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Technical Report TA User Project

Wide area monitoring of power oscillations and determination of mode shapes using PMU signals

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Abbreviations

DER	*Distributed Energy Resource*
TA	*Trans-national Access*
WMPOMS	*Wide area monitoring of power oscillations and deter-mination of mode shapes using PMU signals*
NSGL	*National Smart Grid Laboratory*
PMU	*Phasor measurement unit*
PDC	*Phasor data concentrator*
FO	*Forced oscillation*
MSC	*Magnitude squared coherence*
EMD	*Empirical mode decomposition*
DM	*Decomposed modes*
T-EMD	*Target-EMD*
CEEMDAN	*Complete ensamble empirical mode decomposition*
VMD	*Variational mode decomposition*
TSMD	*Two stage mode decomposition*
NRPG	*Northern regional power grid*
NASPI	*North American synchrophasor Initiative*
PSS	*Power system stabilizer*
EA	*Eigen value analysis*
SADF	*Synchro-measurement Application Development Framework*

Executive Summary

This document is a technical report on the ERIGrid TA project, WMPOMS. The report describes the objectives and experiments, and comprising the obtained results and conclusions.

The main collaborative activities in this period have been the information exchange on smart grid scenarios, use cases, research infrastructures requirements and needs, and testing and evaluation methodologies. This collaboration and information exchange, which is realised by means of emails exchange, seminars, joint events like simulation and discussion, is planned and the outcome is described.

1 General Information of the User Project

USER PROJECT PROPOSAL	
User Project title	Wide area monitoring of power oscillations and determination of mode shapes using PMU signals.
User Project acronym	WMPOMS
Host infrastructure	National Smart Grid Laboratory (NSGL), SINTEF Energi AS, Norway
Access period	06/01/2019 - 30/01/2019
User group members	Dr. Lalit Kumar (GBPIET Pauri Garhwal, 246194, India) Prof. Nand Kishor (MNNIT Allahabad, 211004, India)

2 Research Motivation

The spectral contents in the PMU signal are adjacently suffered by heavy ambient noise, multiple events and closely spaced multiple modes appearing and disappearing with time. Researchers keeps on trying to have the accurate spectral estimation. Most of the researchers prefer to incorporate spectral analysis in their approach. But, sometimes, low amplitude-low frequency modes appears, accompanied with mode-mixing. In such cases, the spectral estimation approaches fails to provide accurate spectral estimation.

Recently, Zhou et al. [1] proposed a self-coherence method to detect forced oscillation (FO) in the power system. The magnitude squared coherence MSC estimate is incorporated which consumes two signals obtained from single PMU signal by delaying it. The method is applied on field measurement data from the western interconnection wide area measurement system. The FO is successfully detected at the frequency of 13.35 Hz in 8 hours of collected signal. Processing of the signal is obtained by applying high-pass Butterworth filter to remove DC component.

The researchers also have incorporated mode decomposition technique before applying spectral tools for well spectral estimation [2]–[5]. Regardless of the fact that empirical mode decomposition (EMD) originally belongs to the field of signal processing and the maximum improvements are also reported in signal processing field [6]–[10], the power system researchers also have shown their efforts to make EMD more effective for its application in power system [3], [4], [11], [12]. After decomposition, the decomposed modes (DMs) may indicate the center frequency in its spectrum which was not possible without decomposition. Following the same direction, the authors in [11], have proposed a mode decomposition technique called target-EMD (T-EMD), to aid the performance of traditional FFT spectrum in mode estimation. T-EMD is expected to avoid the problem of mode-mixing and expected to extract a targeted mode frequency. In T-EMD, the signal is first detrended using standard EMD. The targeted mode to be monitored is identified from the FFT spectrum. All the IMFs which have the dominancy of targeted mode are identified and aggregated by summing them all. Such obtained signal after summation is termed as concentrated signal corresponding to targeted mode. Then the mask-EMD (M-EMD) is applied on the concentrated signal. Therefore, it can be said that the authors in [11] incorporated a kind of double stage mode decomposition technique involving standard EMD and mask-EMD to develop T-EMD. Similarly, the authors in [13] uses EMD to have the trend identification and de-noising of measured power system oscillations. It is stated that the use of nonstationary techniques are more suitable than moving-average approaches in analyzing rapid variations in nonstationary phenomenon characterized by short-lived irregularly occurring events.

The motivation of the research stands on the observation that more good decomposition of PMU signal leads to have more good spectral estimation. Therefore two stage mode decomposition (TSMD) technique is designed by incorporating two mode decomposition techniques i.e. CEEMDAN-2014 [7] and VMD [8]. Where, the reported mode decomposition techniques fails to separate out the closely spaced modes from the parent signal, the proposed TSMD eliminates the mode-mixing problem in decomposition of PMU signal and thus helps in accurate spectral and statistical estimation in decomposed modes. Further to mention, decomposition by TSMD is not biased to a specific type of oscillatory mode. In other words, any type of oscillatory mode can be extracted by TSMD and the extracted mode also possess the information of their time range as will be shown in next subsection i.e. objectives. Later on, by spectral & statistical analysis, the type of oscillatory mode can be determined using decomposed mode.

2.1 Objectives

The objective of the research is to

1. Separate out the closely spaced modes of oscillation in real-time. For better understanding, let us consider the PMU signal of Hisar bus from the NRPG system of India [14], [15]. The

said signal is shown in left most column of Fig. 1. In the right most column in Fig. 1, it can be clearly seen that 0.8667 and 0.78 Hz modes which are closely spaced have been separated out efficiently by the propose TSMD.

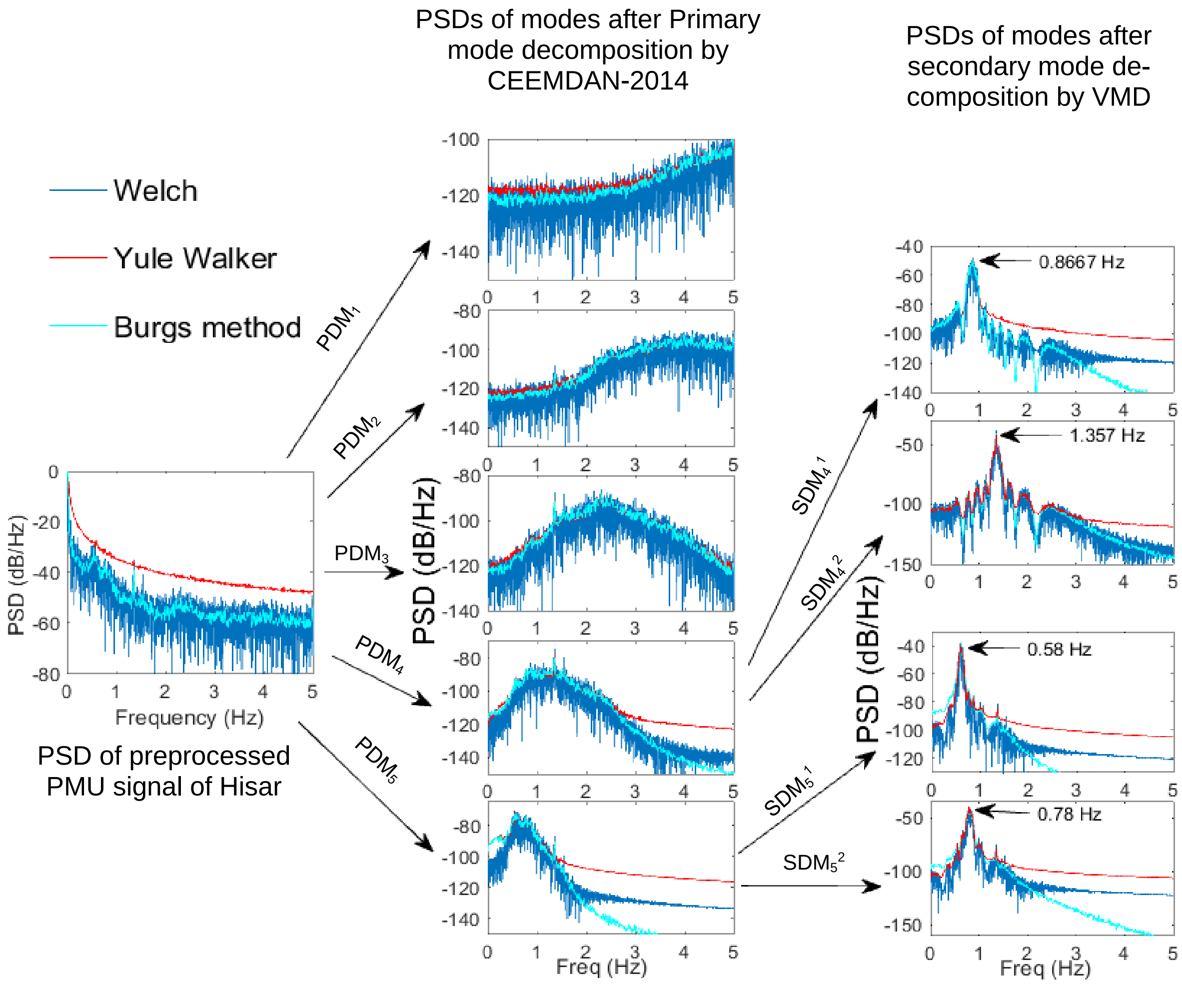

Fig. 1 Spectrum view of TSMD applied on PMU signal of Hisar

2. Monitor the power oscillations specially tracking the frequency & amplitude variation in real time. Again, for better understanding, the tracking of 0.58 Hz inter-area mode is shown in Fig. 2 which is determined in North American Synchrophasor Initiative (NASPI) system [16].

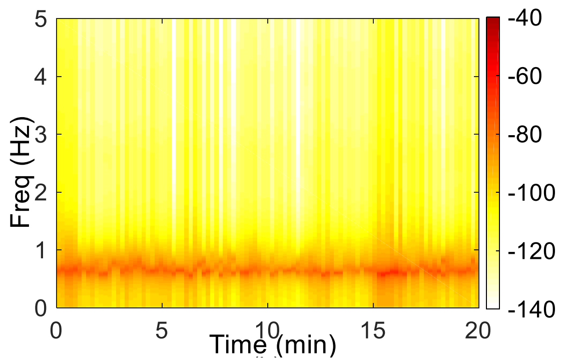

Fig. 2 Tracking of 0.58 Hz mode in NASPI system

3. Quickly and accurately inform the control operator about the appearance/disappearance of new modes and the variations in the ongoing tracked modes.

2.2 Scope

The proposed research (WMPOMS) can contribute in many ways to make the stressed grid, a healthy and smart grid.

1. WMPOMS can allow the operator to monitor & track all the critical oscillations in real-time. The particular oscillation is sensitive to the particular disturbances occurring at particular location. The list of disturbances can be made in correlation with particular mode base on close tracking. And thus, the past experience (list) can be taken into consideration in the rescheduling of bulk power transmission.

2. Proposed WMPOMS can fastly warn the control operator about any threat inflicted by power oscillation such as arising of new mode, significant frequency deviation and increase in mode amplitude etc.

3. Significant frequency deviation in inter-area mode may require re-tuning of power system stabilizer (PSS). In this way, WMPOMS can help in minimizing the risk of instability in the power system.

3 State-of-the-Art/State-of-Technology

Power oscillations in power system affect the economical load dispatch, degrade the reliability, lead to system instability and equipment failure, and may cause even cascaded blackout. Power oscillations in power systems are classified as shown in Fig. 3. In all the power oscillations shown in Fig. 3, one types of oscillation is very common and severe in power system i.e. “inter-area oscillations”.

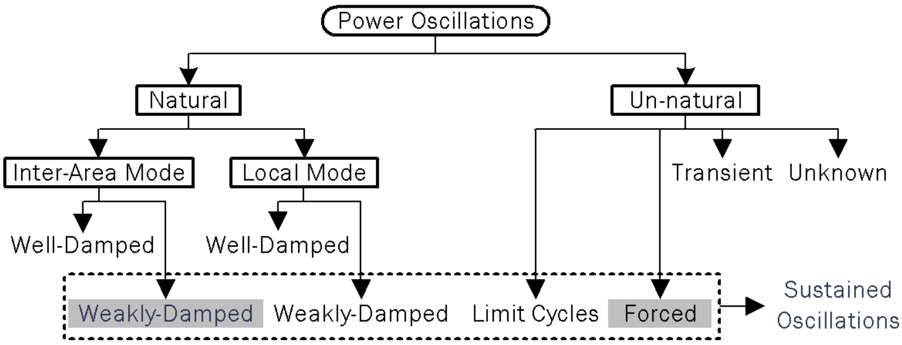

Fig. 3 Classification of power oscillations

3.1 *Review on natural oscillations*

Electromechanical or natural oscillations are said to exist due to interaction between electrical and mechanical variables or parameters. Load variations, switching actions, faults, and other disturbances can trigger electromechanical oscillations. These oscillations occur due to the lack of damping torque at the generators and are referred as the characteristics of the system. In general, the electromechanical oscillations are of 2 types: local and inter-area modes of oscillations. The local modes are witnessed when a plant or single generator oscillates against the rest of the generators, whereas the inter-area modes exist when multiple generators in an area oscillate against generators in another area. Frequency of local mode lies in the range of 0.7 to 2 Hz, while those of inter-area mode are in the range of 0.1 to 1 Hz.

3.2 *Review on monitoring of power oscillations*

In small signal stability analysis, eigenvalue analysis (EA) is a traditional offline method to analyze electromechanical oscillations. EA has never been criticized on its accuracy for modal analysis. The only drawback is that it requires accurate modelling data and linearization around the operating point. These limitations restrict the use of EA for online applications. The requirement of real-time ‘wide-area monitoring’ pushed the researchers to identify oscillatory dynamics using phasor measurement units (PMUs) data. In order to meet this requirement, spectral analysis tools are widely adopted for mode analysis [17]. But, the direct (without mode decomposition) use of spectral approach on PMU signal is not effective when there exist several low frequency modes and forced oscillations near natural mode frequency. One way to enhance the performance of spectral estimation is to implement the mode decomposition technique before applying the spectral analysis [11].

Empirical mode decomposition (EMD) [18] is one of the benchmark technique for mode decomposition. But sometimes EMD fails due to its inherent shortcomings such as mode mixings [6], [19]. The authors in [11], have proposed an improved mode decomposition technique, T-EMD, to aid the performance of traditional FFT spectrum in mode estimation. In the similar line, TSMD has been designed in the proposed research and has been incorporated in the WMPOMS algorithm as shown in Fig. 4. The goal of the test/research is to clearly observe one single power oscillation in one single screen (figure). In other words WMPOMS should be able to provide the decomposed mode comprising the mono-frequency component corresponding to power oscillation.

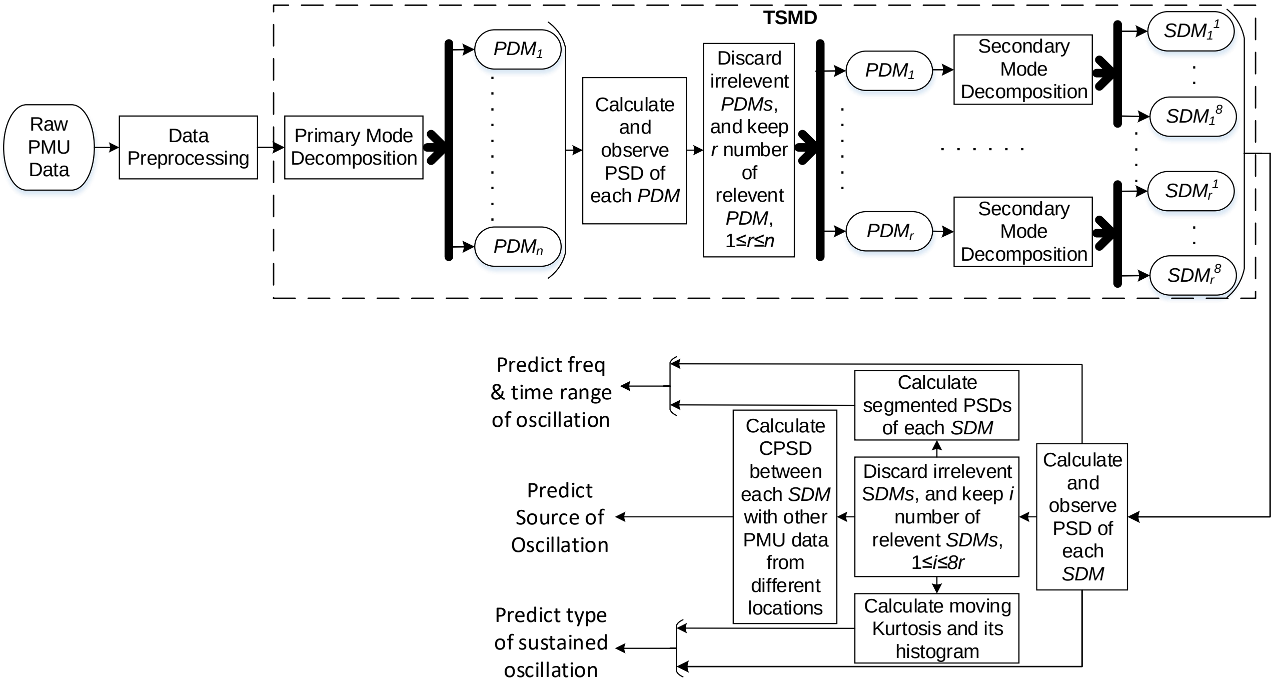

Fig. 4 Flow chart of proposed monitoring approach, WMPOMS

4 Executed Tests and Experiments

4.1 Test Plan

Testing of WMPOMS must need/consume PMU signal. Therefore the test plan broadly consists two parts i.e. “PMU signal generation/access” and “Real-time testing of WMPOMS” as shown in Fig. 5. The real-time PMU signal can be made available in two ways. First, by simulating the offline system in Opal-RT and second, by requesting/writing to power company for the access. These ways can be treated as two subparts of part I of the test plan as shown in Fig. 5.

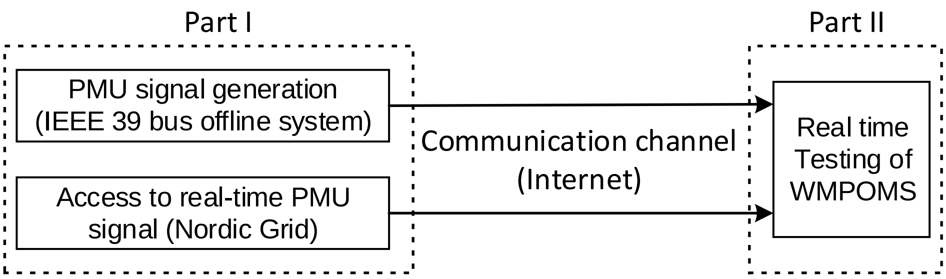

Fig. 5 Broad test plan

The complete block diagram for the part II of the test plan i.e. real-time testing of WMPOMS is shown in Fig. 6. However this block diagram has linkage with Part I also. Part II is implemented on two platform.

1. NSGL Opal-RT PC
2. Non Opal-RT Laptop

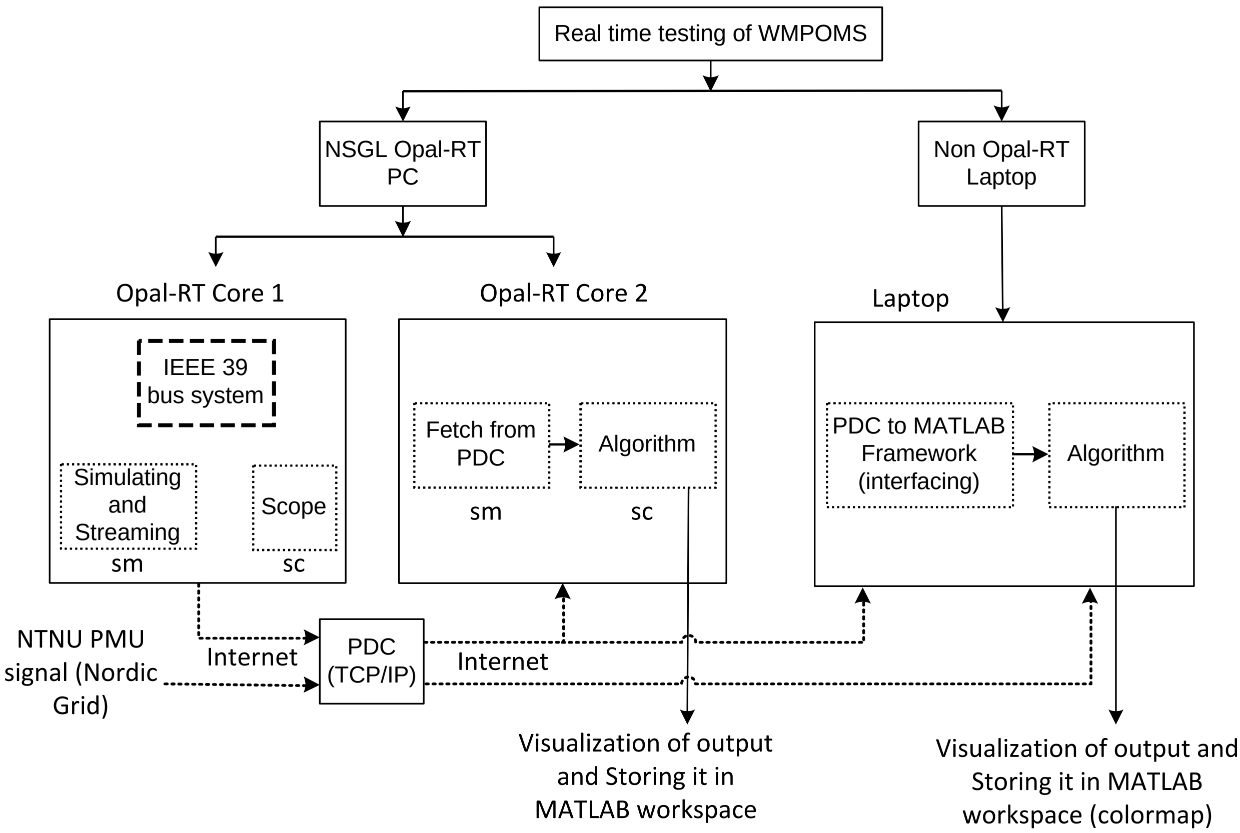

Fig. 6 Flow chart for real-time testing of WMPOMS

4.1.1. NSGL Opal-RT PC platform: Part I & II

This platform has served for both parts of the test plan. However, in part I, this platform has only served for its first subpart i.e. PMU signal generation. Under this subpart, IEEE 39 bus system [20] is simulated in ePHASORsim in core 1 of Opal-RT while the network data is provided in PSS/E file format. The default model given in PSS/E is taken for simulation. To mimic the random load deviation, the ambient noise is given to all loads ranging from ±5 % from the per unit load values. The voltage magnitude signal from the bus-39 is collected and sent to PDC in real-time, the procedure of which will be discussed in section 4.3. All the things related to signal communication, signal stream, and signal fetching etc. will be discussed in section 4.3. The voltage magnitude signal can now be streamed out to internet from the PDC.

Execution of part II on this platform is done in core 2 of Opal-RT. The block diagram to be dumped to core-2 is shown in Fig. 7. In this part II of the test plan, the RT-Lab is configured with PDC to fetch the signal from PDC to RT-Lab via internet. Once, the configuration is made, the same is also applicable to the subpart 2 of the part I i.e. access to real-time PMU signal (Nordic Grid). This configuration is kept inside the master subsystem, "sm_StreamIN". Now, the fetched signal is given to console subsystem, "sc_Compute" as an input, where the WMPOMS algorithm is executed in real-time. PMU signal is streamed/received at the sampling frequency of 50 Hz. It takes less than 5 sec for the algorithm to execute on 60 sec data. So, the receiving signal is buffered every 5 sec with a window size of 60 sec i.e. 3000 samples which is sliding every 5 sec to buffer the data. The block "sc_Compute is explored in Fig. 8. The important blocks inside "sc_Compute" are;

- **OpComm:** To transfer the signal from one block to another
- **Integrated MATLAB function:** To bypass any Matlab function from RT-Lab to Matlab for its execution in Matlab. Here the buffer function is used.
- **Pulse generator:** To start the algorithm after each window frame.
- **To workspace:** To store the relevant input/output to Matlab workspace after the experiment termination.

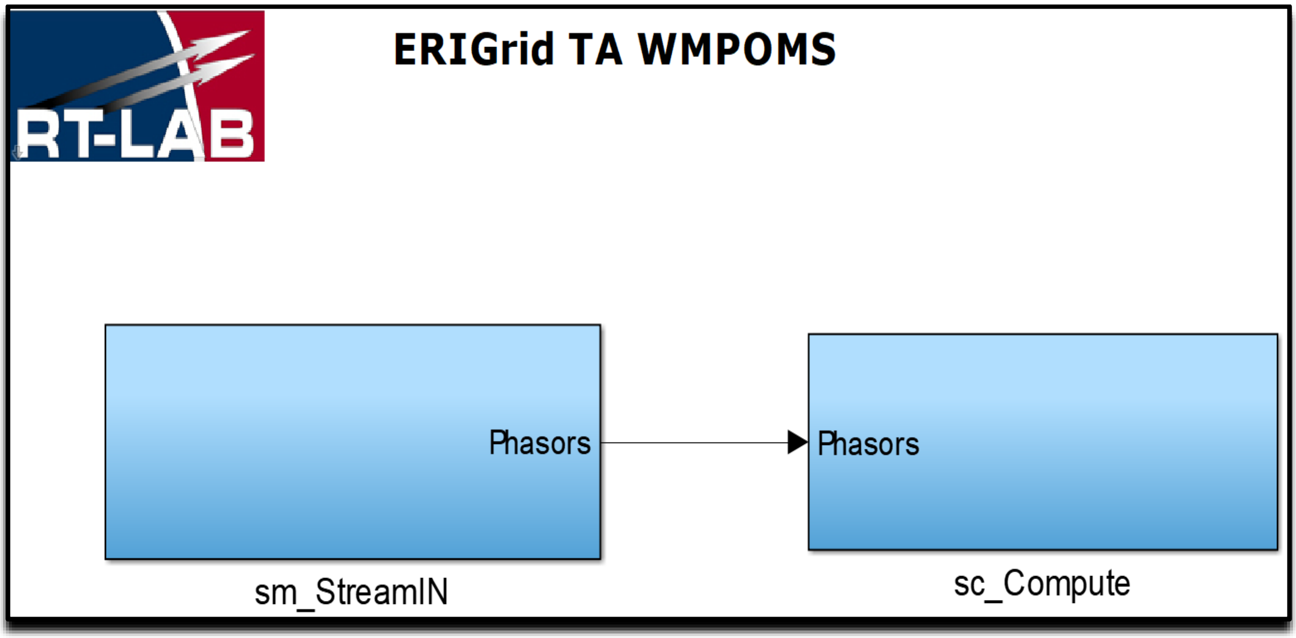

Fig. 7 Outermost block diagram in RT-Lab

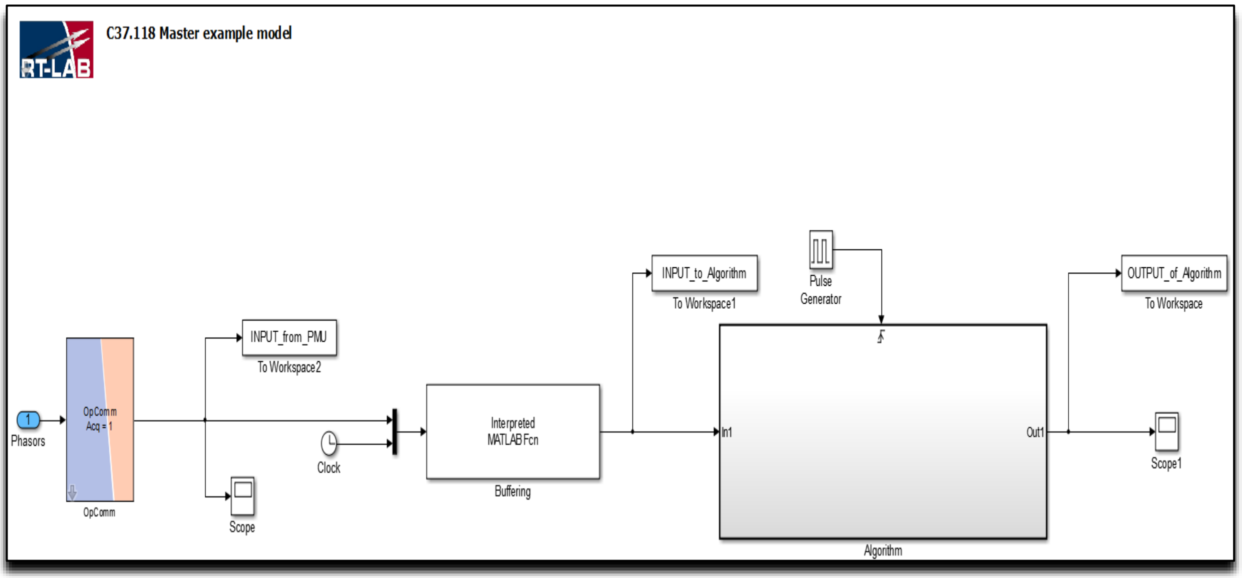

Fig. 8 Inside block diagram of sc_Compute subsystem

4.1.2. Non Opal-RT Laptop platform: Part II

In this platform, a non-Opal RT laptop is used to fetch the signal stream to MATLAB in real-time. The most important tool in this platform is Synchro-measurement Application Development Framework (SADF) [21]. SADF is a Matlab coding based library which enables receiving of TCP, UDP, or TCP/UDP synchro-measurement data. SADF not only serve for the purpose of receiving the signal, but it has a broad application in wide area monitoring, protection, and control (WAMPAC) including the verification of compliance and PMU/PDC performance under realistic conditions. The downloaded SADF library [21] should be added to the Matlab path to be able to use it. The function "SADF_setting" allows to configure the PMU/PDC connection settings. The function "SADF_run" allows to embed the WAMPAC algorithm in it which may require the understanding of the function "demo_WAMS" first.

In this platform of part II, the algorithm (coding) is restructured according to the compatibility of SADF which is given the filename as "WMPOMS_embed". This function is embedded into the "SADF_run" function. Now there are two function embedded in the main function, "SADF_run", which are, "demo_WAMS" and "WMPOMS_embed". The function "demo_WAMS" is given by default in SADF which is to plot the signal in real time with its stream specifications mentioned. And, the function "WMPOMS_embed" is to plot the figure for the dominant mode monitoring similar to as shown in Fig. 2. The function "SADF_run" is edited so that the embedded functions, "demo_WAMS" and "WMPOMS_embed" will plot the two figures each of which will be displayed/fitted in the right and left half of the laptop screen. And the results will be displayed in real-time.

4.2 Standards, Procedures, and Methodology

The standards, procedure and methodology which has been followed is tabulated in Table 1.

Standards	Procedures	Methodology
• The PMU signal is streamed according to IEEE C37.118.2-2011 compliance with a specific host ID (TCP/IP), port and device ID code.	• The overall procedure is discussed in section 4.1	• SADF [21] • WMPOMS [22] and its embedding in SADF • Master subsystem (sm_) and console subsystem (sc_) [23]

Table 1 Standards, procedure and methodology

The availability of the stream was checked by the open source software called PMU connection tester [24] installed in computer as shown in Fig. 9.

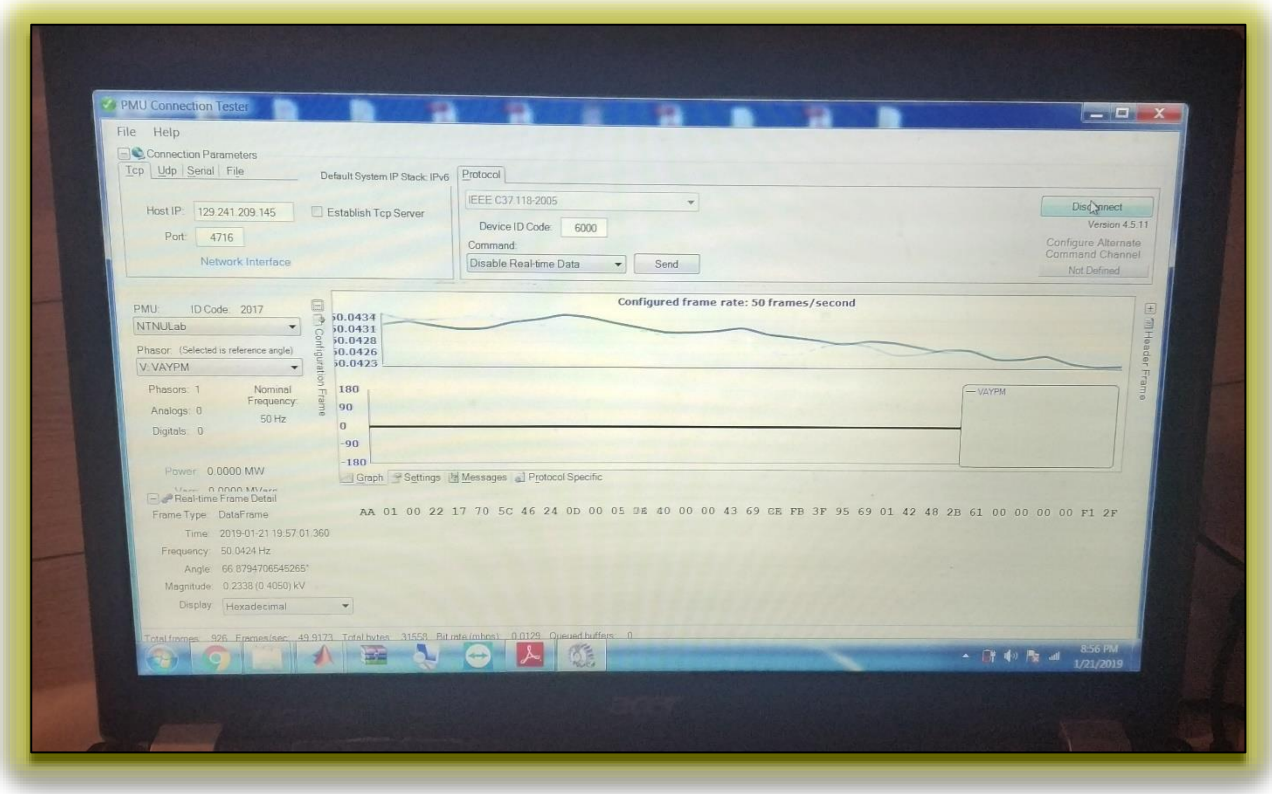

Fig. 9 PMU connection tester

4.3 Test Set-up(s)

The test set-up is followed as shown in Fig. 6. The components of the setup is shown in Table 2.

Implementation details	Equipments	Communication in-volved	Monitoring aspects
• MATLAB version 2015 or above • PSS/E network file • RT-Lab	• Computer with con-figuration as; 6 GB RAM, 3.2 GHz speed, Window 7 or above (64 bit) • Opal-RT (ePHAS-ORSIM) • Matlab 2013 and above	• Purchased code to fetch the streamed out signal to RT-Lab • SADF library to fetch the signal to MATLAB • TCP/IP for internet channel	• Monitoring of domi-nant power oscilla-tion frequency in real-time.

		• OpCommm to com-municate between the subsystems • Bus signal from PSS/E model to PDC	

Table 2 Components of the setup

4.4 Data Management and Processing

The data is managed to store in workspace of Matlab as discussed in section 4.1.1. Then from workspace, it is save in the computer as ".mat" file. The data quality is good and does not has the measurement errors therefore the data pre-processing is not required. The algorithm can directly consume the signal to process it to produce the results. The main processing function is "WMPOMS_embed", which is designed for the real-time monitoring of dominant power oscillation. The algorithm is written in such a way that whichever power oscillation (frequency) will be most dominant at current time will only be displayed in the colormap. The stored data in workspace can also be analysed later for the other monitoring information or application.

5 Results and Conclusions

5.1. Results

As mentioned before, the testing of WMPOMS has been done for offline IEEE 39 bus system and for online Nordic grid system.

The main goal is the validation of WMPOMS for fast and accurate real-time monitoring of low frequency power oscillations. The real-time monitoring of the most dominant power oscillation is the system allows the operator to monitor the real-time stability condition and risk if any. The video result for online monitoring is only shown for IEEE 39 bus system simulated in Opal-RT which is given at the link in Ref. [25].The three phase fault at Bus-39 is also given in real-time. The snapshot of the video is also shown in the Fig. 10. For, NTNU low voltage PMU signal (Nordic Grid), the result-data is generated and stored in real-time but the figures are plotted offline which is shown in Fig. 11.

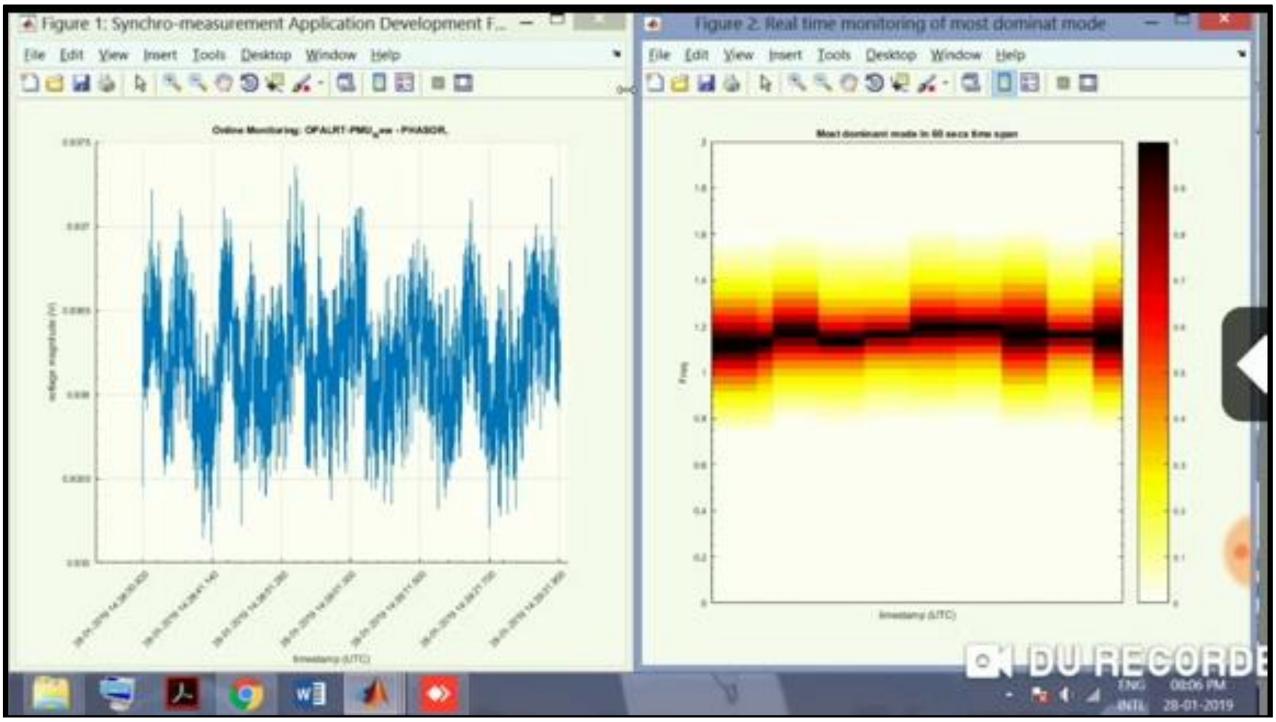

Fig. 10 Real-time monitoring of Opal-RT PMU signal (IEEE-39 bus system)

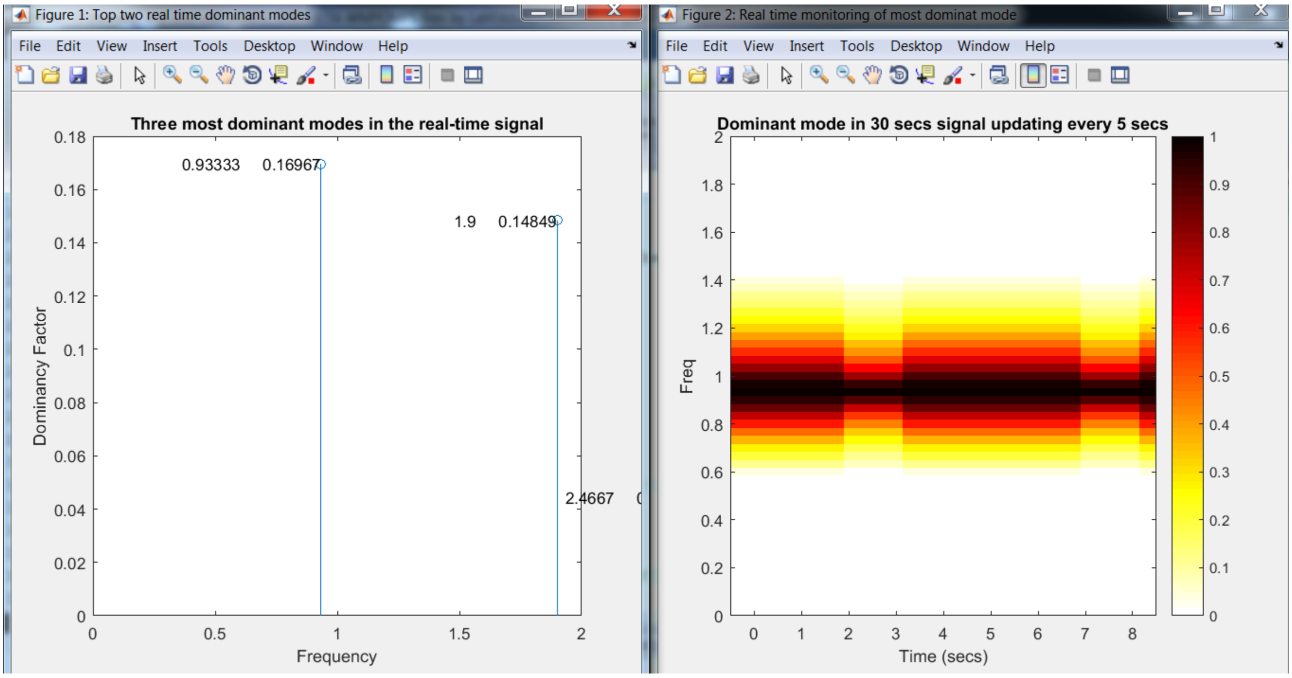

Fig. 11 Offline figure-results using real-time stored output for the monitoring of NTNU PMU signal

5.2. Conclusions

- WMPOMS is effective and accurate in monitoring of real-time power oscillations.
- Further improvement is needed in WMPOMS algorithm to increase its speed of processing the PMU signal, particularly by re-writing the code to achieve fastness.

6 Open Issues and Suggestions for Improvements

Open issue is the time taken to execute for the algorithm. Not enough fastness in the algorithm may restrict it to get implemented in real-time power system.

The suggestion for improvements are;

- Appropriate selection of the parameters so as to achieve fast monitoring with maintaining the accuracy.
- Time to execute for algorithm can be minimized by reducing the window size and by looking into many other factor involved in the coding.
- Observe multiple PMU signals. Study the effect of controllable input parameter variation on complete monitoring.
- Multiple power oscillation can be monitored in multiple figure/screen each with fix mode monitoring.

7 Dissemination Planning

- Writing research paper in collaboration with the TA user group manager and other group members after making improvements. For conference publication, the target is to publish in reputed IEEE conference and for Journal, the target is to publish in SCI indexed journal having impact factor more than 1.

- Confidentiality of Nordic grid PMU data

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9 Annex

9.1 List of Figures

9.2 List of Tables