Time-varying coherency study using TFC

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***Abstract* — An assessment of the dynamic interactions between generators will provide valuable information which could improve control action and hence maintain stability in the interconnected system. The paper presents the study on dynamic interaction in terms of coherency established among the generators following a particular event. Time Frequency Coherency (TFC) method is applied to trace the coherency among the generators. The dominant inter-area modes on which TFC is applied has been extracted from empirical mode decomposition of the swing curve. The phase difference between the dominant modes will verify and refine the coherency results. The potential of TFC in power system application has been evaluated on test cases, power system model & Phasor Measurement Unit (PMU) signals.**

***Index Terms*— Coherency, Time Frequency Coherency, Wide Area Monitoring System, Empirical Mode Decomposition (EMD).**

I. INTRODUCTION

THE advantages of interconnections in wide-area power system are great such as exchange of peak loads, increase in diversity factor, increase in reliability of supply etc. However, it increases the complexity of dynamic characteristics which is important to track in real time for secure operation. A wide area measurement system which consists of PMUs, gives the synchronized phasor information of voltage, power, frequency, current etc. [1] at higher sampling rate. Generator coherency is one of the important aspect of dynamic analysis because it reduces the order of large power system which will be important for security and protection point of view. Coherency in general terms means a set of generators whose swing curve are of same nature. [2]

In past, there are many researches has been done on coherency by using slow coherency methods [3], [4], time-domain analysis on the linear dynamic model of power systems [5] and also frequency response analysis [6]. There are many methods used to find the coherency but they are operated on specific operating point, and the coherency is going to shift with the operating condition, which is required to be examined. So, continuation method [7] is used to detect the coherency. In [8], the author has used Hilbert–Huang transform (HHT) for coherency detection from the phase of oscillation.

In this paper, we have detected time varying coherency by Time- Frequency Coherency (TFC) method. We have used Smoothed Pseudo-Wigner-Ville distribution (SPWVD) method for the analysis of TFC. This method has been applied in the bio-medical field [9]. For evaluating TFC, it is used to characterize the changes in synthetic signals, also tested on the standard IEEE 50 machine system and on PMU signals from Indian grid & Nordic grid.

The remaining portion of the paper is organized as follows, Section II contains the basics of generator coherency in real time. Section III consisting of techniques which are used for the analysis. Section IV discusses about the proposed approach for implementing the technique. Section V describes the simulated studies of cases taken. Section VI describe the results on the PMU signal for both the grids and the conclusion part in Section VII.

II. GENERATOR COHERENCY IN REAL TIME

It has been observed that due to sudden disturbance in multi-machine power systems, some of the machines shows similar responses to the disturbance which means that they swing together and are called coherent. In power system dynamic, coherency is an important factor which is useful in dynamic reduction, emergency protection and in control schemes.

Generally, the disturbance is taken as a single perturbation of the power system. Typically, oscillation in the generator swing curves can be compared to the system modes. These modes are mainly the slower modes (0.1 to 1 Hz) [10], [11].

In [7], for determining the coherency in real time or at different operating conditions, continuation method is used. There are certain drawbacks of it, they are as follows;

1. complete knowledge of the system is required, which is very difficult to obtain.
2. technique is steady state, so unable to track the coherency where there is *rapid change*.

In [8], the author has used Hilbert–Huang transform method. In this method, the signal is decomposed by EMD [12] which generates Intrinsic mode function (IMFs) then Hilbert Transform is applied to obtain the instantaneous phase of the generator and lastly the phase difference is traced which gives the information about the coherency.

While in paper [13], author has used spectral analysis for detecting the coherency, the low frequency signal is separated out by low pass filter and then the spectrum analysis is done. The spectrum analysis is for finding the cross-correlation between the generator's signals. In this paper, a new approach i.e. TFC has been applied, by which coherency can be find out in context of time and frequency. Hence, correlation coefficient $\acute{C}(t,f)$ is expressed as a function of time and frequency. This approach has been applied in the bio-medical field for estimating the dynamic interactions between the cardiovascular signals, which will be going to help in its controlling analysis [9] but to the best of our knowledge it has

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never been used in power system application. In our study, IEEE 50 machine power system model is simulated at randomly distributed disturbance in order to resemble the real load variation. The time-varying coherency identification is demonstrated for simulated signal obtained from above model and PMUs signal as well from real power network. The proposed approach successfully identifies the time varying coherency between the signals.

III. Analytical Techniques

A brief discussion on the techniques involved in this method of tracking coherency is presented here.

A. *Spectral Coherency*

Spectral coherency measures the degree of correlation between two signals. Thus, it is evident that the PMUs signals available from two buses (of generators) can be utilized to analyze the dynamically time-varying coherency following the disturbances in the system. The non-stationary signal analysis can be performed as time frequency representation (TFR) using Smoothed Pseudo Wigner-Ville distribution (SPWVD) technique. The spectral coherency function between two non-stationary zero-mean random signals; $d_1(t)$ and $d_2(t)$ are normalized version of the cross-power spectral density, $\mathfrak{S}_{d_1d_2}(t,f)$. Its magnitude can be named as coherency coefficient (CC) and is defined as:

$$\acute{C}(t,f) = \frac{|\mathfrak{S}_{d_1d_2}(t,f)|}{\sqrt{\mathfrak{S}_{d_1d_1}(t,f)\mathfrak{S}_{d_2d_2}(t,f)}}, \acute{C}(t,f) \in [0,1] \quad (1)$$

$\mathfrak{S}_{d_1d_2}(t,f)$, the non-stationary cross spectrum doesn't have a unique definition and its Wigner-Ville spectrum (WVS) is defined as [14]:

$$\mathfrak{S}_{d_1d_2}(t,f) = \mathfrak{F}_{\tau\to f}\{\mathfrak{E}\left[d_1\left(t+\frac{\tau}{2}\right)d_2^*\left(t-\frac{\tau}{2}\right)\right]\} \quad (2)$$

where $\mathfrak{F}$ {.} stands for Fourier transform, $\mathfrak{E}$ [.] stands for expectation operator. Under some conditions, the WVS is ensemble average of the Wigner-Ville distribution, $\grave{W}_{d_1d_2}(t,f)$ of the realizations of the signal [14].

$$\mathfrak{S}_{d_1d_2}(t,f) = \mathfrak{E}\left[\grave{W}_{d_1d_2}(t,f)\right] \quad (3)$$

$$\grave{W}_{d_1d_2}(t,f) = \mathfrak{F}_{\tau\to f}\left[d_1\left(t+\frac{\tau}{2}\right)d_2^*\left(t-\frac{\tau}{2}\right)\right] \quad (4)$$

$\mathfrak{S}_{d_1d_2}(t,f)$ can be estimated via local averaging

$$\mathfrak{S}_{d_1d_2}(t,f;\,\theta) = \grave{W}_{d_1d_2}(t,f) \otimes \theta(t,f) \quad (5)$$

where, $\otimes$ is the convolution on t and f, and $\theta(t,f)$ is a smoothing function expressed in (6) guaranteeing the positiveness of the spectra.

The SPWVD belongs to Cohen's class for the particular case of smoothing function in separable form. It is defined as:

$$\mathfrak{S}^W_{d_1d_2}(t,f) = \grave{W}_{d_1d_2}(t,f) \otimes \theta(t,f)$$

$$\mathfrak{S}^W_{d_1d_2}(t,f) = \mathfrak{F}_{(v,\tau)\to(t,f)}\{\mathcal{A}_{d_1d_2}(v,\tau)\vartheta(v,\tau)\}$$

$$\mathcal{A}_{d_1d_2}(v,\tau) = \mathfrak{F}_{t\to v}\{d_1\left(t+\frac{\tau}{2}\right)d_2^*\left(t-\frac{\tau}{2}\right)\}$$

$$\vartheta(v,\tau) = \mathfrak{F}^{-1}_{(t,f)\to(v,\tau)}\{\theta(t,f)\} \quad (6)$$

where, $\mathfrak{F}_{(v,\tau)\to(t,f)}$ is the Fourier transform, passing the ambiguity function domain to TF domain and $\mathcal{A}_{d_1d_2}(v,\tau)$ is the cross-ambiguity function of signals $d_1(t)$ and $d_2(t)$. For coherency to be in the limit of 0 and 1, the kernel should completely suppress the interference terms [15], [16].

B. *Time varying coherency*

The coherence function (1) defines the coherency between the two signals across the time and frequency range. It also defines how the signals are correlated. This coherence function is not sufficient to represent phase information between the coherent generators. The signals may be positively or negatively coherent, since $\acute{C}(t,f) \in [0,1]$. This is resolved by computing the phase difference (ϕ) of cross spectral density function $\mathfrak{S}_{d_1d_2}(t,f)$ and can be calculated as;

$$\phi = tan^{-1}\frac{img(\mathfrak{S}_{d_1d_2}(t,f))}{real(\mathfrak{S}_{d_1d_2}(t,f))} \quad (7)$$

It is now convenient to represent the angle variation of the generators that are correlated in time and frequency for the range of inter-area oscillatory modes. So if the angle is close to zero then the generators are positively coherent and belongs to one particular group and if close to 180°, it means the generators are negatively coherent. Such generators need to be classed together in different group.

IV. Proposed Approach

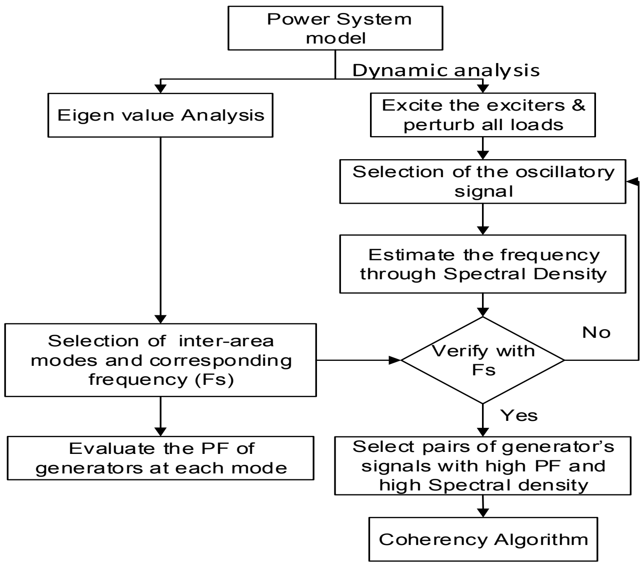
In this section, we present the approach applied to analyze the coherency between the generators. This is necessary to ascertain mode of oscillation (obtained from modal analysis) with those estimated from PMUs signal, so that coherency between the generators is computed at mode of interest in study.

The flow chart illustrating the approach applied in determining the coherency between the generators following a disturbance shown in Fig. 1. Initially, modal analysis is performed on the system to investigate the low frequency inter-area modes and participation factor of the generators [17], [18]. The dynamic simulation of system model, having exciters excited by sinusoidal signal at 10 Hz and loads being perturbed [13] by 5% around the linearized operating point is conducted to validate the presence of inter-area modes via estimation of spectral density in the generator signals.

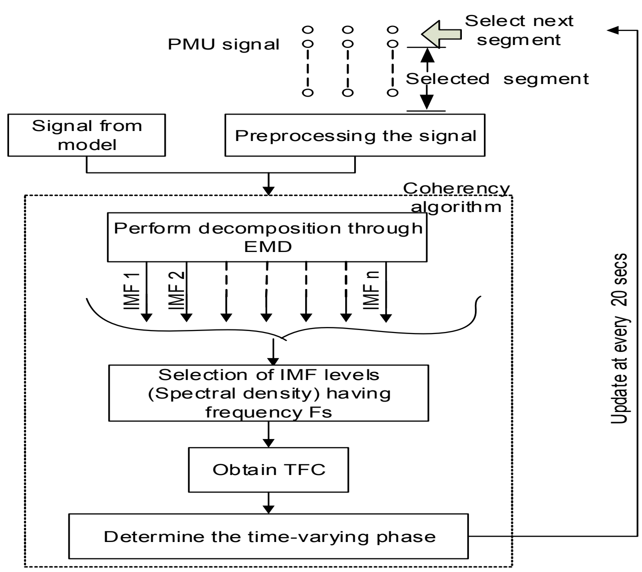
In order to apply on real power system, the proposed approach is tested on PMUs signals. The dynamic signals obtained from simulation of the system model and PMUs are decomposed using decomposition technique called EMD. This results into 'n' number of IMFs depending upon the frequency component available in the signal. It is assumed that each decomposed IMF is monotonic, i.e. single frequency component is present. The presence of mode of interest is confirmed by estimation of power spectral density.

In next step, time-frequency coherency (TFC) is computed for IMFs corresponding to given oscillation mode using SPWVD. For the duration, wherein both the signals are highly correlated to each other, high coherency between them is expected. In contrast, for the duration where the signals are uncorrelated, low coherency or non-coherent is obvious. The proposed approach is illustrated the flow chart in Fig.1.

Fig. 1(a) is the generalized one which mainly deals with the power system model while Fig. 1(b) illustrates for PMU signals and explains the process of detecting coherency among the generators.



(a) Generalized Flow chart



(b) Flow chart of Coherency algorithm

Fig.1. Flow Chart of the proposed approach

V. Simulated Case Studies

To demonstrate the performance of proposed scheme on coherency detection, we present the discussion on simulated signals.

A. *Case 1: Designed synthetic signal*

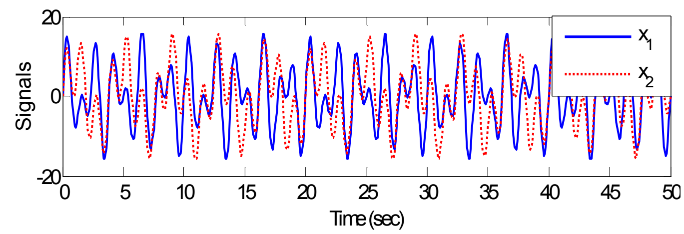
In this case study, two un-damped synthetic signals having superposition of two-frequency components are considered. These synthetic signals are defined as:

$$x_1 = 8\,sin(2\pi 0.8t) + 8\,sin(2\pi 0.5t) \qquad (8)$$

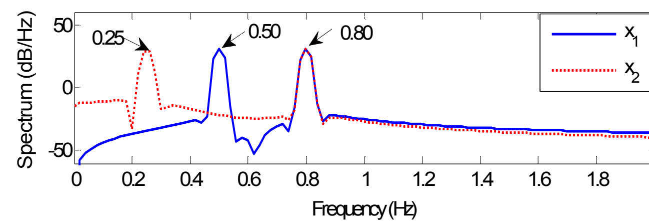
$$x_2 = 8\,sin(2\pi 0.8t) + 8\,sin(2\pi 0.25t) \qquad (9)$$

It may be observed that, these signals have a common frequency component of 0.8 Hz. Fig. 2(a) shows the time variation of synthetic signals; x_1 and x_2 and their corresponding spectral density is shown in Fig. 2(b). It is clear that 0.8 Hz frequency component is present in both the synthetic signals. In addition, x_1 and x_2 have 0.5 Hz & 0.25 Hz component respectively.

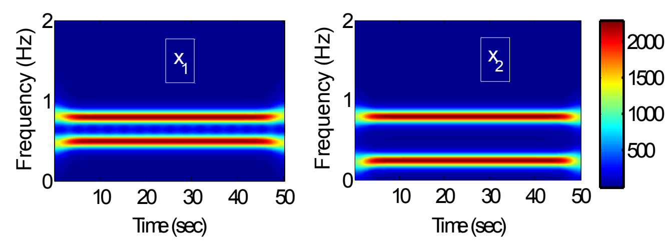
After applying the SPWVD technique for obtaining TFC, the spectra of individual signals are shown in Fig. 2(c). This further validates the presence of two frequency components in each synthetic signal for the complete duration. Now, the computed coherency between these signals and their TFC representation is illustrated in Fig. 2(d). It is suggested that the signals have high level of coherency for the common frequency component, i.e. 0.8 Hz. The color map/heat map remains approximately 1.0. On the other hand, for those frequency components which are not common in them, the uncoherency remains low. This is because the signals are un-correlated at these frequencies, i.e. 0.25 Hz & 0.5 Hz.



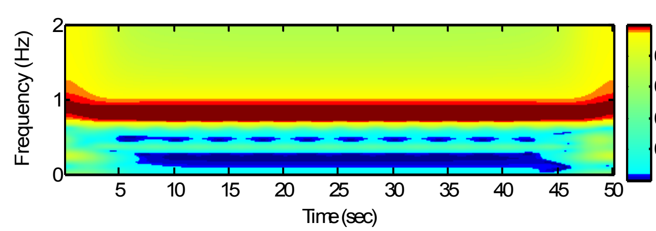
(a) Time variation



(b) Spectral analysis



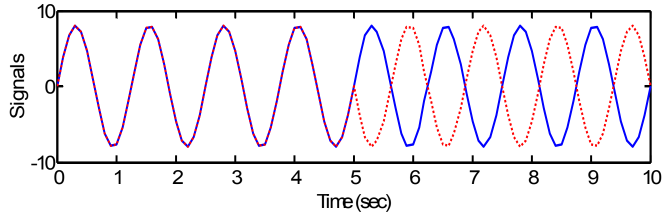
(c) Time-frequency representation of signals



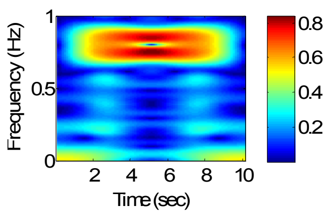
(d) Time-frequency contour

Fig. 2 Coherency analysis on synthetic signal

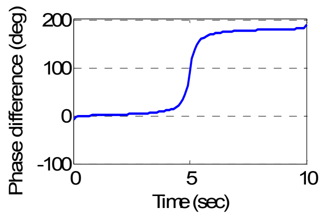
Now consider the synthetic signals, having only mono-component frequency of 0.8 Hz associated with in-phase (0°) and out-of-phase (180°) oscillation as shown in Fig. 3(a). As it can be observed, the two synthetic signals oscillate in-phase up to 5 sec and goes out-of-phase for the remaining time. It is worth mentioning to note 0.8 Hz oscillation from Fig. 3(b) and in-phase and out-of-phase information in Fig. 3(c) extracted from above discussed approach. This confirms the applicability of proposed approach for analyzing the coherency between the two signals at a given oscillation mode and their phase information.



(a) Time variation of in-phase and out-of-phase signals



(b) TFC



(c) Phase plot

Fig. 3 Coherency analysis on in-phase and out-of-phase synthetic signal

B. *CASE 2: Simulated signals from IEEE 50 machine system*

In this simulated case, the proposed method is applied on generator signals obtained from IEEE 50 machine system. All the generators are represented by classical model. Firstly, we perform the small-signal analysis to determine the low damped inter-area modes. Table I shows the mode properties of the said system. The simulation is done in Power System Toolbox (PST) on MATLAB platform [19].

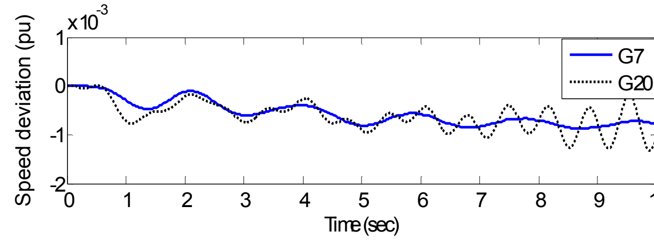
TABLE I INTER-AREA MODES

Modes	Frequency [Fs] (Hz)	Damping ratio
1	0.5055	0.0335
2	1.0673	0.0288
3	1.1010	0.0168

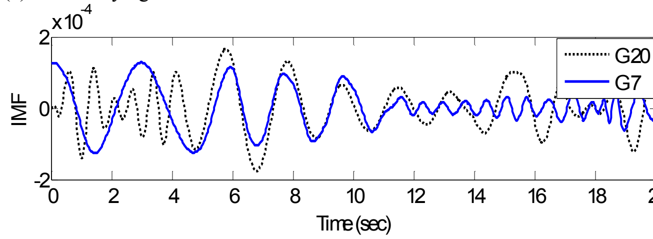
In the next step, the loads are randomly perturbed by 5% and dynamically varying generator signals (speed deviation) are collected. The calculation of power spectral density on these signals suggests the presence of 0.5055 Hz mode. Further, computation of participation factor at this mode indicates the generators; G7,G20, G24, G3, G5, G4 & G36 are dominant. By doing so, pairing of the generators is possible to analyze the coherency between them.

Fig. 4(a) depicts the time varying speed deviation of generator pair G7-G20 and their corresponding IMF having 0.5055 Hz mode is shown in Fig. 4(b). The speed deviations are shown for 10 secs only instead of simulated period of 20 secs for better representation of swing dynamics. It is worth noting that IMF variation of these generator pairs are in phase during 5-11 sec approximately and the same is also validated from TFC plot shown in Fig. 4(c). In other words, the generator pair G7-G20 show a high level of coherency during this period of dynamic disturbance.

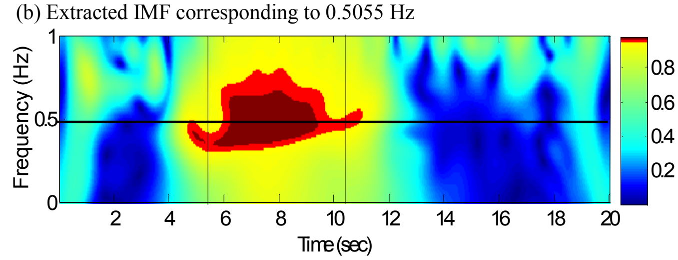
Similarly, the above analysis is carried out on generator pair G20-G24 and the results are shown in Fig. 5. Due to space restriction in manuscript, such analysis can be performed on several generator pairs, having same oscillatory mode. Nevertheless, the computed coherency between some of generator pairs is shown in Fig. 6.



(a) Time-varying deviation

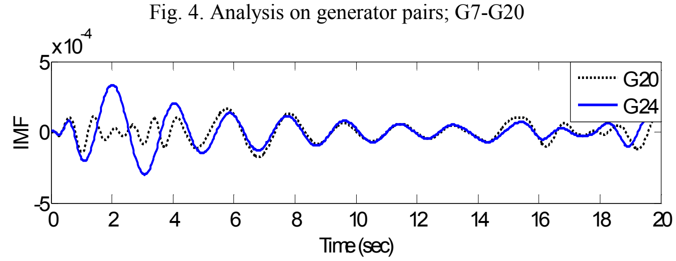


(b) Extracted IMF corresponding to 0.5055 Hz

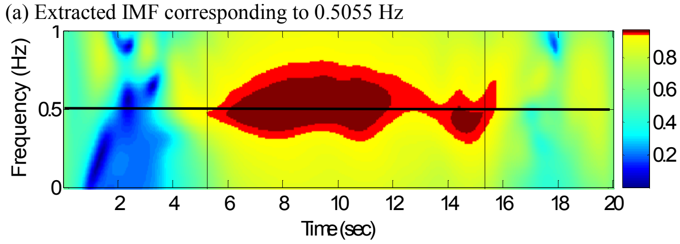


(c) TFC between the signals

Fig. 4. Analysis on generator pairs; G7-G20



(a) Extracted IMF corresponding to 0.5055 Hz



(b) TFC between the signals

Fig. 5 Analysis on generator pairs; G20-G24

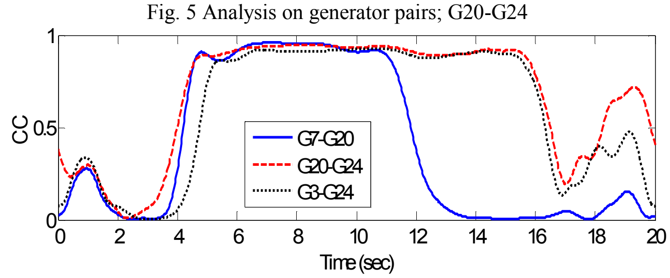


Fig. 6 Coherency between generator pairs of IEEE 50 machine system

From the above discussion, it is interesting to note the applicability of proposed approach for determining coherency between the generators.

VI. PMUs Signal

Now, we investigate the coherency using PMUs signals. In study, PMUs signals from Northern Region Indian grid and Nordic grid are considered.

A. *Northern region Indian grid*

This test is on Northern Indian Grid PMU signal. The variation of voltage angle difference of Dadri and Hissar buses with respect to Agra bus are shown in Fig. 7. The analysis on signals is carried out on selected window frames; F1, F2 & F3 as indicated in said figure. The presence of low frequency modes estimated using power spectral density in these frames are given in Table II.

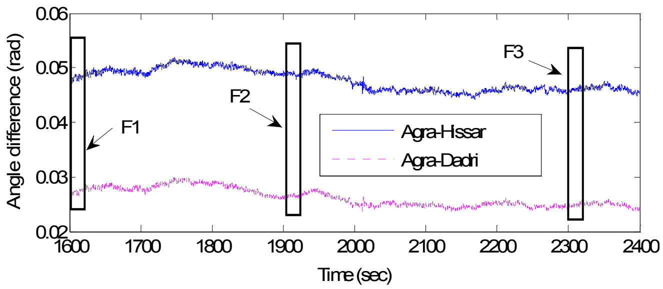
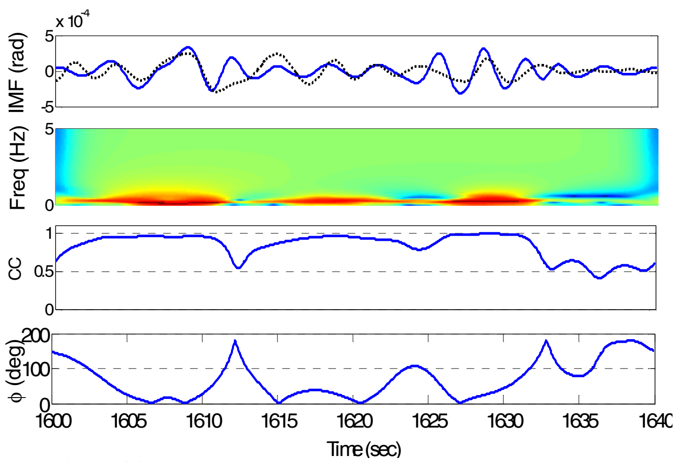


Fig. 7 Angle deviation between the buses

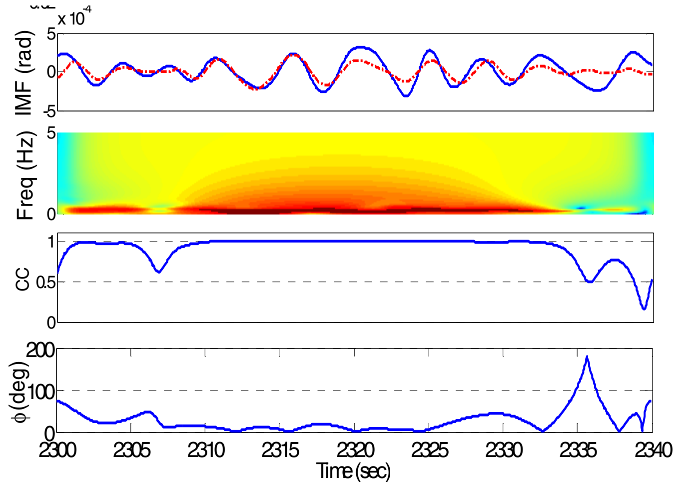
TABLE II Dominant modes along with their time duration

Window frame	Time duration (sec)	Frequency [F_s] (Hz)
F1	1600-1640	0.2997
F2	1900-1940	0.2498
F3	2300-2340	0.2248

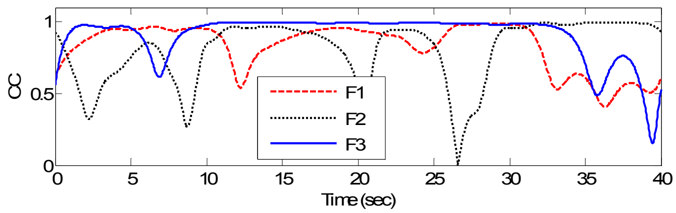
As presented and discussed above for coherency determination between the signals, similar analysis is performed on three frames of PMUs signals and results are illustrated in Fig. 8. The coherency between the signals in window frame F3 reaches to high value for most of the time (Fig.8(c)).



(a) Analysis of frame F1



(b) Analysis for frame F3

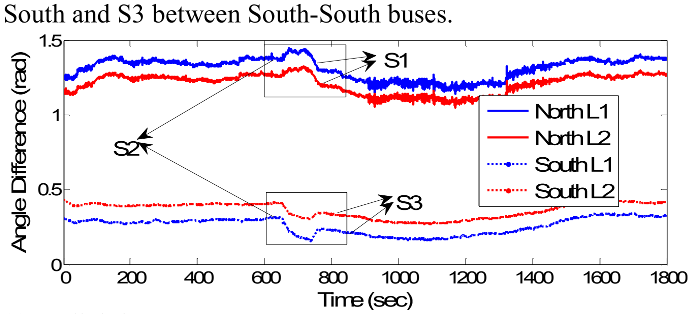


(c) Correlation coefficient, $C(t, f)$ for selected window frames

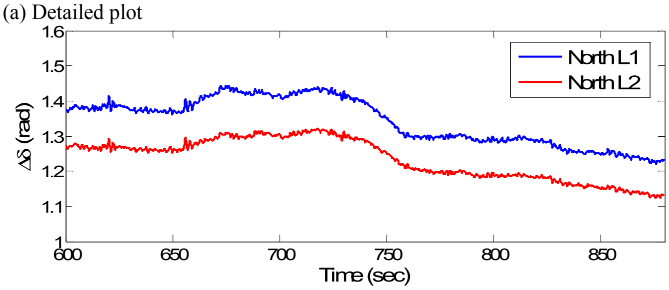
Fig. 8 Coherency between PMUs signals from Northern Region Indian grids

B. *Nordic grid*

Furthermore, the analysis is extended to PMUs signals collected from buses located in Norway. The variation of voltage angle for the buses located in North and South of Norway is shown in Fig. 9. The analysis is performed on selected window frame of duration 40 sec considering pair-wise signals from these regions. For instance, frame S1 refers to signal pair between the buses of North, S2 between North-South and S3 between South-South buses.

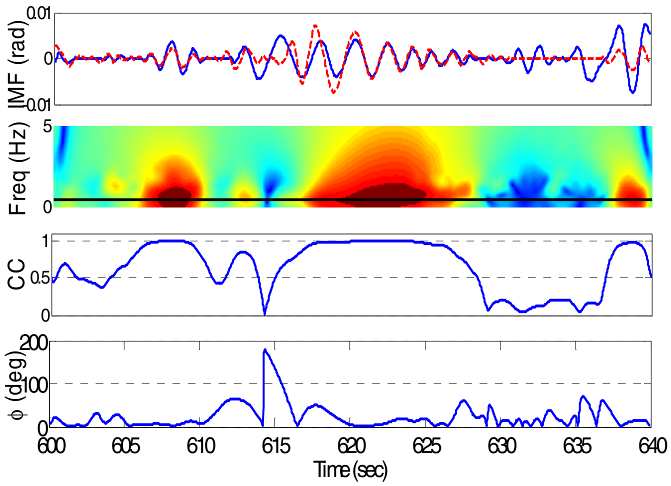


(a) Detailed plot

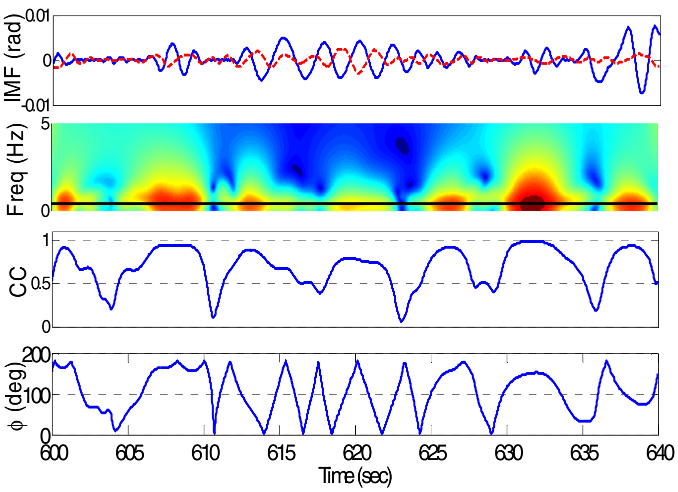


(b) Zoomed plot of S1 frame

Fig. 9Angle difference of PMUs signal of Nordic grid



(a) Analysis for frame S1 of duration 40 sec



(b) Analysis for frame S2 of duration 40 sec.

Fig. 10 Coherency between PMUs signals from Nordic grid

The coherency determined on frames S1 and S2 shown in Fig. 10 suggests that a high level and low level of coherency for most of the duration respectively. In other words, signals from PMUs of same region remain in phase, while between the two regions (S2: North-South) are out-of-phase. Findings on S3 are similar to S1 and not presented in paper due to space limitation.

VII. CONCLUSIONS

This paper presented time frequency coherency method for tracking the instantaneous coherency among the generators. The time-varying coherency relationships among the generators had been monitored using this technique, in WAMS based system. In real time PMUs signals, using the proposed method, it is possible to assess the coherency variation among the generators in a large power system network. The dynamically varying phase relationship between the generators is also visualized in time domain. This method is also useful in analyzing the sequence of events, which will provide better understanding of system dynamics. The presented approach was shown to identify the time-varying coherency using PMUs signals and thus suitable for real –time implementation. In future, this assessment will be useful in dynamic reduction of size of a large power system into a smaller one without having the need for complete knowledge of the system. Thus, can be applied in protection and security, which will improve the reliability and stability of the system.

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