Experimental Real-Time Testing of a Decentralized PMU Data-Based Power Systems Mode Estimator

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***Abstract*—This paper presents the results and testing of a Phasor Measurement Unit (PMU) data-based mode estimation application deployed within a decentralized architecture using a real-time test platform. This work is a continuation of that in [1], which described a decentralized mode estimation architecture that enables the application to better detect local modes whose observability is affected by other more observable modes. The tests in this paper were carried out using an active distribution network (ADN) comprised of a high voltage network connected to a distribution grid including renewable energy resources (RES). The developed application was run in a decentralized architecture where each PMU was associated with its own processing unit which was running the application to estimate modes from the time-series data. The results of the decentralized mode estimation architecture are analyzed and compared with its centralized counterpart.**

***Index Terms*—Power System Monitoring, Phasor Measurement Unit (PMU), Mode-meter, Decentralized Mode Estimation, Oscillations.**

I. Introduction

Wide-Area Monitoring System (WAMS) applications have been developed to acquire critical information about a network's dynamics. Modal frequencies and damping ratios are useful indicators of power system stress, which usually deteriorates with increased burden on the system. Real-time estimation of these and related metrices from time-series measurements have become the base for real-time power system monitoring and early warning applications. In the past, applications utilizing PMU data have been developed and implemented in WAMS for real-time monitoring [2], [3] and [4].

In practice, today's applications utilize a centralized architecture where a central processor acquires data from all the connected PMUs. Acquired data is processed and fed to applications such as mode estimators that provide estimates of modal parameters. Although [3] indicates that other architectures can aid in the performance of the mode-meter applications, no experimental testing (real-time, PMU-in-the-loop) or field implementations had been implemented. In [1], the authors have shown the benefits of using a decentralized architecture by analyzing synthetic PMU data. This paper tests the same architecture and application by performing experimental laboratory tests including commercial PMUs interfaced with a real-time simulator running model of an ADN.

The remainder of the paper is arranged in the following way: A brief introduction of the application is given in Section II. Section III describes the test system and Section IV presents the results. Conclusions are drawn in Section V.

II. Real-Time Mode Estimator Application

The application employs measurement-based system identification methods to estimate a power system's modal properties. In quasi steady state, the application acquires 'ambient' data, and runs an Auto-Regressive Moving Average (ARMA)-based *Modified Yule Walker* method to estimate modal parameters. The application acquires PMU data using the S^3DK toolkit which was developed on LabVIEW platform [5] and its source-code can be found on github [6]. The tool acts as a parser receiving signals using the IEEE C37.118.2 standard and converts the signals into LabVIEW data-types.

This paper tests a decentralized architecture for mode estimation where system modes are estimated by individual processors using single PMU data streams instead of centralized estimator where all the different PMU data streams are processed by a single processing unit. The locally estimated modes can be collected and sent to higher level aggregators. This architecture aims to increase identification capability of oscillations at a more local level that may be neglected by centralized architecture. For testing, the mode estimator application was run using both architectures.

III. Test System

The mode-meter application was tested to identify the modes present in an ADN model that includes a transmission grid along with a highly active distribution grid with distributed generation in form of wind farms and solar parks. More information about the grid can be found in [7]. Measurement locations at the HV, MV and LV levels were equipped with PMUs to acquire data, as shown in Fig. 1. The reference grid was simulated in real-time using a real-time

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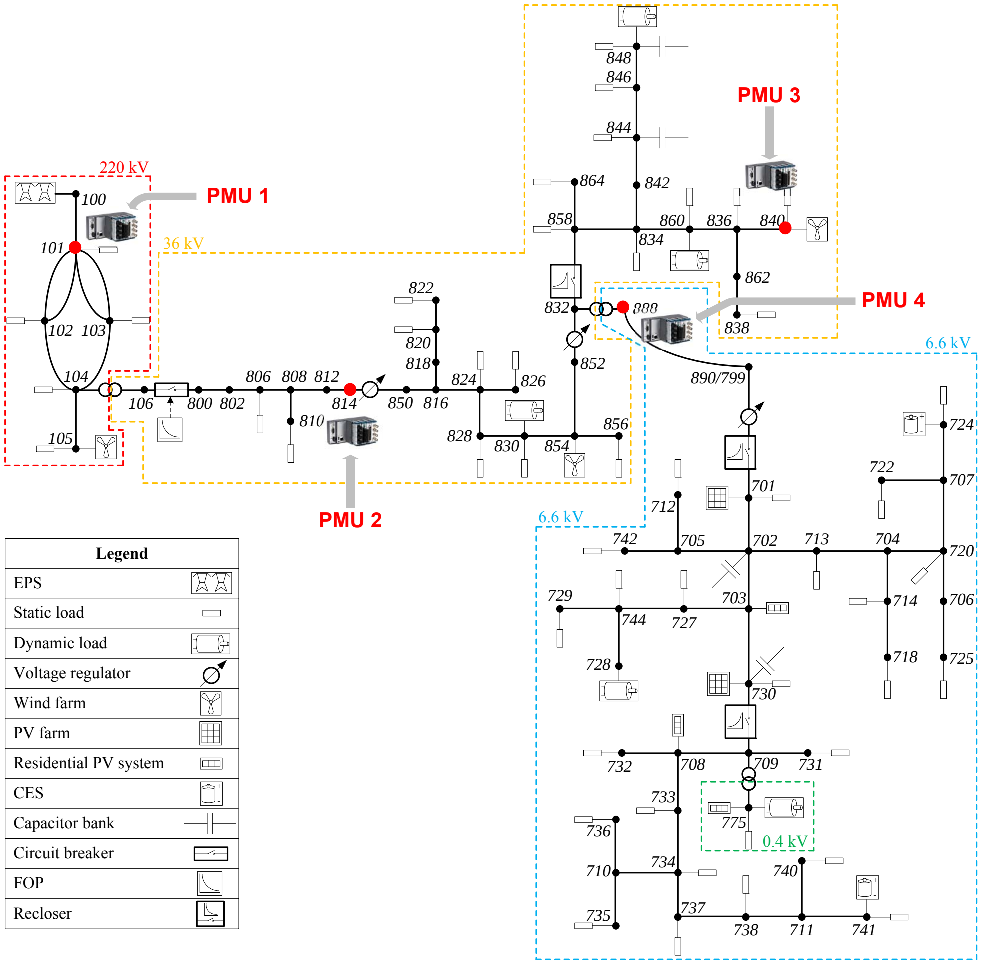

Fig. 1. ADN model with marked PMU locations

simulator. Measured PMU data from nodes 101 (HV), 814 (MV), 840(MV) and 888(LV) were stored.

To assess the results from the mode-meter application using PMU data, Fast Fourier Transform (FFT) was used to identify the inter-area and/or local modes present in the different measurements and to compute the modal frequencies in the spectra. When the reference grid was simulated and voltage magnitude and voltage angle data were obtained directly from the model. To induce some oscillations, the inertia of the synchronous generator at bus 100 was decreased gradually until the main inter-area mode was visible.

The FFT analysis allowed to identify the frequency of the oscillations to be 0.42 Hz. This inter-area oscillation was present throughout the grid. Next, the ADN model was run in real-time and data was acquired using four PMUs. The FFT analysis of the stored PMU data confirmed the presence of an inter-area mode of frequency 0.42 Hz as identified earlier in the previous step.

To illustrate the advantages of decentralized mode-estimation in identifying local oscillations, a localized forced oscillation was created by introducing sinusoidal load variation at node 799 in the LV section with a frequency of 1.7 Hz. Table I presents both the modes to be identified by the mode-meter. For comparison purposes, the real-time experiments are run for both the centralized and decentralized architecture. Section IV presents the results.

IV. Results

This section presents the results obtained by the mode-meter application running in real-time. Results obtained from both the architectures are presented for comparison and analysis. PMU estimates of Voltage magnitudes are used as input signals to the application. Estimates were calculated on a moving window ten minutes of time-series data which is a parcel of 6000 samples. Each test was run for about one hour. The estimated results were stored for further analysis. Probability Distribution Function (PDF) plots were plotted for both frequency and damping ratio estimates, as shown in Figs. 2 and 3.

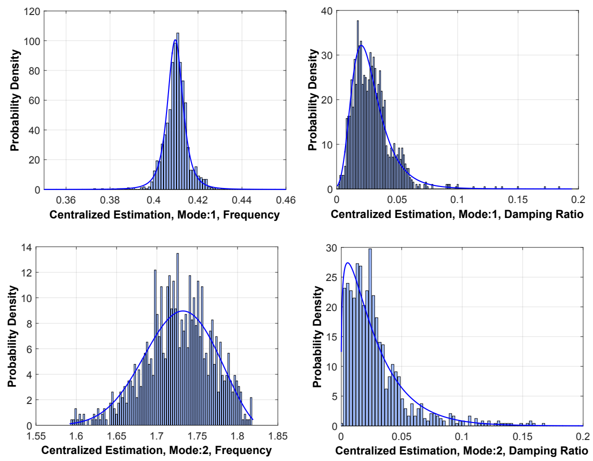

Fig. 2. Estimates from centralized estimation with voltage magnitude signals; TOP: PDF of Mode 1 frequency (left), PDF of Mode 1 damping ratio (right); BOTTOM: PDF of Mode 2 frequency (left), PDF of Mode 2 damping ratio (right).

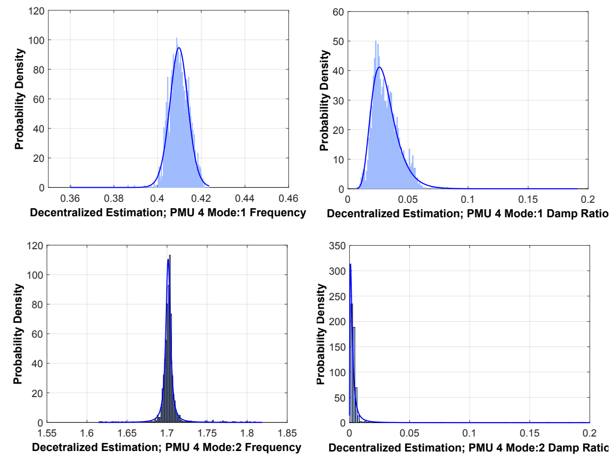

Fig. 3. Estimates from decentralized estimation with voltage magnitude signals; TOP: PDF of Mode 1 frequency (left), PDF of Mode 1 damping ratio (right); BOTTOM: PDF of Mode 2 frequency (left), PDF of Mode 2 damping ratio (right).

TABLE I
INTER-AREA AND FORCED LOCAL MODES IN THE GIRD

Mode	Frequency
Mode 1 (inter-area)	0.42 Hz
Mode 2 (forced local)	1.7 Hz

A. *Voltage Magnitude Signals*

Positive sequence voltage phasor magnitudes acquired form the four PMUs were used as input signals for the mode-meter application. PDF plots of the estimates were obtained. Results from centralized estimation architecture show high density of estimates around mode 1 with mean frequency and standard deviation [0.4093, 0.0076] Hz. For mode 2, the mean frequency and standard deviation of estimates are [1.7256, 0.0425] Hz. The mean and standard deviation of the frequency and damping of the two modes identified are presented in Table II. The summary of results in terms of PDF plots for centralized architecture is presented in Fig. 2.

The next case aims to demonstrate the decentralized mode estimator which attempts to improve the identification of the local forced oscillation (mode 2). All the PMU data streams were processed individually. Based on data from PMU 4 at node 799, mean frequency and standard deviation calculated are [0.0425, 0.045] Hz for mode 1 and [1.702, 0.013] Hz for mode 2. Fig. 3 presents the PDF plots based on the estimates obtained using PMU 4 data in decentralized architecture. The plots also suggest high density of estimates with mean frequency of 0.41 Hz and also around the frequency of 1.7 Hz. The damping ratio of the forced oscillation is estimated to be 0.68% with a standard deviation of 2.75%. This means the damping ratio is nearly 0% as expected. The mean and standard deviation of the frequency and damping of the two modes identified by decentralized estimates from all the PMUs are presented in Table III.

TABLE II
STATISTICAL ANALYSIS OF CENTRALIZED MODE ESTIMATES

Mode 1				Mode 2			
Freq. (Hz)		Damp. (%)		Freq. (Hz)		Damp. (%)	
μ [a]	σ [b]	μ	σ	μ	σ	μ	σ
.4093	.0076	2.84	1.7	1.726	.0425	2.78	2.79

[a] μ: mean
[b] σ: Standard deviation

On comparison of mean and standard deviation of frequency and damping ratio estimates, it is evident that the local oscillation is better identified when using the decentralized architecture in case of voltage magnitude signals.

V. CONCLUSION

A mode-meter application was tested and validated in a real-time experimental environment using PMU data streams. The application was run in two different architectures: centralized and decentralized. Voltage magnitude estimates from PMUs were tested as input signals to both architectures. It was shown that the application was able to detect the major inter-area oscillations using both architectures. It was found out that in

TABLE III
STATISTICAL ANALYSIS OF DECENTRALIZED MODE ESTIMATES

PMU ID	Mode 1				Mode 2			
	Freq. (Hz)		Damp. (%)		Freq. (Hz)		Damp. (%)	
	μ	σ	μ	σ	μ	σ	μ	σ
PMU 1	.41	.054	3.11	1.16	1.71	.071	4.68	5.55
PMU 2	.41	.049	3.15	1.12	1.71	.047	3.11	5.04
PMU 3	.41	.053	3.14	1.17	1.705	.022	1.09	4.49
PMU 4	.41	.045	3.13	1.09	1.702	.013	0.68	4.41

case of voltage magnitude signals, the decentralized architecture provides better estimates for the localized oscillations. One more scenario, testing the mode-meter application using measured voltage angle differences as input signals would be presented in the full paper.

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