4ème Conférence Internationale des Energies Renouvelables (CIER-2016)
Proceedings of Engineering and Technology – PET
Vol.18, pp.10 - 15

Wind Power Induced Inter-area Oscillations Frequency Domain Analysis

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***Abstract*— This paper addresses the issue of inter-area oscillations induced by wind power fluctuations. The study is based on frequency domain analysis of the wind output power, and modal analysis of the system dynamics. Different wind turbine technologies are tested in search of inter-area forced oscillations. Methodologically, the wind power output of turbine generators is analysed using Fast Fourier Transform FFT and the mechanism of forced oscillation (GFO) is used to determine whether power wind fluctuations can induce inter-area oscillation modes. The study is applied on a four-machine two areas power system. The results show that wind power fluctuation may excite inter-area oscillations if its FFT covers the frequency of the inter-area modes.**

***Keywords*— Wind power fluctuation, inter-area oscillation, linear analysis, general forced oscillation, Fast Fourier Transform**

I. Introduction

Inter-area oscillations are a common phenomena observed in wide area interconnected synchronous power systems. System operators have long been searching for techniques for their detection, characterization and their stabilization. These oscillations modes are of low frequency (0.1-0.7 Hz). They imply oscillations between two groups of synchronous machines connected by weak transmission lines. The slowest inter area mode usually involves all generators in the system. If poorly damped, they limit the transmission capability of the power grid and may lead to major system instabilities [1].

The analysis of actual accidents shows that these oscillations are generally induced by existing periodic disturbance sources [2 – 3]. Under a periodic disturbance, the power system may be forced to oscillate with the same frequency as the disturbance, and the amplitude of the oscillations reaches its maximum value when the oscillating frequency matches one of the natural oscillation frequencies of the power system. Many studies have shown that various power system disturbances may induce forced oscillations such as cyclic loads [4-5], turbo-pressure pulsations [6], pressure fluctuations in hydraulic turbine draft tubes [7], and wind power fluctuations [8-9].

In many power systems, wind power generation has reached a significant penetration level such as China (41%), USA (30%) and UK (15%) [10]. the variability and the randomness of wind power generation inject more random components in the grid [11], and may excite low frequency oscillations. Indeed, from the dynamics of recorded oscillations in various wide area power systems [12-13], the observed active power signals varied with random amplitude within a narrow frequency band. This observation led to speculate that these oscillations could be induced by some random excitation, such as the random fluctuation of wind power. In [12], the effect of power fluctuations of fixed-speed wind farm in the Northern Ireland power system on the inter-area oscillations was investigated. It was found by simulations that there is a correlation between the inter-area oscillation and the wind power output in the Irish electricity system. In [13], the general forced oscillation mechanism GFO has been applied to study the inter-area oscillations observed on the power grid of China. It has been proved that the wind power fluctuations may induce the observed inter-area oscillations where the power spectral density of the wind power covers the frequency of the inter-area oscillation modes.

In this paper, both linear modal analysis and frequency domain analysis are used to characterize the inter-area oscillations observed in the presence of wind power fluctuations. Different wind turbine technologies are tested in search of inter-area forced oscillations: the Squirrel Cage Induction Generator (SCIG), the Doubly Fed Induction Generator (DFIG) and the Direct Drive Synchronous Generator (DDSG). The analysis of the wind power output of turbine generators is performed using a Fast Fourier Transform FFT and the mechanism of forced oscillation (GFO) to determine if there is a correlation between the frequency band of wind power and the frequency of the resulting inter-area oscillation modes. The study is applied on a four-machine two areas power system.

ISSN 2356-5608

II. General Forced Oscillation Mechanism

The general forced oscillation is the power oscillation excited by random excitations, such as wind power fluctuations. This mechanism is regarded to be applied to study the oscillations observed in the real power systems [16].

The linearized power system can be modeled as [17]:

$$S_y(f) = |H(f)|^2 S_u(f) \quad (1)$$

Where $S_u(f)$ and $S_y(f)$ are the power spectral density (PSD) of the input stationary random process and the PSD of the output stationary random process respectively. $H(f)$ is the frequency-domain transfer function of the linear system.

It's difficult to obtain an exact value of $|H(f)|^2$ in case of high-order power system. To solve this issue equation (1) will be used to make a qualitative analysis. From equation (1), it's clear that the frequency-domain property of the system response depends on the frequency-domain property of the input random excitation and the squared amplitude-frequency property of the transfer function.

For example, assuming that the power system has three oscillation modes with natural frequencies f_1 , f_2 and f_3. If the power spectral density of the input random excitation covers one mode frequency f_1 , the power spectral density of the output random excitation is very large at f_1, and small at f_2 and f_3 as shown in Fig.1.

The General forced oscillation (GFO) mechanism indicates that if the frequency bands of the input random excitations cover the inherent frequencies of some weaker damping modes in power systems, a forced oscillation with frequency bands around the covered mode frequencies is excited [17]. Based on the general forced oscillation mechanism, it can be speculated that if there is some random excitations in the real power system such as wind power fluctuation and its power spectral density covers the frequency of the inter-area oscillation mode, the observed oscillation is the GFO caused by this random excitation.

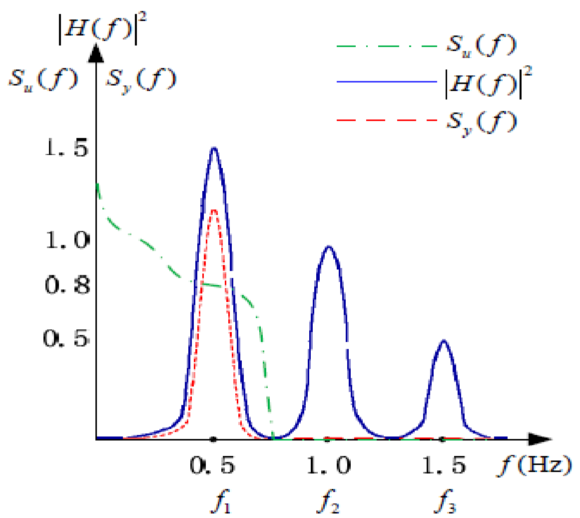

Fig. 1 Principe of GFO

III. Study Cases

This study is carried out on a four-machine two areas power system [14]. It is a well-known test system for small-signal stability. It comprised 2 equivalent generators in each area. Each synchronous generator is presented by a six-order model with magnetic saturation neglected and voltage regulators. The two areas are interconnected. There is 2800MW installed generation capacity in this system, and 400 MW of the total active power is transmitted from area 1 to area 2. At the sending end of area 1 (Bus 6), a wind farm is connected (fig.1). The penetration level is 10% of the total installed active power of area 1. The case studies are summarized in Table 1.

Simulation results were carried out using a Power System Analysis Toolbox (PSAT) [15], which is a MATLAB-based toolbox for power system studies.

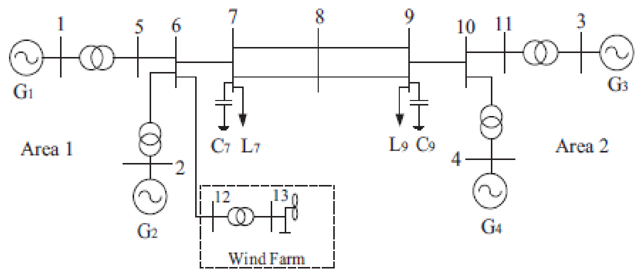

Fig. 2 Four-machine two areas power system with wind farm

TABLE I
Study Cases

Wind generator technology	Linear modal analysis	FFT of wind power output
No WTG	X	
SCIG	X	X
DFIG	X	X
DDSG	X	X

1) *Linear modal analysis*

In this section, linear modal analysis is performed to assess the resulting oscillation modes for different cases. Results are summarized in Tables 2, 3, 4 and 5. From Tables 2, 3, 4 and 5 it can be seen that without integration of wind farm there are two local modes and one inter-area mode:

- Local mode 1: Characterize oscillations of G1 against G2 in area 1.
- Local mode 2: Characterize oscillations of G3 against G4 in area 2.
- Inter-area mode 1: Characterize oscillations of generators in area 1 against generators in area 2.

With the integration of wind farm there is one more inter-area oscillation mode and its frequency depends on the type of

ISSN 2356-5608

the wind turbine technology. The frequency of the excited inter-area mode is approximately (0.16 Hz, 0.1 Hz and 0.66 Hz) in case of (DFIG, DDSG, SCIG) respectively. Thus, the wind farms when connected to the power system, they may excite oscillation modes.

TABLE II

ELECTROMECHANICAL OSCILLATIONS WITHOUT WTG

	λ	F(Hz)
Local Mode 1	-0.96513 ± 6.4296	1.0348
Local Mode 2	-0.9525 ± 6.2296	1.003
Inter-area mode 1	-0.20038 ± 3.535	0.56352

TABLE III

ELECTROMECHANICAL OSCILLATIONS WITH SCIG

	λ	F(Hz)
Local Mode 1	-0.97824 ± 6.4119	1.0323
Local Mode 2	-1.09 ± 6.0751	0.98231
Inter-area mode 1	-0.27129 ± 3.4281	0.5473
Inter-area mode 2	-0.90001 ± 4.0914	0.66673

TABLE IV

ELECTROMECHANICAL OSCILLATIONS WITH DFIG

	λ	F(Hz)
Local Mode 1	-0.96432 ± 6.4292	1.0347
Local Mode 2	-1.108 ± 6.0921	0.98549
Inter-area mode 1	-0.23235 ± 3.5819	0.57128
Inter-area mode 2	-0.277 ± 0.96701	0.16009

TABLE V

ELECTROMECHANICAL OSCILLATIONS WITH DDSG

	λ	F(Hz)
Local Mode 1	-0.96609 ± 6.4268	1.0343
Local Mode 2	-1.1049 ± 6.0819	0.9838
Inter-area mode 1	-0.23619 ± 3.5165	0.56093
Inter-area mode 2	-0.2624 ± 0.6141	0.10629

Therefore it's necessary to explain how wind farms excite oscillation modes in interconnected power system, using the mechanism of general forced oscillation which is the power system oscillation excited by the random excitations [13] given that the power wind fluctuations are considered as random excitations. For this purpose, we use the FFT analysis to convert wind power from the time domain into the frequency domain. Analyzing the frequency domain of wind power would provide the frequency band of the random excitations.

If the frequency band of the power output of the various wind turbine technologies (SCIG, DFIG, and DDSG) covers the natural oscillation frequencies of the power system, a forced oscillation with frequency bands around the covered frequencies would be excited [13].

2) *Fast Fourier Transform (FFT)*

In this section, we apply the FFT on the output power of each wind turbine generator (SCIG, DFIG and DDSG). Fig 2 depicts the wind speed profile used in our study. It's described by a Weibull distribution.

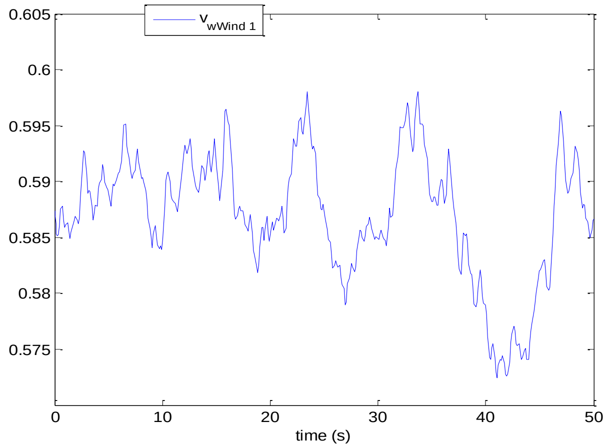

Fig. 3 The wind speed profile (PSAT)

Figures 3-8 illustrate the wind power generated by the different wind turbines (SCIG , DFIG and DDSG) and their respective FFT.

From Fig.4 it can be seen that wind power output of SCIG is distributed on a narrow frequency band ranging from 0.02 to 1 Hz. The band covers the frequency of the inter-area oscillation excited by the integration of wind farm which is approximately 0.6 Hz. Figures 6 and 8 show that the frequency band of the wind power output of DFIG and DDSG ranges from 0.02 to 0.3 Hz. This band covers the frequency of the forced inter-area oscillation mode which is (0.16 Hz, 0.1 Hz) in case of the DFIG and DDSG respectively. Therefore, the wind power fluctuation can be regarded as a narrow-band random excitation of inter-area oscillations. Its FFT covers the frequency of the induced inter-area oscillation mode. So wind power fluctuations may be considered as an excitation source of power oscillations in interconnected power system and the induced inter-area mode can be considered as the GFO caused by the wind power fluctuations.

ISSN 2356-5608

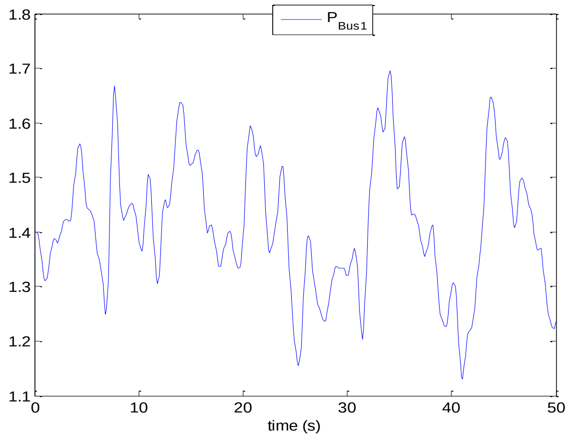

Fig. 4 The power output of SCIG wind farm

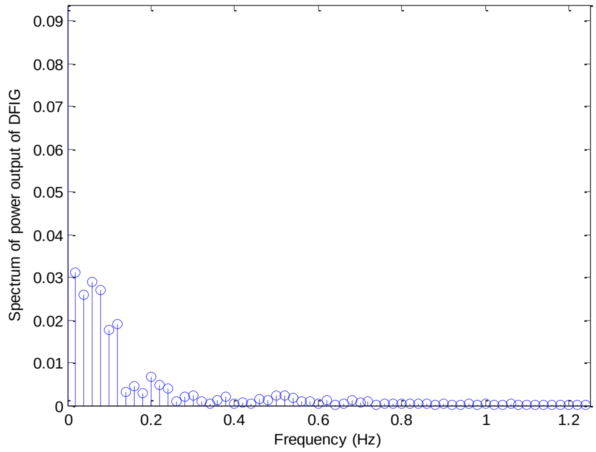

Fig.7 FFT of the power output of DFIG wind farm

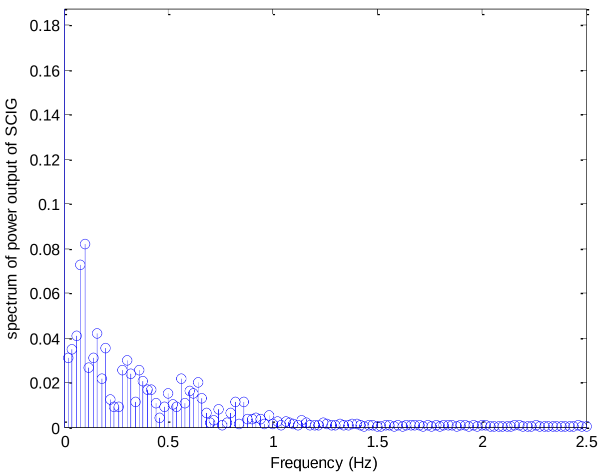

Fig. 5 FFT of the power output of SCIG wind farm

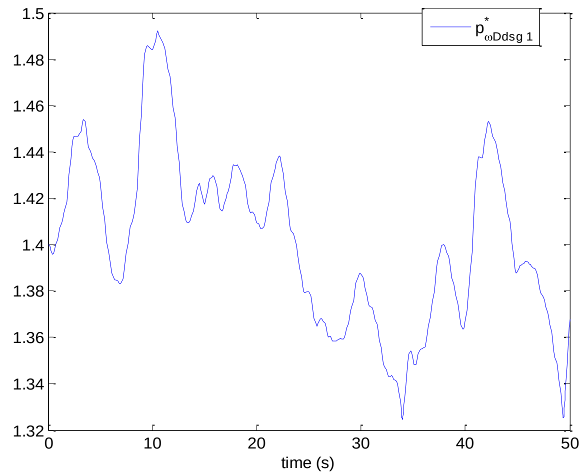

Fig.8 the power output of DDSG wind farm

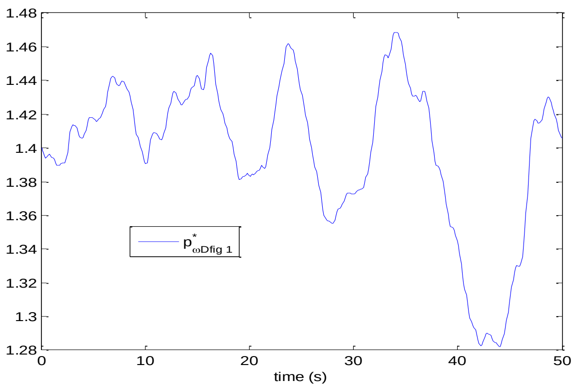

Fig.6 the power output of DFIG wind farm

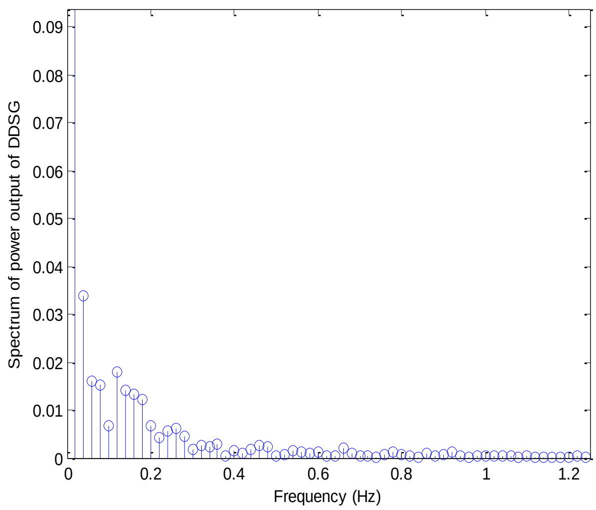

Fig.9 FFT of power output of DDSG wind farm

IV. CONCLUSIONS

This paper investigated the issue of inter-area oscillation mode excited by wind power fluctuation. The study is based on frequency domain analysis of the wind output power. Various wind turbine technologies are tested in search of inter-area forced oscillations. A FTT analysis was performed to determine if there is a correlation between the frequency band of wind power and the frequency of induced inter-area oscillation mode. The study was carried out on a four machine two areas power system.

Frequency domain analysis shows that wind power output is distributed on a narrow frequency band. This band depends on the type of wind turbine technology. It's the same in the case of variable speed generator (DFIG and DDSG). From linear modal analysis, it can be found that this frequency band covers the frequency of the induced inter-area oscillation mode. Thus, wind power fluctuation can be regarded as a narrow band random excitation to the power system. It has a considerable probability to induce inter-area oscillations in interconnected power system.

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ISSN 2356-5608