A Modified ERA Algorithm for Mode Estimation in Power System

Angelica Wartina and Shekha Rai

1 Introduction

In power system, the main agenda is to convert mechanical form of energy to electrical form and route it to the consumer through a proper arrangement. The instability issues arise when there is an imbalance in power generation and power requirement. The rotor angle has to be maintained with adequate damping for maintaining stability. In energy management system, blackout might be a result of poorly damped oscillations [1]. So by identifying the critical modes, a proper controller can be designed which in turn improves the damping of the system. There are traditional methods for analysing modes which are based on Eigenvalue analysis [2]. But the conventional methods have limitations in determining the non-linear characteristics of the system.

With the deployment of wide area monitoring, a signal is transmitted from phasor data concentrator (PDC) to phasor measurement unit (PMU) through a transmission link in a phasor network. PMU has the ability to accomplish synchronized data with high precision on a global positioning system (GPS) [3] which facilitates real-time monitoring. The online mode estimation techniques used for low-frequency mode identification are fast Fourier transform (FFT) [4], Kalman filter [5, 6], ERA [7–9], Prony analysis [10, 11] and TLS-ESPRIT [12]. The FFT has the advantage of less computational complexity and also less sensitive to noise. But this technique has the drawback of resolution of frequency. Kalman filter has been applied in positioning of GPS; it is fast and efficient but has the limitation that it is only worthiness to linear system. The signal's frequency and attenuation factor can be directly calculated by Prony algorithm, but this method is sensitive to noise. TLS ESPRIT can withstand high variance Gaussian noise, and it can identify modes at different SNR.

A. Wartina (✉)
Department of Electrical Engineering, Jorhat Engineering College, Jorhat 785007, India

S. Rai
Department of Electrical Engineering, NIT Rourkela, Rourkela, Odisha 769008, India

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Because of network crowding and particular hardware issues, the data from PDC may not always transmit to PMU [13] within the specific time frame, and this is classified as missing values. The presence of missing values in PMU might be a reason for less precise results and may lead to biasness in mode estimations. To overcome these problems, an online mode estimation technique, i.e. a modified Eigen-system Realisation (ERA) algorithm, has been introduced in this paper to deal with the insufficient data. The effectiveness of the proposed ERA method has been compared with the other two algorithms like ERA and Prony. The rest of the paper is standardized as follows: Sect. 2 illustrates the proposed method, Sect. 3 describes online identification of proposed method; the simulation results have been discussed in Sect. 4, and finally, the conclusion is presented in Sect. 5.

2 Description of Proposed Modified ERA Algorithm

2.1 Eigensystem Realization Algorithm [7–9]

For a discrete system, the state-space representation can be considered as,

$$\boldsymbol{p}(r+1) = \boldsymbol{A}\boldsymbol{p}(r) + \boldsymbol{B}\boldsymbol{u}(r) \tag{1}$$

$$\boldsymbol{q}(r) = \boldsymbol{C}\boldsymbol{p}(r) + \boldsymbol{D}\boldsymbol{u}(r) \tag{2}$$

where $\boldsymbol{p}(r)$ is the state vector, $\boldsymbol{u}$ is the system input, r is the step size; $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$, $\boldsymbol{D}$ are the matrices for discrete-time-state-space. To achieve a state-space representation the Eigensystem, realisation algorithm approaches the minimum realisation principle and only the smallest number of states are taken. The matrix $\boldsymbol{A}$'s Eigenvalues are complex conjugate, and it is used to determine the damping and natural frequency. Matrix $\boldsymbol{A}$ gives the modal parameter of the system. The steps to apply ERA are,

Step1: The first and foremost step is to form the Hankel matrix.

$$\boldsymbol{H}(r) = \begin{bmatrix} \boldsymbol{q}(r+1) & \boldsymbol{q}(r+2) & \cdots & \boldsymbol{q}(r+m) \\ \boldsymbol{q}(r+2) & \boldsymbol{q}(r+3) & & \boldsymbol{q}(r+m+1) \\ \vdots & & \ddots & \vdots \\ \boldsymbol{q}(r+n) & \boldsymbol{q}(r+n+1) & \cdots & \boldsymbol{q}(r+m+n) \end{bmatrix} \tag{3}$$

Here, $n \times n$ and m are the number of rows and columns of Hankel matrix.

Step2: The singular value decomposition of the Hankel matrix $\boldsymbol{H}(r)$ at $r = 0$ has to be performed.

$$\boldsymbol{H}(0) = \boldsymbol{R} \sum \boldsymbol{S}^{T} \tag{4}$$

Here, $\boldsymbol{R}$ and $\boldsymbol{S}$ are the orthonormal matrices of order $m \times m$ and $n \times n$, respectively. The $\sum$ is the $m \times n$ matrix whose diagonal has non-negative values.

In ideal case,

$$\sum = \begin{bmatrix} \sum_s & 0 \\ 0 & 0 \end{bmatrix} \tag{5}$$

$\sum_s$ is the matrix of order $s \times s$, s is the order of the system.

The matrix $\boldsymbol{A}$ can be calculated as

$$\boldsymbol{A} = \sum^{-\frac{1}{2}} \boldsymbol{R}^T \boldsymbol{H}(1) \boldsymbol{S} \sum^{-\frac{1}{2}} \tag{6}$$

2.2 *Improved ERA with Non-linear Filter*

ERA algorithm involves the formation of Hankel matrix which may contain missing values and lead to bias in the estimation. Thus, to preserve the non-linear characteristics, data restoration using a probable value in place of missing measurement is highly essential. This paper imputes the missing data by using a non-linear filtering process. At first, the median of the non-missing entries in a column are determined and then the missing values are replaced within each column separately as described below [14].

If $\boldsymbol{x}(n)$ is a vector of values

$$\boldsymbol{x}(n) = \{x(n), x(n-1), \ldots x(n-m)\}^T \tag{7}$$

The median filter output $y(n)$ can be obtained by middle value from the particular collection of elements of vector $\boldsymbol{x}(n)$.

$$y(n) = \text{med}\{x(i)\}, \text{where } i = n, n-1, \ldots, n-M \tag{8}$$

where M + 1 is taken as an odd number and is termed as the length of the median filter. The Hankel matrix, thus, obtained via the filtering process is free from missing measurements.

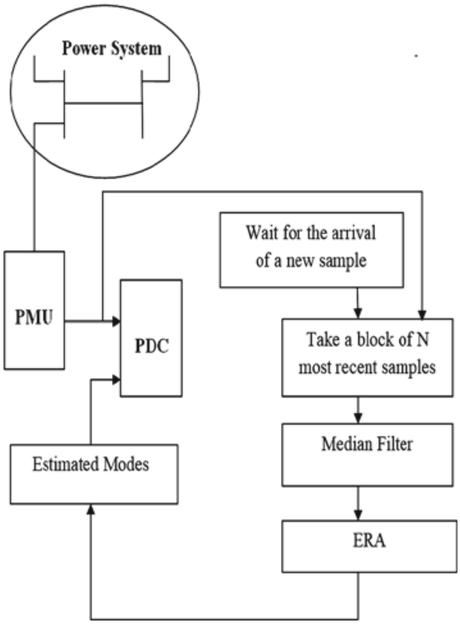


Fig. 1 Block diagram of online detection of modes for proposed modified ERA

3 Online Identifications of Modes Using Proposed Modified ERA

Figure 1 represents the general block diagram of the proposed method which is used for online detection of oscillatory modes. There is a wired link between phasor measurement unit (PMU) and phasor data concentrator (PDC), and through this link, the power signal has been transferred from PMU to PDC. The power signals that have been received from PDC can estimate the critical modes. These critical modes occur because of the imbalance between power generation and power requirement. As there are some incomplete data present in PMU, this may lead to some unwanted results. So to minimise this incomplete measurement issues, modified ERA algorithm has been anticipated. In Fig. 1, a block of N most recent samples has been retained. Then Hankel matrix **A** has been formed. In the formation of Hankel matrix, there are some particular missing data. So, to deal with these incomplete data, a non-linear median filter has been introduced. The output of the median filter is fed into the ERA algorithm for obtaining modal parameters.

4 Simulation Result

Two test signals with known damping and frequency are taken for local mode as well as for inter-area mode for the comparison of performance of the proposed modified

ERA algorithm with different methods such as ERA and Prony. The different methods are estimated by simulating 20,000 Monte Carlo cycles at some particular SNR values. For the accomplishment of simulation of the two test signals, a sample window of 250 samples and a sampling frequency equal to 12.5 Hz are used. Later, to establish the effectiveness of the proposed scheme, actual PMU signal attained from WECC system is also tested.

4.1 Test Signal Interrelated to Local Mode

Comparison of the proposed method, i.e. Modified ERA with ERA and Prony algorithm

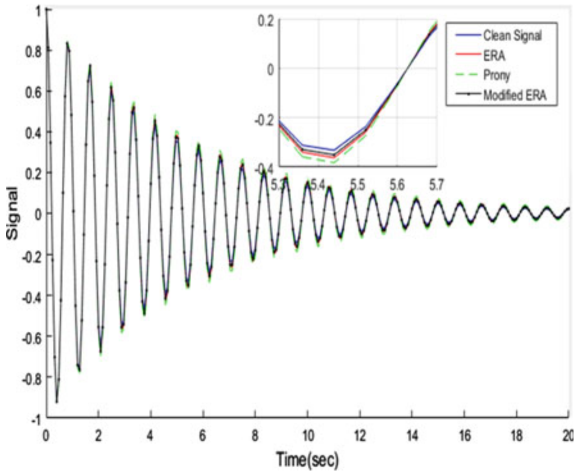
The simulation results that have been provided in Table1 show the mean and variance of the attenuation factor and frequency for local modes. For local modes, the attenuation factor has been considered as −0.20. At 50 dB SNR, the attenuation factor of ERA, Prony and modified ERA are −0.1839, −0.1740 and 0.1901, respectively. So, in percentage, the experimented value of ERA deviates 8.05% from the actual value, and for Prony, it is deviated 13% from the true value, whereas for modified ERA, it is 4.95% deviation from the considered value. And also, at SNR 40, 30 and 20,

Table 1 Mean and variance for the ERA, Prony and proposed modified ERA at particular SNR values

SNR	Modes		ERA	Prony	Modified ERA
50 dB	d	μ	−0.1839	−0.1740	−0.1901
		σ^2	1.1787×10^{-08}	1.0277×10^{-07}	1.2273×10^{-08}
	f	μ	1.2000	1.2000	1.2000
		σ^2	1.7391×10^{-10}	6.0017×10^{-10}	1.7842×10^{-10}
40 dB	d	μ	−0.1839	−0.1742	−0.1901
		σ^2	1.1833×10^{-07}	1.0120×10^{-06}	1.2286×10^{-07}
	f	μ	1.2000	1.2000	1.2000
		σ^2	1.7251×10^{-09}	5.8569×10^{-09}	1.7650×10^{-09}
30 dB	d	μ	−0.1839	−0.1758	−0.1901
		σ^2	1.1816×10^{-06}	9.2751×10^{-06}	1.2360×10^{-06}
	f	μ	1.2000	1.2000	1.2000
		σ^2	1.7271×10^{-08}	5.7858×10^{-08}	1.7571×10^{-08}
20 dB	d	μ	−0.1840	−0.1817	−0.1903
		σ^2	1.1789×10^{-05}	4.6895×10^{-05}	1.7571×10^{-05}
	f	μ	1.2000	1.2000	1.2000
		σ^2	1.7466×10^{-07}	5.4812×10^{-07}	1.8196×10^{-07}

True Values: damping, $d = -0.2$ frequency, $f = 1.2$ Hz

Fig. 2 Signal reconstructed using different methods



the proposed method gives more nearby value than that of the other two algorithms. For higher SNR, the variance is less and for lower SNR, it is more. The frequency has been considered as 1.2 Hz for local mode. The ERA, Prony and modified ERA give comparative results at all taken SNR values.

The signals reconstructed using these methods are shown in Fig. 2. It is seen that the signal obtained from proposed scheme almost matches with the clean signal, while the other schemes deviate (Fig. 3).

Graphs

4.2 Test Signal Interrelated to Inter-Area Mode

For the inter-area mode, the signal with attenuation factor has been considered as −0.06 and the frequency 0.6 Hz and corrupted with missing values are taken for the calculation.

Comparison of the Proposed modified ERA algorithm with ERA and Prony algorithm:

For three of the methods, the mean and variance of the attenuation factor and frequency for inter-area modes at particular SNR are provided in Table 2.

In inter-area mode, the true value of attenuation factor is −0.06. At SNR 50 dB, the attenuation factor of ERA, Prony and modified ERA are −0.0617, −0.0580 and −0.0597, respectively. For attenuation factor estimation, the proposed algorithm gives more accurate results than that of ERA and Prony. In percentage, the attenuation factor of ERA is deviated −2.83% from the true value, and for Prony, it is deviated 3.33% from the actual value. And in case of proposed modified ERA, it is just 0.5% deviated from the actual value.

Fig. 3 Damping plots for SNR different SNR for ERA, prony and modified ERA

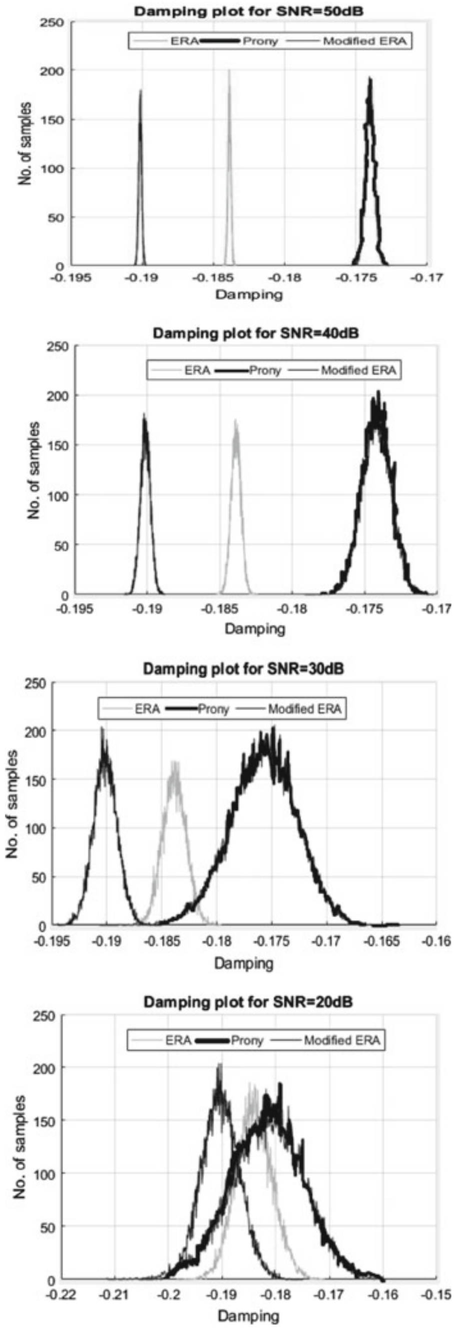


Table 2 Mean and variance for the ERA, Prony and proposed modified ERA at particular SNR values

SNR (dB)	Modes		ERA	Prony	Modified ERA
50	d	μ	−0.0617	−0.0580	−0.0597
		σ^2	2.1898×10^{-8}	9.7310×10^{-8}	2.6508×10^{-8}
	f	μ	0.5948	0.6001	0.5999
		σ^2	1.0424×10^{-9}	2.0193×10^{-8}	7.5456×10^{-10}
40	d	μ	−0.0617	−0.0399	−0.0597
		σ^2	2.1692×10^{-7}	6.7420×10^{-6}	2.6889×10^{-7}
	f	μ	0.5948	0.6006	0.5999
		σ^2	1.0298×10^{-8}	2.0235×10^{-7}	7.6769×10^{-9}
30	d	μ	−0.0617	0.1395	−0.0597
		σ^2	2.1697×10^{-6}	6.3724×10^{-4}	2.6631×10^{-6}
	f	μ	0.5948	0.6051	0.5999
		σ^2	1.0361×10^{-7}	2.1693×10^{-6}	7.5489×10^{-8}
20	d	μ	−0.0617	1.8457	−0.0597
		σ^2	2.1783×10^{-5}	0.0570	2.6578×10^{-5}
	f	μ	0.5948	0.5843	0.5951
		σ^2	1.0322×10^{-6}	1.9390×10^{-4}	7.5923×10^{-7}

True Values: damping, $d = -0.06$, frequency, $f = 0.6$ Hz.

And at SNR = 30 as well as at SNR = 20, the attenuation factor of ERA and modified ERA are −0.0617 and −0.0597, respectively, and the Prony algorithm shows positive results.

The distribution of damping for various methods at different SNR is shown in Fig. 4. It is seen that the proposed estimator gives better mean value with less variance in comparison with the other conventional schemes.

The frequency has been considered as 0.6 Hz for inter-area mode. The ERA, Prony and modified ERA give comparative results at all taken SNR values.

Graphs

4.3 *Mode Estimation of WECC with Practical Data for ERA, Prony and Proposed Modified ERA*

To analyse the performance of the proposed modified ERA, ERA and Prony algorithm, they are all evaluated with practical data from phase measurement unit which is in WECC [15, 16] as in Fig. 5. The data which is used for analysis by various methods is listed in Table 3 [3]. For window 1, the ERA gives 9.17%, the Prony

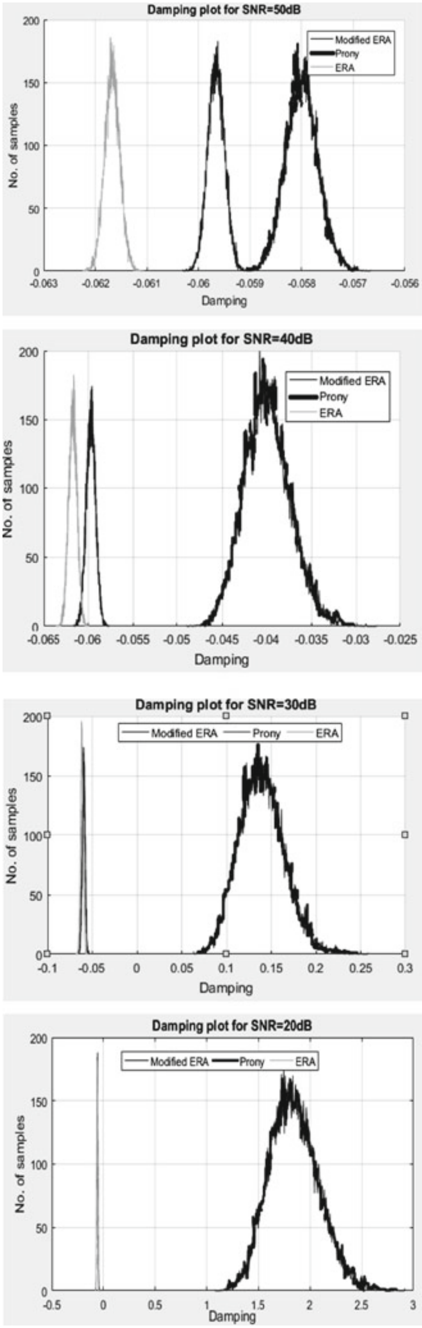


Fig. 4 Damping plots for SNR different SNR for ERA, Prony and modified ERA

Fig. 5 Probing data of WECC

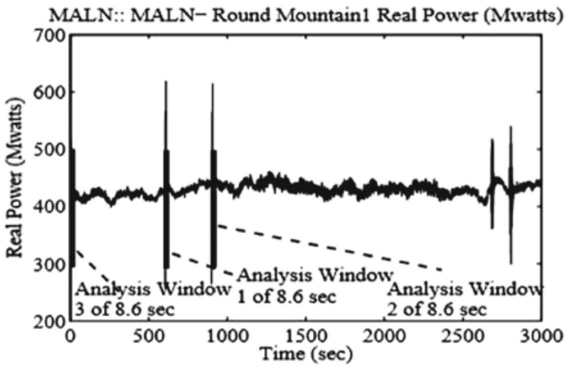


Table 3 Mean and variance for the ERA, Prony and proposed modified ERA at particular SNR values

Wind-ow	Mode	ERA	Prony	Modified ERA
1	Damp	−0.1917	−0.1938	−0.1650
	fr	0.3312	0.3301	0.3287
	% damp	9.17	9.304	7.96
2	damp	−0.2140	−0.1190	−0.1951
	fr	0.3102	0.3162	0.3107
	% damp	10.912	5.982	9.945
3	damp	−0.0568	0.1062	−0.0622
	fr	0.3038	0.3074	0.3019
	% damp	2.976	−5.48	3.275

estimates as 9.304% from the practical value, whereas the proposed modified ERA has 7.96% damping which is closer to real value (8.3% damping).

For window 2, the proposed method gives better modal estimates than the other two considered algorithms. The proposed scheme provides superior damping (3.275%) estimate than ERA (2.976%) and Prony (−5.48%).

5 Conclusion

This paper proposes a modified ERA estimator to deals with incomplete PMU measurements using a non-linear filter for the detection of critical modes for low-frequency oscillations in power system. A comparative study has been done among the algorithms, such as Prony and ERA. From the results, it can be concluded that the modified ERA method gives better performance as the other estimators do not account for the missing PMU measurements. Thereby, this algorithm can be implemented for real-time applications in power systems.

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