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A Novel ESPRIT Algorithm for Analysis of Low Frequency Oscillations in Power System

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Abstract- With rapidly increasing load and randomly varying load scenarios in a densely connected power system may lead to low-frequency oscillations which can further make a power system unstable. To keep the power system in stable operating limits identifying such dominant low-frequency oscillations is essential. Numerous signal processing techniques are used to detect low-frequency oscillations in a power system. Different techniques have their advantages and disadvantages. Estimation of signal parameters via rotational invariance technique (ESPRIT) is a signal processing technique by which low-frequency oscillations can be identified even under noisy conditions. In this paper, a novel ESPRIT algorithm for identifying low-frequency oscillations is proposed. This methodology is based on the ESPRIT algorithm, whose key concept is that real modes existing in oscillations emerge consistently regardless of the algorithm's order. The performance of this algorithm is verified through a set of synthetic signals generated in MATLAB with different noise levels and varying PMU rates and compared with the traditional Prony algorithm. The performance of the proposed algorithm is also verified on real-time test data obtained from the Western Electricity Coordinating Council (WECC). This technique performs fairly well in finding low-frequency oscillation characteristics in the power grid.

Keywords Attenuation factor, Damping ratio, Low-frequency oscillations, Power system, Synthetic signal.

1. Introduction

Today's power grids are strongly integrated to effectively share the growing demand of the load. These interconnected complex networks provide several issues for power system engineers, including monitoring and diagnosing low frequency oscillations that are not well damped [1–2]. The world's third largest power producer and consumer is India and was seriously impacted by the cascading blackout in 2012 dated 30 July and 31 July, affecting almost 620 million people across nearly eighteen nation states and becoming one of the major energy outages compared to the previous one in 2001 with nearly 230 million people. At 02.35 IST, the Circuit Breaker was disconnected from the Bina-Gwalior 400 kV line, the fault extended to the Agra-Bareilly transmission segment, and the breakdown was cascaded through the grid, this is a real time example of the issue faced due to stability concern. The capacity of the power system to maintain synchronism in the event of minor disturbances is referred to as small signal stability. Modal analysis is typically used to analyze the small-signal stability of the power system as a useful method for studying nonlinear dynamic systems. At a particular operating point, the modal analysis will linearize the nonlinear differential-algebraic equations (DAE) of the system [3–5]. The eigenvalues obtained from the state matrix of the linearized model provide information about parameters of low-frequency oscillatory mode. Through model-based techniques, dynamic characteristics of the power system can be obtained around a certain point of operation. However, as the operating point of the power system is continuously changing due to generation demand fluctuations and system contingencies, it is challenging to develop an accurate model of the power system with accurate parameters. Due to the drawbacks described above, the applicability of such model-based techniques is limited to off-line analysis of small signal stability, in present days various signal processing based techniques are employed in the real-time power system to overcome the drawback of modal analysis [6].

Electromechanical oscillations occur during the operation of a power system between the synchronous generators that are interconnected with each other. For secure and reliable system operation stability of oscillations is very essential. When a large system is connected through weak tie lines, low-frequency oscillations occur, resulting in unstable behaviour. Low-frequency oscillations occur when a set of generators or generating plants on one side of the tie-line oscillates against generators on the other side. The local modes of oscillations have a frequency range from 0.7Hz to 2.0 Hz and are due to a single generator or plant whereas inter-area modes have a frequency from 0.1Hz to 0.8 Hz and involve a group of generators [7–8]. Instability can occur, and sometimes the system collapse, if the oscillations are not damped sufficiently. As a result, it is critical to monitor and identify any low-frequency oscillations in the system on a continuous basis. In the past, various researchers used many signal processing methods to identify low-frequency modes [9–10]. In the literature, a variety of measurement-based approaches have been suggested and applied in practice because of the rapid growth and large implementations of the Phasor measurement units (PMUs). The dominant mode of oscillations in power systems can be calculated by such approaches directly from PMU data [6, 9].

The PMU is the fundamental component of the Wide Area Measurement System (WAMS). At a rate of multiple samples per second, the PMU offers dynamic time-stamped measurements of the system state, namely voltage, current, and angle, at a particular location. Furthermore, these collected PMU data are sent to the control office through a communication channel and the complex behaviour of the system can be obtained. Parameters like frequency and damping, which define the system's electromechanical modes are estimated and provided to the system's operator so that unstable oscillations can be monitored if any occurring in the system and necessary protective action can be initiated [11–13]. Due to the rapid development of WAMS, many measurement-based approaches for detecting low-frequency oscillations in the power grid are previously employed ex. Prony analysis, Fast Fourier transform, Matrix pencil, ESPRIT, etc [14–19]. As per the literature survey, among the several existing signal processing techniques, the Prony algorithm is the most reliable, easy to implement and also widely accepted algorithm for low frequency oscillation analysis in real time applications, so in this research paper, the Prony algorithm is compared for performance with the proposed novel ESPRIT algorithm. There are several shortcomings with these techniques, the major drawback is that it requires exact model order estimation for accurate estimation of parameters and these algorithms are very sensitive to noise [14, 20].

Various authors in the past have remarkably improved the accuracy of the algorithm but still, improvement is required. The shortcomings with other algorithms also include their sensitivity towards noise and if the modes corresponding to low-frequency signals are closely spaced with respect to their frequency component the algorithm may give inaccurate results. Similarly, if the algorithm which requires pre-model order estimation and if the model order isn't exact and accurate it will result in fictitious modes which are not part of the signal[16, 21–24]. Various controllers are designed to improve the stability and dynamic performance parameters like settling time, overshoot as given in [27-31], but it is beyond the scope of this research work.

ESPRIT method first split the auto-correlation matrix into noise and signal subspaces and then from signal subspace modes are identified. It can distinguish among closely spaced modes and even has improved efficiency in the presence of noise, although one of the prerequisites for this algorithm is the reliable model order estimation that has been solved in this research[1, 15, 18, 25]. In this research, efforts have been made to improve an ESPRIT algorithm to avoid the disadvantages of determining model order and to produce reliable results for characterizing low-frequency oscillations in the power system. The novel algorithm is also verified through a set of synthetic signals generated in MATLAB with varying sampling rates and different noise levels. The novel algorithm also provides an accurate and precise result for real-time signal obtained from the WECC system. The remaining part of the paper is divided into the following sections. The novel ESPRIT-based algorithm is described in Section 2, results and discussion for synthetic and real-time signal are provided in Section 3, and the conclusion is given in Section 4.

2. Proposed ESPRIT Algorithm for low-frequency oscillation parameters

In this section novel ESPRIT method is presented for identifying parameters of low-frequency oscillations (inter-area) in the power system. ESPRIT is a technique of signal processing that breaks down complex signals to the number of sinusoids using a sub-space approach. The mathematical equation can be written as

$$\mathrm{x}(t) = \sum_{i=1}^{\mathrm{n}} \left(a_{\mathrm{i}} \cos 2\pi f_{\mathrm{i}} t + \phi_i \right) + w_t \quad (1)$$

The signal x (t) is to be decomposed here. It is assumed that signal x (t) is acquired from several PMUs positioned across the power system. Here in the above equation (1) f_i represents frequency and ϕ_i is the phase of damped sinusoid for the identification of inter-area modes. w_t represents white Gaussian noise.

Mathematical details for the ESPRIT method are elaborated in section 2.2 in [1]. The novel concept described in this paper is that the proposed ESPRIT method is independent of model order estimation. The proposed algorithm is based on the observation that, regardless of the algorithm's model order, the signal's dominant modes, which are characteristics of the power system, occur consistently. The dominant modes are then extracted through a special filtering process. The results obtained through simulation for real-time and synthetic signal proves that the proposed novel algorithm is capable of identifying the parameter of low-frequency oscillations in the power system. The procedure for the novel ESPRIT method is summarized as follows:

(i) Initialize sampling rate and main window length. The main window length is 18 sec as it provides modes for all ranges of frequency and damping ratio corresponding to low-frequency oscillations.

(ii)In the second step, two sub-windows with lengths 16 and 14 sec are considered and the sampling rate is kept constant.

(iii) Apply the ESPRIT algorithm to each of the above-mentioned cases separately and sort only the frequency components with a frequency less than 2 Hz.

(iv) As the true modes will be present in all the main and sub-window analyses whatever is the order of the ESPRIT algorithm and it will be finally sorted through a filtering process described below.

In order to filter out true modes present in the signal, the distance between modes in a complex plane is compared as given in [20]. The proposed algorithm can identify true modes but there will exist fictitious modes along with true modes in the ESPRIT algorithm so in order to identify true modes it is required to filter out only true modes which is done through the threshold technique given below, this threshold technique finally provides only true modes of the signal. Assume that p_1, p_2, and p_3 are the numbers of modes identified by the ESPRIT algorithm by three windows as explained in the above section then true modes can be identified as follows:

If

$$\sqrt{(f_a-f_b)^2+(f_b-f_c)^2+(f_a-f_c)^2+(\sigma_a-\sigma_b)^2+(\sigma_b-\sigma_c)^2+(\sigma_a-\sigma_c)^2} \le \beta \quad (2)$$

a = 1, 2…….p_1

b = 1, 2…….p_2

c = 1, 2…….p_3

$$f = \frac{f_a + f_b + f_c}{3} \quad (3)$$

$$\sigma = \frac{\sigma_a + \sigma_b + \sigma_c}{3} \quad (4)$$

where β is the threshold to filter true modes, in this research paper β is assigned as 0.05. *f* and σ denote the frequency and attenuation factor of true modes to be identified.

True modes for low-frequency oscillations existing in the power system at various noise levels can be identified using the filtering process and the ESPRIT algorithm in combination, as detailed in the next section. A low pass filter is also employed to eliminate the effect of measurement noise on mode estimation.

3. Results and Discussion

To evaluate the proposed algorithm's performance, a set of simulated signals with varying noise levels and PMU reporting rates (sampling rates) is analyzed. The simulation is run for 50 trials and the average value calculated of parameters is shown in the analysis.

Considering synthetic signal as given by equaiton (5):

$$x_1(t) = cos(2\pi * 0.3t)\, e^{-0.2t} + cos(2\pi * 0.6t)\, e^{-0.4t} \quad (5)$$

The signal $x_1(t)$ is a two-mode synthetic signal with true values of frequency as 0.3 and 0.6 Hz, the attenuation factor of 0.2 and 0.4, the damping ratio is 10.61% for both the modes. The signal is analyzed through a novel ESPRIT and Prony algorithm with different levels of white Gaussian noise with SNR 20dB, 30dB, and 40 dB respectively. The sampling rate is 60 samples per second.

Table 1. Analysis of signal $x_1(t)$ with varying noise level

Method	Noise (SNR)	40dB	30dB	20dB
Novel ESPRIT Algorithm	Estimated Frequency (Hz)	0.301	0.299	0.290
		0.600	0.598	0.589
	Attenuation factor	0.195	0.195	0.190
		0.400	0.395	0.390
	Damping ratio (%)	10.31	10.38	10.43
		10.61	10.51	10.54
	Absolute percentage error in damping ratio	2.82%	2.17%	1.70%
		0%	0.94%	0.66%
Prony Algorithm	Estimated Frequency (Hz)	0.297	0.285	0.250
		0.610	0.575	0.575
	Attenuation factor	0.185	0.170	0.215
		0.410	0.380	0.370
	Damping ratio (%)	9.91	9.49	13.68
		10.61	10.51	10.24
	Absolute percentage error in damping ratio	6.60%	10.56%	28.93%
		0%	0.94%	3.48%

From the analysis of signal $x_1(t)$, it is very noticeable that the algorithm being proposed can estimate modes for the synthetic signal even if modes are spaced far apart from each other with respect to the frequency component present in it with the different noise levels up to 20dB, whereas the Prony algorithm isn't identifying the modes accurately. The plot of synthetic signal with the noise level of 20dB and estimated signal obtained by the proposed algorithm indicates how closely the proposed algorithm can estimate the original synthetic signal as shown in Fig.1

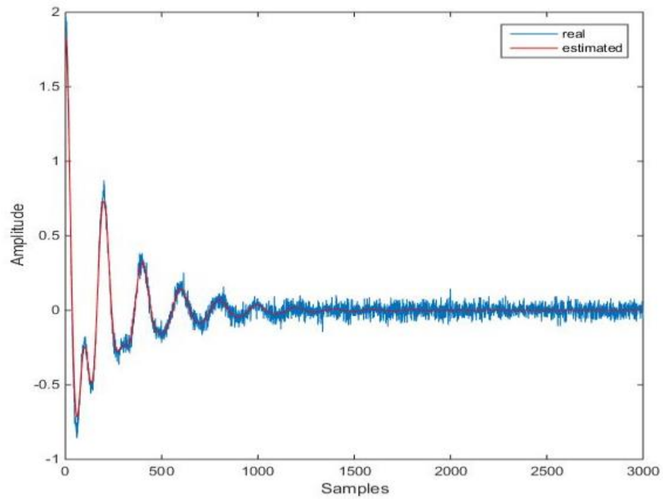

Fig. 1. Real and estimated signal $x_1(t)$ by a novel ESPRIT algorithm for 20dB noise

Now considering the second synthetic signal as given by the given equation (6) :

$$x_2(t) = cos(2\pi * 0.6t)\, e^{-0.3t} + cos(2\pi * 0.8t)\, e^{-0.2t} \quad (6)$$

The signal given by equation (6) is a two-mode synthetic signal with true values of frequency as 0.6 and 0.8 Hz, attenuation factor as 0.3 and 0.2, the damping ratio is 7.95% and 3.97% respectively. The signal is analyzed through a novel ESPRIT and Prony algorithm with different levels of white Gaussian noise with SNR 20dB, 30dB, and 40 dB respectively.

From the analysis of signal $x_2(t)$, it is very noticeable that the algorithm being proposed can estimate modes for the synthetic signal even if modes are closely spaced to each other with respect to the frequency component present in it with the different noise levels up to 20dB, whereas the Prony algorithm isn't even able to identify true modes in presence of higher noise level. Fig. 2 is the plot of the synthetic signal with noise level 20dB and the estimated signal obtained by the proposed algorithm verifies how closely the proposed algorithm can estimate the original synthetic signal.

Table 2. Analysis of signal $x_2(t)$ with varying noise level

Method	Noise(SNR)	40dB	30dB	20dB
Novel ESPRIT Algorithm	Estimated Frequency (Hz)	0.601	0.603	0.605
		0.799	0.795	0.789
	Attenuation factor	0.300	0.292	0.305
		0.200	0.195	0.191
	Damping ratio (%)	7.94	7.70	8.02
		3.98	3.90	3.85
	Absolute percentage error in damping ratio	0.12%	3.14%	0.89%
		0.25%	1.76%	3.02%
Prony Algorithm	Estimated Frequency (Hz)	0.615	0.620	Not able to identify true modes
		0.775	0.831	
	Attenuation factor	0.290	0.275	
		0.180	0.167	
	Damping ratio (%)	7.50	7.05	
		3.69	3.19	
	Absolute percentage error in damping ratio	5.67%	11.32%	
		7.05%	19.65%	

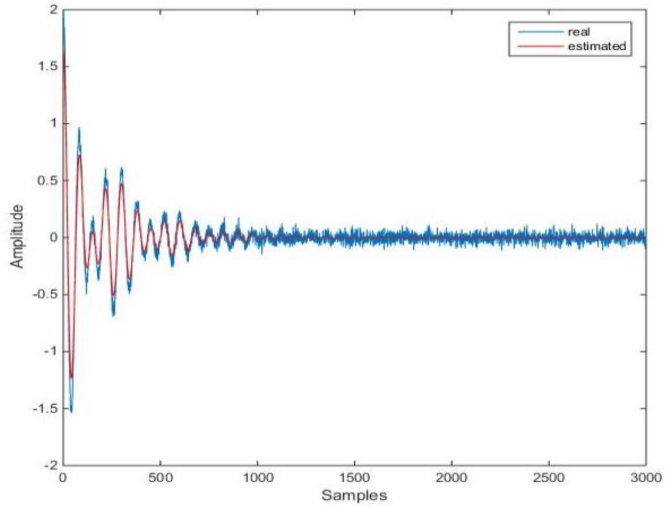

Fig. 2. Real and estimated signal $x_2(t)$ by a novel ESPRIT algorithm for 20dB noise

Now considering the third synthetic signal as given by the equation (7):

$$x_3(t) = cos(2\pi * 0.25t)\, e^{-0.1199t} + cos(2\pi 0.5t)\, e^{-0.1596t} + cos(2\pi * 0.8t)\, e^{-0.1102t} \quad (7)$$

The signal given by equation (7) is a three-mode synthetic signal with actual values of frequency as 0.25Hz, 0.5Hz, and 0.8 Hz, attenuation factor of 0.1199,0.1596 and 0.1102, the damping ratio is 7.63%,5.08%, and 2.19% respectively. The signal is analyzed through a novel ESPRIT and Prony algorithm with different levels of white Gaussian noise with SNR 20dB, 30dB, and 40 dB respectively.

Table 3. Analysis of signal $x_3(t)$ with varying noise level

Method	Noise (SNR)	40dB	30dB	20dB
Novel ESPRIT Algorithm	Estimated Frequency (Hz)	0.251	0.249	0.245
		0.500	0.495	0.489
		0.799	0.805	0.791
	Attenuation factor	0.1199	0.1180	0.1185
		0.1596	0.1589	0.1585
		0.1102	0.1105	0.1110
	Damping ratio (%)	7.60	7.54	7.69
		5.08	5.11	5.16
		2.19	2.18	2.23
	Absolute percentage error in damping ratio	0.34%	1.18%	0.78%
		0%	0.60%	1.57%
		0%	0.455	1.82%
Prony Algorithm	Estimated Frequency (Hz)	0.245	0.220	Not able to identify true modes
		0.477	0.575	
		0.767	0.671	
	Attenuation factor	0.1055	0.1010	
		0.1767	0.1677	
		0.1278	0.1373	
	Damping ratio (%)	6.85	7.30	
		5.89	4.64	

Method	Noise (SNR)	40dB	30dB	20dB
		2.65	3.25	
	Absolute percentage error in damping ratio	10.22%	4.32%	
		15.94%	8.66%	
		21%	48.40%	

From the analysis of signal $x_3(t)$, it can be concluded that the novel ESPRIT algorithm can estimate correct modes for a synthetic signal having three frequency components ranging from 0.25 to 0.8Hz and provide better results even under noisy conditions, whereas the Prony algorithm isn't even able to identify true modes in presence of higher noise level. Fig. 3 is the plot of synthetic signal with three modes for the noise level of 30dB and the estimated signal obtained by the proposed algorithm also verifies how closely the proposed algorithm can estimate the original synthetic signal.

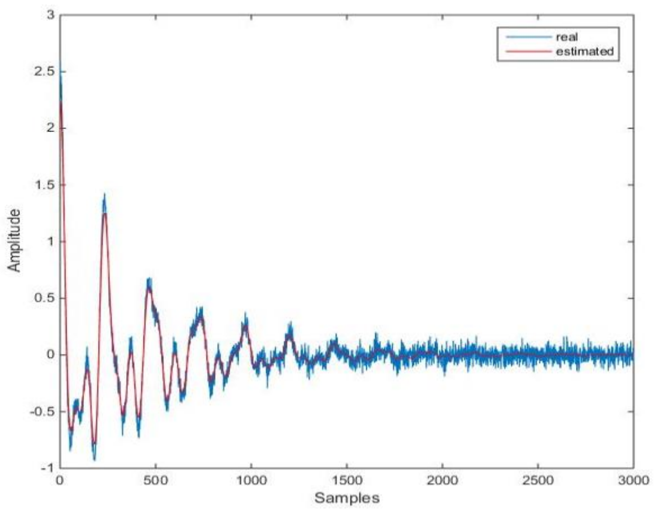

Fig. 3. Real and estimated signal $x_3(t)$ by a novel ESPRIT algorithm for 20dB noise

For all the above analyses of synthetic signals $x_1(t)$, $x_2(t)$, and $x_3(t)$ the percentage error in damping ratio for the proposed algorithm is less than 5% whereas for the Prony algorithm it exceeds above 10%. Hence the proposed algorithm has better performance in terms of accuracy as seen in the above analysis for different synthetic signals.

In a practical system, the PMU may have reporting rates from 10 Hz to 100Hz. So simulation is carried out with varying PMU rates for synthetic signal $x_2(t)$ and the noise level is set to 30dB. The signal $x_2(t)$ is considered which has true values of frequency as 0.6 and 0.8 Hz, attenuation factor as 0.3 and 0.2, the damping ratio is 7.95% and 3.97% respectively. From the analysis given in Table 4, it can be concluded that the novel ESPRIT algorithm can estimate low-frequency oscillations parameters i.e., damping ratio and frequency of the synthetic signal accurately irrespective of the PMU reporting rate which means that the proposed algorithm can identify true modes for varying PMU reporting rates in presence of noise.

Table 4. Analysis of signal $x_2(t)$ with varying PMU rate by novel ESPRIT algorithm

PMU Reporting Rate (Hz)	Estimated Frequency (Hz)	Attenuation factor	Damping ratio (%)
30	0.600	0.300	7.96
	0.799	0.200	3.98
50	0.601	0.295	7.81
	0.797	0.195	3.89
70	0.595	0.291	7.78
	0.791	0.190	3.82

In the next part of the analysis, two performance indices are defined i.e. α1–number of trails in which algorithm determines all true modes, α2–number of trails in which algorithm determines only one true mode present in the signal, and the analysis is done for signal $x_2(t)$ as given in the following table for 50 trials with an accuracy of ±5% with respect to true modes of the signal.

Table 5. True modes identification of signal $x_2(t)$ for multiple trials by novel ESPRIT algorithm

Method	Noise(SNR)	α1	α2
Novel ESPRIT Algorithm	40dB	50	0
	30dB	50	0
	20dB	47	1
Prony Algorithm	40dB	45	5
	30dB	35	7
	20dB	7	3

From the analysis of Table 5, it is very clear that the proposed novel ESPRIT algorithm accurately tracks true modes for more number of trails in presence of noise whereas the Prony algorithm isn't capable of identifying the true modes for different trials, which means the proposed algorithm performance is not affected due to random nature of noise.

The proposed novel ESPRIT method is validated using probe testing data collected on 14th September 2005 from the WECC system. Two main windows as shown in Fig. 4 are used for analysis. Main window 1 corresponds to data obtained after probing of ± 125MW, a single-mode is observed with a frequency of 0.318 Hz and 8.3% damping as reported in [1, 26]. Similarly, main window 2 corresponds to probing of ± 125MW and a single-mode is observed with a frequency of 0.315 Hz and 7.88% damping. To verify the performance of the algorithm with noise, white Gaussian noise is added with SNR as 30dB. Amplitude corresponds to real power flow with time. The results obtained by the proposed novel ESPRIT algorithm are shown in Table 6.

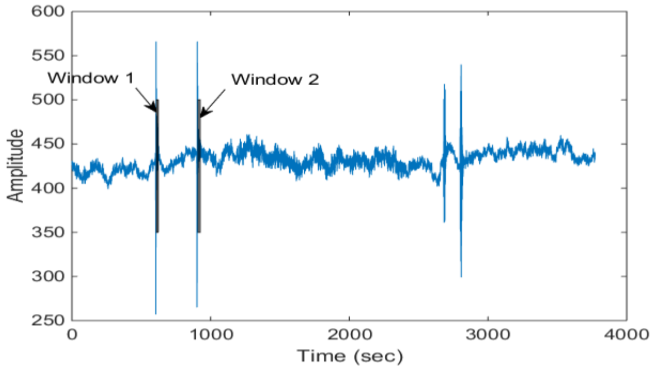

Fig. 4. Test probe data of WECC system on 14th September 2005 with consideration of two windows to be analyzed [1]

From the analysis, it can be concluded that the proposed novel ESPRIT algorithm provides almost the same modes as reported in [26] for both window 1 and window 2. The absolute percentage error for the proposed algorithm is less than the Prony algorithm as seen from the analysis of Table 6. Hence it proves that the proposed algorithm is effective and robust enough to estimate modes of the real-time signal obtained from the WECC system.

4. Conclusion

This research paper proposes a novel ESPRIT algorithm for the identification of low-frequency oscillation parameters in the power system. This novel algorithm is based on the fact that true modes present in oscillations appear consistently no matter whatever is the order of the algorithm. The proposed algorithm estimates accurate and true modes under different noise levels and varying sampling rates which are verified through a different set of the synthetic signals generated in MATLAB, whereas the Prony algorithm fails to identify the true modes for higher noise levels for different cases as discussed in the analysis section of the paper. The proposed algorithm in comparison with the Prony algorithm has better performance as the percentage error in damping ratio is very less for different combinations of the synthetic signal as well as for WECC system, also the proposed algorithm correctly identifies the true modes even for the higher number of trails whereas the Prony algorithm fails for the same. The effectiveness of the algorithm proposed is also verified by the real-time data of the WECC system. It can therefore be inferred that in presence of noise and various PMU reporting rates, the proposed algorithm gives a precise estimate of frequency and damping ratio for both synthetic and real-time signal, proving the efficacy and robustness of the proposed algorithm. The future scope of the work would be to implement a controller to damp low frequency oscillations which may overall improve the stability of the power system.

Table 6. Estimated modes (frequency and damping ratio) of WECC system

Main Window	Proposed ESPRIT Algorithm			Prony Algorithm			Suggested value as given in [1, 26]	
	Estimated Frequency (Hz)	Damping ratio (%)	Absolute percentage error in damping ratio	Estimated Frequency (Hz)	Damping ratio (%)	Absolute percentage error in damping ratio	Estimated Frequency (Hz)	Damping ratio (%)
1	0.3201	8.50	2.40%	0.2011	8.97	8.07%	0.318	8.30
2	0.3170	7.40	6.09%	0.4071	6.87	12.81%	0.315	7.88

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