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FREQUENCY ESTIMATION OF DISTORTED POWER SYSTEM SIGNALS USING MULTIPLE SIGNAL CLASSIFICATION ALGORITHM

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Abstract

In this paper a sub-space based fundamental frequency estimator of multiple signal classification (MUSIC) algorithm for distorted power system signals is proposed. Noise and signal sub-spaces are obtained from eigenvalue decomposition and desired frequency is estimated. Distortion level of the power system signals which have been observed from measurements may affect the accuracy of frequency measurement in a power system. Thus, the proposed method is employed to decompose noise sub-space for white and harmonic noises which are common in power systems. Computer simulations have been carried out for the performance analysis of the proposed method and the comparison results of the proposed method for different signal to noise ratios (SNR) are given. The fast tracking performance of the proposed approach in power system frequency estimation is emphasized.

Keywords: *MUSIC, Power System, Frequency Estimation*

1. INTRODUCTION

In a power system fast and accurate estimation of frequency and reliable tracking of frequency deviation is important for control and protection of the system. The accuracy, speed of tracking and noise immunity parameters determine the performance of an estimator [1]. Estimation performance is highly dependent on distortion strength which is measured with the SNR values. In this work white noise distortion and harmonic distortion are used to contaminate power system signal. To estimate frequency of the power systems several algorithms have been used. Zero-crossing [2], Discrete Fourier transform (DFT) [3], Kalman filtering [4], phase locked loop (PLL) [5], and adaptive filtering [6, 7] are among the most popular algorithms for frequency estimation. In the presence of noise with low SNR values these well-known methods cannot accurately and quickly track the frequency of the system [1].

MUSIC is a sub-space based algorithm which can estimate frequency components from noisy measurements and has applications in many areas such as communications, radar, sonar and especially direction of arrival (DOA) [8]. MUSIC algorithm decomposes observation space into signal and noise sub-spaces. MUSIC algorithm has good estimation accuracy and resolution. Although MUSIC

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algorithm has many applications in spectral analysis in literature, it has been used in fundamental frequency estimation recently.

The paper is organized as follows. In Section 2, the signal model is presented. Then, in Section 3, the MUSIC algorithm model and mathematical definitions are given. In Section 4, some numerical results are presented. Also computer simulations have been carried out for different types of noises and SNR values. Finally, Section 5 is the conclusion of the work.

2. SIGNAL MODEL

The general distorted power system signal model with multiple frequency components is given in equation (1) [1].

$$x[n]=\sum_{k=1}^{K}A_k e^{\left(jw_k n\right)}+z[n] \qquad (1)$$

Where A_k is a complex number representing the magnitude and phase of the *k*-th frequency component. The noise component observed on the system signal is z[n]. The analysis of sub-space structure of signals which are composed of several frequency components can be fulfilled with analyzing its autocorrelation matrix.

$$\mathrm{R}_x=E[xx^H]=\begin{bmatrix} r_x[0] & \cdots & r_x[M-1] \\ \vdots & \ddots & \vdots \\ r_x[M-1] & \cdots & r_x[0] \end{bmatrix} \qquad (2)$$

Superscripts $\{.\}^H$ and E{.} denote conjugate transpose and mathematical expectation, respectively. It is assumed that the correlation matrix R_x can be eigen-decomposed.

$$\mathrm{R}_x=\mathrm{U}^H\Lambda_x\mathrm{U} \qquad (3)$$

The matrix U contains the orthonormal eigenvectors of R and Λ is a diagonal matrix containing the corresponding eigenvalues (λ). The most significant eigenvectors will span the signal subspace while the noise subspace is spanned by the least significant eigenvectors [9]. Using the decomposition idea we may decompose autocorrelation matrix into signal and noise sub-spaces.

$$R_x=R_s+R_n=\sum_{k=1}^{K}\left|A_k\right|^2 e_k e_k^{*T}+\sigma_0^2 I \qquad (4)$$

$$e_k=[1,e^{jw_k},e^{jw_k 2},...,e^{jw_k(M-1)}] \qquad (5)$$

In the equations σ_0^2 is the noise variance and I is the identity matrix. Equation (4) can be expressed in vector-matrix expression clearly [9].

$$\mathrm{R_x}=\mathrm{E}\Lambda\mathrm{E}^H+w^2\mathrm{I} \qquad (6)$$

$$\mathrm{E}=[\mathrm{e_1},\mathrm{e_2},...,\mathrm{e_K}] \qquad (7)$$

$$\Lambda=\begin{bmatrix} |A_1|^2 & & & & 0 \\ & |A_2|^2 & & & \vdots \\ & & \ddots & & \vdots \\ & & & |A_K|^2 & 0 \\ 0 & \cdots & \cdots & 0 & 0 \end{bmatrix}_{MxM} \qquad (8)$$

Autocorrelation matrix easily decomposes into signal and noise sub-spaces. This algebraic form is given in equation (9).

$$\mathrm{R}_x=\sum_{i=1}^{K}\left(\lambda_i+\sigma_w^2\right)\mathrm{u}_i\mathrm{u}_i^H+\sum_{i=K+1}^{M}\sigma_w^2\mathrm{u}_i\mathrm{u}_i^H \qquad (9)$$

The U matrice contains eigenvectors (u_i) which are given in equation (10) [10].

$$\mathrm{U_{signal}}=[\mathrm{u_1},...,\mathrm{u_K}]\ ,\ \mathrm{U_{noise}}=[\mathrm{u}_{K+1},...,\mathrm{u}_M] \qquad (10)$$

3. MUSIC ALGORITHM

MUSIC is a sub-space based algorithm which was developed by Schmidt [11]. Pisarenko found that the frequencies of the distorted signal could be derived from the eigenvector corresponding to the minimum eigenvalue of the autocorrelation matrix. Also the zeroes obtained from z transform of the eigenvectors corresponding to eigenvalues of the covariance matrice lays on the unit circle. Besides, the angles obtained according to zeroes locations are related to the frequency of the sinusoids [12]. In MUSIC algorithm averaging was proposed for improvement of the performance of Pisarenko estimator. The eigenvectors can be separated into two groups. The signal subspace is spanned by the most significant (maximum valued) eigenvectors and the noise subspace is spanned by the least significant (minimum valued) eigenvectors which represent the noise power [10]. The signal and noise eigenvalues are lined up in equation (11).

$$\lambda_1 \geq \lambda_2 \geq ... \geq \lambda_K \quad \geq \quad \lambda_{K+1} \geq ... \geq \lambda_M \qquad (11)$$

Instead of using only one noise eigenvector, the MUSIC algorithm uses many noise eigen-filters. The eigenvector matrix on the z plane with the eigen-filter form is given in equation (12). The number of roots of the every eigen-filter is M-1 and the roots of the eigen-filters represent the frequency. In the equation (12) *z=exp(jw)* is given.

$$\mathrm{U}_i(z) = \sum_{m=0}^{M-1} \mathrm{u}_i[\mathrm{m}]\mathrm{z}^{-\mathrm{m}}, \quad i = K+1,...,M \qquad (12)$$

Also pseudo-spectra expression for w_0 frequency values based on MUSIC can be generated [10].

$$\hat{P}\left(e^{jw0}\right) = \frac{1}{\sum_{k=K+1}^{M} \left| e(w_0)^H (u)_k \right|^2} \qquad (13)$$

And then the fundamental frequency estimation is obtained by using this expression.

$$\hat{w}_0 = \arg\max P(w_0), \quad \mathrm{w}_0 \in \Omega_0 \qquad (14)$$

4. SIMULATION RESULTS

Computer simulations were carried out for power system signal with white noise and harmonic distortion. Matlab mathematical tool is used for computer simulations. In power distribution systems it is very rare to face much frequency-deviated signals. So in our scenario simulations were carried out for 50 Hz regular power signal. The MUSIC algorithm is applied on the distorted voltage waveforms.

4.1. White Noise Distortion

In the first part of the study power system signal is corrupted with a zero-mean white Gaussian noise with variance σ^2. The power system signal and distorted power system signal is given in Figure 1.

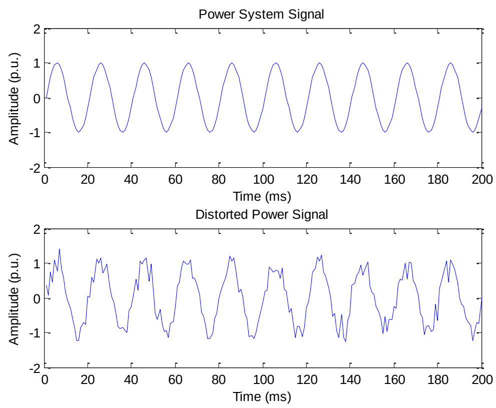

Figure 1. Distorted and undistorted power system signal

Frequency spectrum of the distorted signal is useful tool to analyze the estimation performance. The frequency spectrum is given in Figure 2.

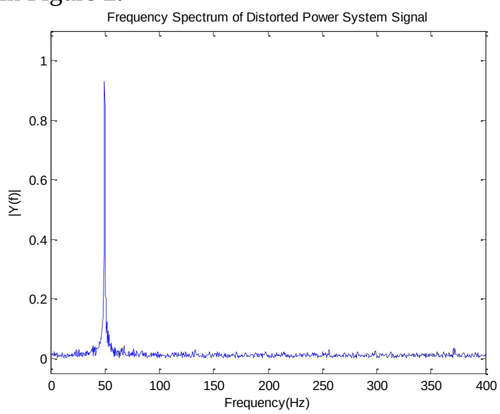

Figure 2. Power spectrum of distorted system signal

SNR is important parameter which defines the strength of the noise on the signal. Also estimation performance is strictly dependent on SNR. So the estimation performance of the MUSIC algorithm is analyzed according to SNR values. The frequency estimation performance of MUSIC algorithm for white noise distortion is given in Figure 3.

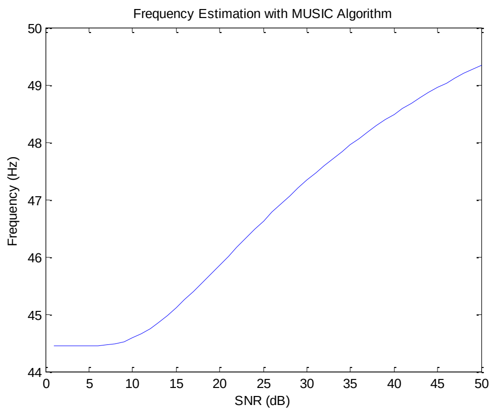

Figure 3. Frequency estimation with MUSIC algorithm for white noise distortion

4.2. Harmonic Distortion

In the second part of the study a 50 Hz pure sinusoidal signal with unity amplitude is corrupted with harmonic distortion [13]. The power system signal is subjected to 3rd, 5th and 7th harmonics. The 9th harmonic and the rest of the harmonics were ignored due to the insignificant distortion effects on the signal. The power system signal and distorted system signal is given in Figure 4.

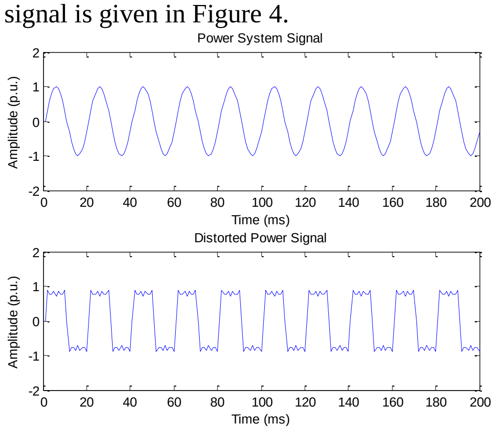

Figure 4. Distorted and undistorted power system signal

The frequency spectrum of distorted signal is given in Figure 5. The 3rd, 5th and 7th harmonics are clearly displayed in the frequency domain.

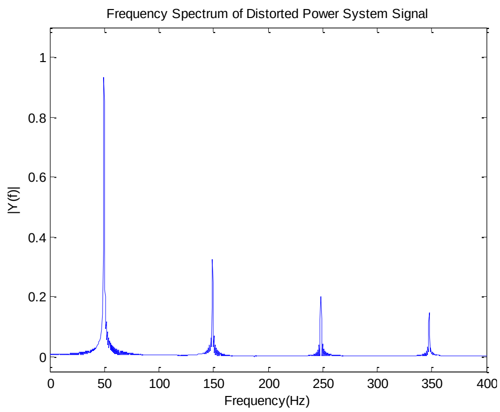

Figure 5. Power spectrum of distorted system signal

The frequency estimation performance of MUSIC algorithm for harmonic noise distortion is given in Figure 6.

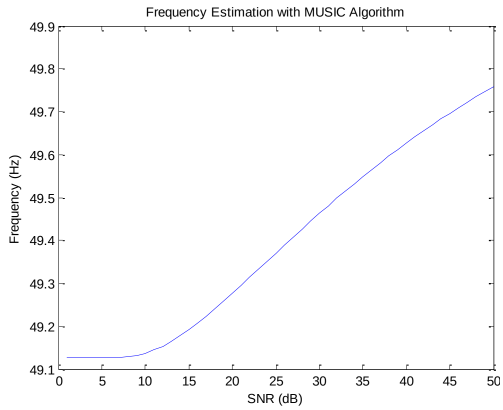

Figure 6. Frequency estimation with MUSIC algorithm for harmonic distortion

In order to analyze estimation performance of the MUSIC algorithm for white noise and harmonic distortion the estimation results for different SNR values are given in Table 1.

Table 1. Estimation performance comparison results for white and harmonic noise

SNR (dB)	MUSIC Estimation for white noise (Hz)	MUSIC Estimation for harmonic noise (Hz)
5	44,4396	49,1264
10	44,5815	49,1371
20	45,8569	49,2767
30	47,3353	49,4631
40	48,4900	49,6265
50	49,3447	49,7589

5. CONCLUSION

In this paper, MUSIC algorithm approach is proposed for frequency estimation of distorted signals in a power system. The MUSIC algorithm is an eigenvalue based sub-space decomposition method for estimation of the frequencies of complex sinusoids observed in distorted signals. In this study in order to simulate distortion of power system signal, the white noise and harmonic contamination is used. Estimation performance of the proposed method is quite satisfactory under acceptable SNR values. With the increasing SNR value, estimation performance of MUSIC algorithm for white noise and harmonic noise gets better but in the harmonic case MUSIC is more immune to SNR. Simulation results monitored that the performance of proposed algorithm under harmonic distortion is better than the one with the noise distortion. With the acceptable SNR values, proposed algorithm is suitable for real time applications where the noise and the harmonic disturbances displayed.

6. REFERENCES

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