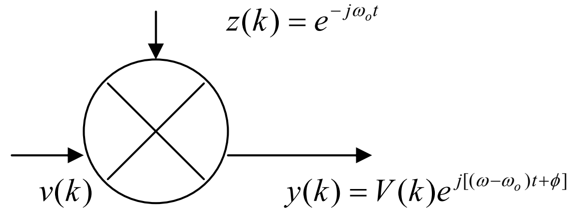

Fig. (1) Demodulation of voltage signal

The phase angle of the demodulated signal y(k) can be calculated as:

$$\psi(k) = \tan^{-1}\frac{\operatorname{Im} y(k)}{\operatorname{Re} y(k)} \tag{8}$$

From Figure 1 the phase angle of *y(k)* is

$$\begin{aligned}\psi(k) &= (\omega - \omega_o)k\Delta T + \phi \\ &= \Delta\omega(k\Delta T) + \phi\end{aligned} \tag{9}$$

where $\Delta\omega$ is the frequency drift. For m samples available for $\psi(k)$, $k=1,..,m$, then equation (9) can be written as

$$\underline{\psi} = A\,\underline{X} + \underline{\varepsilon} \tag{10}$$

where $\underline{\psi}$ is mx1 vector of the phase angle of the demodulated signal, A is mx2 matrix of samples whose elements are given as; $a_{i1} = (k\Delta T)$; $a_{i2} = 1.0$, $\underline{X}$ is 2x1 vector of the frequency drift and phase angle ϕ, and $\underline{\varepsilon}$ is mx1 errors vector associated with the samples to be minimized. Equation (10) is an overdetermined set of equations, which can be solved using the least error squares as;

$$\underline{X} = [A^T A]^{-1} A^T \underline{\psi} \tag{11}$$

Having identified the state vector X then the frequency of the three-phase voltage signal and the phase angle can be determined as

$$f = f_o + (1/2\pi)\, X_1 \tag{12}$$

$$\phi = X_2 \tag{13}$$

If one performs the matrix operation in equation (11), the results are:

$$\Delta\omega = \frac{\Delta\omega_1}{D} \times F_S \tag{14}$$

$$\phi = \frac{\phi_1}{D} \tag{15}$$

where

$$\Delta\omega_1 = m\sum_{i=1}^{m}(i)\psi(i) - \sum_{i=1}^{m}(i)\sum_{i=1}^{m}\psi(i) \qquad (16)$$

$$D = m\sum_{i=1}^{m} i^2 - \left(\sum_{i=1}^{m} i\right)^2 \qquad (17)$$

$$\phi_1 = \sum_{i=1}^{m} i^2 \sum_{i=1}^{m}\psi(i) - \sum_{i=1}^{m} i \sum_{i=1}^{m} i\,\psi(i) \qquad (18)$$

Note that for only two successive samples, of the modulated signal, sampled at ΔT and 2ΔT, the frequency of the voltage signal, as well as, its phase angle can be evaluated as:

$$f = f_o + \frac{F_S}{2\pi}\left[\psi(k_2) - \psi(k_1)\right]; k_2 = k_1 + 1 \qquad (19)$$

$$\phi = 2\psi(k_1) - \psi(k_2) \qquad (20)$$

Using equations (19) and (20) recursive equations can be obtained as::

$$f(k) = f_o + \frac{F_S}{2\pi}\left[\psi(k+1) - \psi(k)\right] \qquad (21)$$

$$\phi(k) = 2\psi(k) - \psi(k+1) \qquad (22)$$

III. COMPUTER SIMULATED RESULTS

1. Noise Free Sgnals

The proposed algorithm is tested using a simulated example. The three phase voltage signals used in this study are noise free signals and are balanced with one p.u amplitude and phase angle -30^o . The algorithm is used to estimate the amplitude, phase angle and frequency of the voltage signals, where the signal frequency is assumed to be off nominal, near nominal, and at nominal frequency and takes values of 45 Hz, 49.9 Hz and 50 Hz. It has been shown , through extensive runs, that the proposed algorithm estimates exactly the signal frequency at off nominal, near nominal and nominal frequency. Figures 2 and 3 give the estimated voltage amplitude and phase angle of the voltage signal. The sampling frequency used in this study is 4000 Hz and the number of samples used is 100 samples. Examining these figures reveals the following:

- ♦ The estimated voltage amplitude at the three frequencies equals the exact value of the simulated voltage signal.
- ♦ A poor estimate of the phase angle at off nominal frequency is obtained, while exact estimates for the phase angle near nominal and at nominal frequency are obtained. However, using equation (13), which is based on the least error squares, over the sampling period produces an exact value for the phase angle at the proposed three frequencies.
- ♦ In conclusion the proposed technique successeds in estimating the parameters of the three-phase voltage signal. The proposed algorithm is tested when a ten percent noise on each voltage sample are added. It has been found that the proposed algorithm estimated exactly the nominal frequency, the voltage amplitude and phase angle.

2. Unbalanced Three-Phase Voltage

The proposed algorithm is tested for unbalanced three phase voltages, where we assume unbalanced magnitude of V_a = 1.0, V_b=0.9 and V_c=0.8 p.u for the three voltages and nominal frequency of f_o= 50 Hz. The sampling frequency used in this study is 4000 Hz, with data window size equal 100 samples. Figure 4 gives the estimated frequency, the solid line in this figure gives the best fit, based on least error square, for the curve. Examining this curve reveals the following:

- The estimated frequency is time varying over the data window size, the estimate is almost a cosine function.
- The best fit to this curve gives almost a horizontal straight line at 50.002 Hz, over the data window size.
- The estimated frequency using equation (12) over the data window size is almost the nominal frequency. It is 50.00202 Hz.

Figure 5 gives the estimated voltage amplitude of the complex phasor over the data window size. Examining the figure reveals the following remarks

- The voltage unbalance has a great effect on the estimated voltage amplitude.
- The estimated voltage amplitude is a time varying estimate. The linear best fit for the voltage amplitude gives an approximate value of 1.10 p.u, with an average error of 8.3%.

Figure 6 gives the estimated phase angle of the three-phase voltage signal. Examining this figure reveals that the phase angle estimate is also a time varying estimate. The linear best fit for the phase angle gives almost a constant estimate of -30.2^o. However, using equation (13) produces the same constant estimate of -30.2^o, which is almost the same phase angle of the voltage signals.

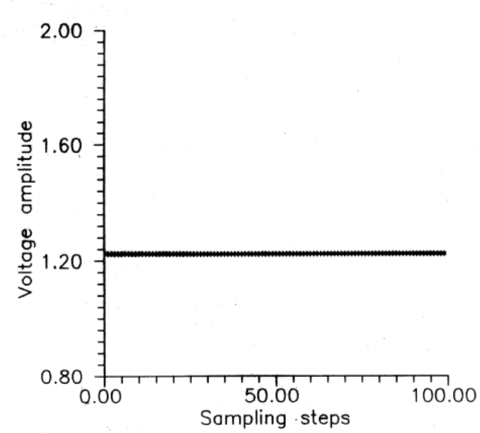

Fig. (2) The Estimated voltage

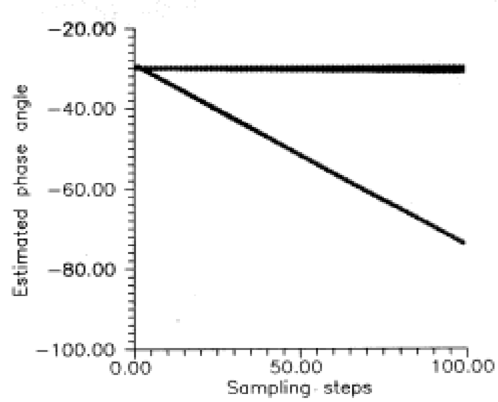

Fig. (3) Estimated phase angle

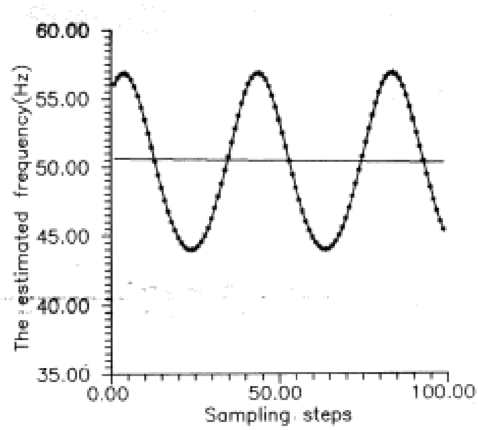

Fig. (4) Estimated, and best fit frequency

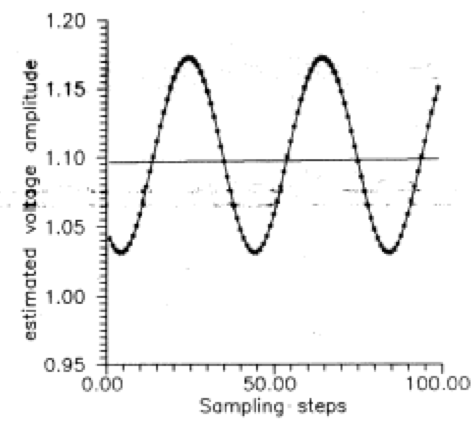

Fig. (5) Estimated voltage amplitude

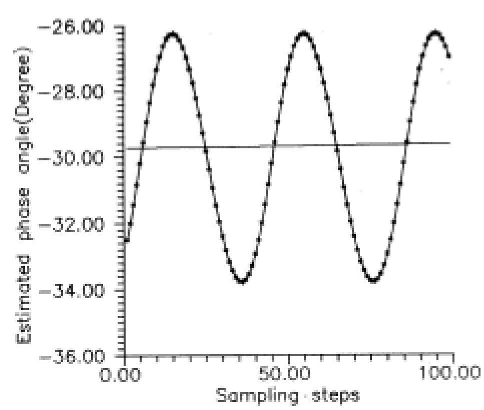

Fig. (6) Estimated phase angle

3. Harmonic Contaminated Signals

The proposed technique is tested for a harmonics contaminated voltage signal, where we assume that the voltage signals contain 0.12 p.u second harmonic, 0.3 p.u third harmonic, and 0.05 p.u fifth harmonic. All these harmonics are balanced in the three phases in addition to the 1.0 p.u-balanced fundamental. A sampling frequency of 4000 Hz and a data window size of 100 samples are used in this study.

Use of $\alpha\beta$- transformation suppresses the third harmonic component in the three phases. This is due to the nature of the transformation. Figures 7,8 and 9 give the estimated frequency, complex phasor voltage amplitude, and fundamental voltage signal phase angle. Examining these figures reveals the following:

- The harmonics contamination has a great effect on the estimated parameters, and the three estimated parameters are time varying parameters during the data window size.
- The linear best fit, based on the LES, for the signal frequency gives
  $f(k) = 53.4756 - 0.062k$ Hz; k=1,….100
- Using equation (12) for static LES estimate produces a frequency estimate of 49.98, with an error of 0.02 %. This static estimate can be considered as a good estimate in such environment of pollution.
- The linear best fit for the complex phasor amplitude based on LES is
  $v(k) = 1.20269 + 5.02 \times 10^{-4}\, k$, $k=1,\ldots,100$
  which is almost a constant of 1.20269 p.u.

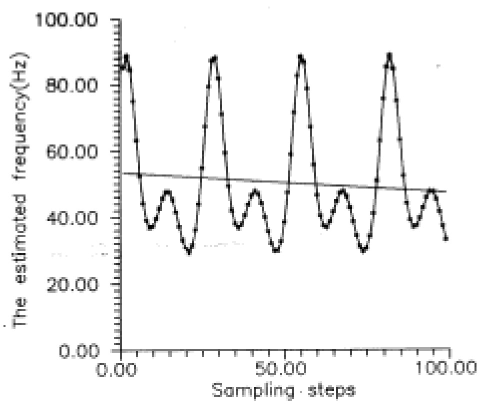

Fig. (7) Estimated and best fit frequency

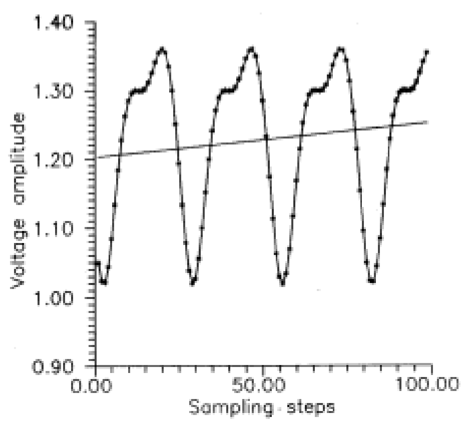

Fig. (8) Estimated and best fit voltage

This value is almost the same value of the complex phasor for noise free signals.

- The estimated phase angle of the fundamental signal is also a time varying estimate during the data window size.
- The linear best fit for such estimate is given by
  $\phi(k) = -29.671 + 3.285 \times 10^{-3} k, k=1,..,100.$
  which is almost a constant of -29.671^{o}.

Using equation (13) for LES static estimation produces almost the same value. This estimate is a good estimate in such case.

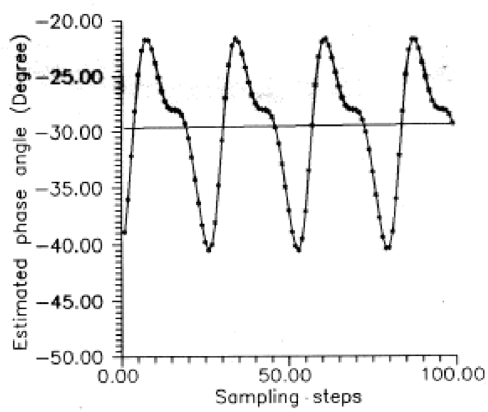

Fig. (9) Estimated and best fit phase angle

IV. CONCLUSION

We present in this paper a demodulation technique to demodulate the complex phasor resulting from the αβ-transformation of the three-phase voltage signal. Using such a demodulation, the double frequency of the conventional modulation in the signal processing techniques that produces slow estimates is avoided. The proposed algorithm produces exact estimates for the signal parameters of a noise free signal. Meanwhile it produces good estimates when the three-phase voltages are unbalanced and contaminated with balanced harmonics of different orders. Static estimation based on LES formulae are derived for the parameter estimates, as well as dynamic formulae. It has been shown that two samples are enough to estimate the signal frequency and signal phase angle for noise free signals. Meanwhile, more samples can be used for static estimation based on LES for polluted signal. This can be considered as a shortest data window size, used for estimation

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