Small–Signal Stability Analysis of Grid Connected Type–A, Type–C and Type–D Wind Power Plants

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Abstract: The increased wind power penetration imposes power system stability issues on the power system. The problems are due to the generators used by different types of the wind power plants as against the conventional synchronous generators in a typical power system. Therefore, a thorough investigation was required. This lead to the study of the response to small signal stability analysis when Type-A, Type-C and Type-D wind power plants are connected to typical transmission system. The power system needs to be analyzed particularly due to the increasing wind penetration by simultaneous integration of different types of WPPs. This paper presents the small-signal stability analysis explicitly for type – A, type – C and type – D wind power plants by connecting them simultaneously. For this paper, the relevant works have been mentioned and taken into consideration. The modeling and the simulation is done with a MATLAB based toolbox especially for stability studies called Power System Analysis Toolbox (PSAT).

Index terms: *Power System Analysis Toolbox (PSAT), Small-Signal Stability, Type-A WPP, Type-C WPP, Type-D WPP, Wind Penetration Level and Wind Power Plant (WPP).*

I. Introduction

Power system stability is defined as 'the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact'[1].

The stability studies are performed for two types of disturbances: small and large disturbances. Small disturbances occur continuously in the system in the form of load changes. Large disturbances are severe in nature and occur due to short – circuit of transmission line, loss of large generator or load or loss of a tie between two subsystems [2].

The small – signal stability is defined as 'the ability of the power system to maintain synchronism under small disturbances' [1]. It depends on the initial operating state of the system [3].

The small-signal analysis is performed by the eigenvalue analysis [2]. The rotor angle deviations of the synchronous generators in normal and three-phase fault conditions are considered for the analysis [2].

Wind Power Plant (WPP), in this paper, is single large unit/cluster of wind turbine generator (WTG) units that are designed to collectively interact with and to assist the operation of host power system in the steady–state, dynamic and transient conditions.

The classification of the WPPs based on electrical generators as per [4] has been used in the paper. The WPPs have been explained in details in [4 and 5]. In this paper, type-A, type-C and type-D WPPs have been used. The working of these WPPs is given in [4].

Various bases of comparison for the different types of WPPs had been considered. These were – low frequency oscillations [6], small – signal stability [6 and 7], voltage stability [7-12] transient stability [13-17], angular stability [18], power quality issues [19] and variable speed constant frequency operation [20]. The comparison bases chosen were not contradictory in nature for a particular type of WPP. So, in this paper an attempt is made to study the small-signal stability of grid integrated type-A, type-C and type-D WPPs.

In this paper, the simulations on the IEEE 14 bus test system, as benchmark, are conducted to discuss the influence and interaction of various types of WPPs on power system transient and small – signal stabilities.

The simulations are performed using Power System Analysis Toolbox (PSAT) which is comparatively newer software (developed in 2004 – 2005) employing the excellent matrix – oriented computation techniques of MATLAB. (PSAT) is an open source MATLAB based toolbox for static and dynamic analysis and control of power system. The PSAT core has a power flow routine, which also takes care of state variable initialization [21]. This toolbox or software – package is designed for electric power system analysis and control. Besides basic power flow analysis, PSAT offers several other static/ dynamic analyses like Continuation Power Flow (CPF), Optimal Power Flow (OPF), small – signal stability analysis and time – domain simulations [22].

II. Organization of the Paper

The paper is divided into seven sections. The first section explains the power system stability along with small-signal stability. It, also, briefly discusses the wind power plants used in this paper. It also justifies the need for the current analysis.

The third section gives the adapted test system. It also gives the cases developed for the analysis. The fourth section discusses the various models of WPPs followed by the method used for small – signal stability infifth section. The sixth gives the small-signal stability analysis performed on the cases developed.The last section gives the conclusions drawn from the analysis.

III. ADAPTED TEST SYSTEM

In this paper, the IEEE – 14 bus test system is used as a test system (figure 1). This standard bus system consists of 5 synchronous generators with capacity: 615 MW, 60 MW, 60 MW, 25 MW and 25 MW. There are 11 loads with a total of 259 MW and 81.3 MVAr. The system also has 21 transmission lines, 31 branches and 4 transformers.
The IEEE – 14 bus test system represents a portion of the American Electric Power System (in the Midwestern US) as of February 1962. A much – Xeroxed paper version of the data was kindly provided by Iraj Dabbagchi of AEP and entered in IEEE Common Data Format by Rich Christie at the University of Washington in August 1993 [23].
For this paper, the models are developed by integrating type – A, at bus 02 and type – C or type – D WPP at bus 08 (table I). The WPPs are connected at buses 02 and 08 of 60 MW and 25 MW capacities respectively. The bus 01 is modeled as slack bus. The buses 02 and 08 are modeled as PV bus. The remaining synchronous generators have the rating same as that of the standard IEEE 14 bus system.

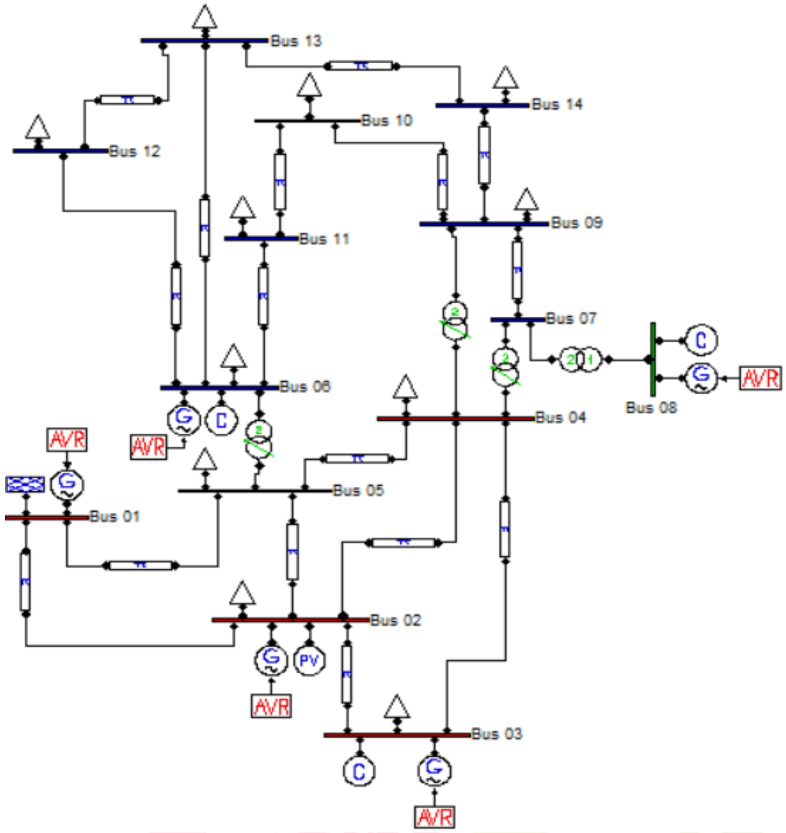

Fig. 1. Adapted Test System

TABLE I: Cases Developed For Analysis

Case	Type of WPP	Rating (MVA)
A	No WPP	-
B	Type – A and Type – C WPPs	60 and 25
C	Type – A and Type – D WPPs	60 and 25

Wind power penetration refers to the fraction of electric power produced by wind power plants compared with the total electric power generation capacity and the formula is–

$$Wind\ Power\ Penetration = \frac{Electric\ Power\ Produced\ by\ Wind\ Power\ Plants}{Total\ Electric\ Power\ Generation\ Capacity}$$

The wind penetration level for the cases B and C–

$$\text{Wind penetration } \% = \frac{60+25}{615+60+60+25+25} \times 100\ \% = 10.82\ \%$$

For the small-signal stability, the models are simulated for eigenvalue analysis which is discussed in the next section.

IV. TYPES OF WPPS

1. Type–A Wind Power Plant

The squirrel cage induction generators (SCIGs) are grid synchronized generators which rotateat a fixed speed determined by the frequency of the grid. For all purposes these machines areconstant speed. So, this Type of WPP is, also, called as constant speed wind turbine (CSWT).These are self–exciting machines without slip rings and can be connected to the grid withouthigh rating power electronic devices.

2. Type – C Wind Power Plant

The term – 'doubly fed' – points to the fact that the voltage on the stator and the rotor both.The voltage on the stator is applied from the grid and the voltage on the rotor is induced bythe power electronic converter. This allows the system to operate in variable – speed modeover a large, but restricted, range. This fact leads to the popularity of Type-C WPP as aprimary choice especially in the range of 1.5 MW and above.The Type-C WPP unites the advantages of induction generator as well as those of thesynchronous generator. It also provides the control technologies for WPPs such that it helps tominimize peak voltage values, flicker and harmonics, thus easing the connection – licensingissues for grid connection.

3. Type – D Wind Power Plant

For varying wind speeds, Type-D direct-drive WPP is used. It provides optimum powergeneration by coordinating the blade pitching and by controlling the active power of the fullycontroller power electronic converter.There are different topologies of this Type of WPP depending upon the wide range variablespeed. These topologies are:
(i) Direct–drive WPPs with large diameter, variable speed, separately excited, multi –pole WRSGs
(ii) Geared WPPs with smaller diameter, variable speed, conventional separately excited,4–pole WRSGs
(iii) Hydro–dynamically geared WPPs with smaller diameter, fixed speed, separatelyexcited, 4–pole WRSGs

V. SMALL-SIGNAL STABILITY ANALYSIS

The eigen value was used to determine the small signal stability of a power system. The eigen values helped to determine the dynamic behaviour of the power system. The response of the system was affected by the location of the eigen values. For the eigen value analysis, the eigen values were plotted on a complex plane with real and imaginary axes. The number of the eigen values increased with the size of the power system. This means, more complex the power system, more the eigen values and more the effect on the small-signal stability.

The Eigen values are categorized in two types:
(i) Real Eigen value: It corresponded to non-oscillatory mode. The real-valued eigen values had negative real value and provided pure damping. The negative real represented decaying mode and positive real showed aperiodic instability. The presence of real eigen values gives the power system stability in certainty depending upon its location, either left- or right-hand side of the complex plane.
(ii) Non real-valued or Complex Eigen value: They occurred in pairs. Each of the pair corresponded to an oscillatory mode. These were complex pairs with inversed imaginary parts which influenced both damping and oscillation. The negative real part showed damped oscillation and positive real showed oscillation with increased amplitude.

The eigen values were plotted on the Re – Im planes. For $\sigma < 0$, the eigen value was damped and it was located on the left-hand side (LHS) Re – Im plane. Such eigen values were called 'stable eigen values'.

The participation factors helped to identify the critical states of a power system. Suppose, that eigen value analysis told that the i^{th} mode was a problem mode. This meant that the mode was marginally damped or negatively damped. So, the modes with larger participation factors were the states which should be the most strongly considered to control in order to affect this problem mode i.

VI. RESULT AND ANALYSIS

For the small-signal stability analysis of case A, B and C, the eigenvalue analysis was performed (figure 2). The eigenvalue analysis, also, enabled to identify the various modes of oscillation (table II).

From the figure 2, it is seen that the eigenvalues are located on the LHS of the complex plane. In the table II, it is seen that the participation factors for some states of type – C and type – D WPPs are quite high as compared to that of type – A WPP.

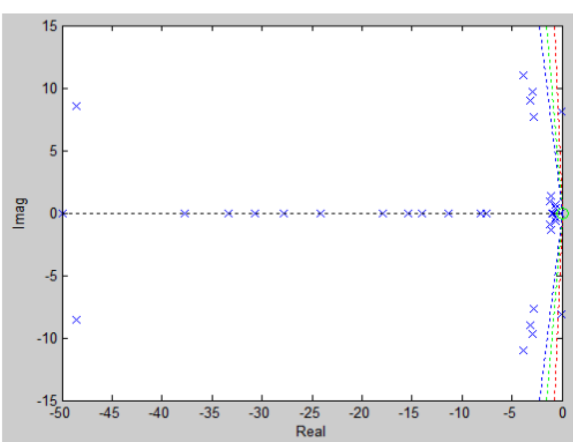

Fig 2: Eigen value analysis of case I

From the figure 2, it is seen that the eigenvalues are located on the left-hand side (LHS) of the complex (Real-Imaginary) plane. From this it is concluded that the case developed is stable.

The wind penetration level increased to 10.82% in case B and case C. All the eigen values (figure 3 and figure 4) total 53 of which 44 were negative eigen values and 9 were complex eigen values.

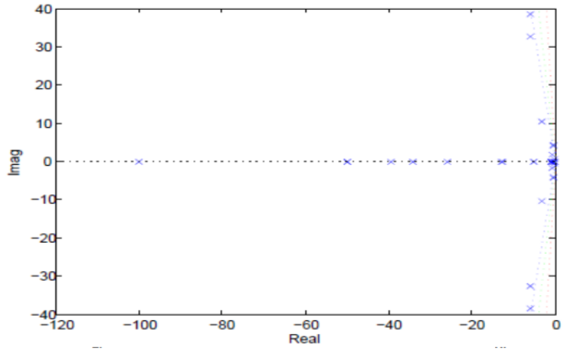

Fig. 3: Eigen value analysis of case B

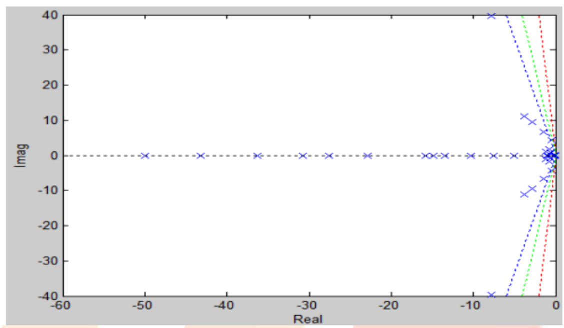

Fig. 4: Eigen value analysis of case C

The increased penetration showed that the damping ratiowas improved as compared to case A (table II). The frequency of modes remained significantly unchanged. Thus, the cases developed were stable.
The dominant modes affecting the test system cases are given in table II. The dominant states of cases A, B and C were analyzed.

Table II: Dominant Modes Affecting the Damping of the Test System

Case	Most Dominant States	Eigen value	Damping Ratio	Frequency (Hz)	Participation factor
A	ω_{Syn_2}, δ_{Syn_2}	-2.8421± 7.6264	0.3492	1.2138	0.26403, 0.26234
	ω_{Syn_3}, δ_{Syn_3}	-3.183 ±8.9765	0.3342	1.4287	0.19891, 0.19786
	ω_{Syn_4}, δ_{Syn_4}	-3.1785±9.7598	0.30966	1.5533	0.226, 0.22469
	ω_{Syn_5}, δ_{Syn_5}	- 4.0032±10.8854	0.34516	1.7325	0.27854, 0.27694
B	$i_{dr\_dfig\_1}$	-1.3304	-	0	0.79572
	$\theta_{\_p\_dfig\_1}$	-0.33333	-	0	0.73719
	$\omega_{\_m\_dfig\_1}$	-0.73323	-	0	0.99166
	$\omega_{t\_Cswt\_1}$, γ_{Cswt_1}	- 0.51911±4.1917	0.122903	0.67222	0.48151, 0.45318
C	$i_{dc\_ddsg\_1}$	- 13.1789±1.5164	0.99344	2.1113	0.34513
	$i_{qs\_ddsg\_1}$	-85.4319	-	0	0.99436
	$\theta_{\_p\_ddsg\_1}$	-0.33333	-	0	1
	$\omega_{t\_Cswt\_1}$, γ_{Cswt_1}	- 0.53082±4.2492	0.12395	0.68154	0.48371, 0.46796

As the real part of the eigen value (column 3) of the Type-A WPPs become more negative, their damping ratios (column 4) increases. The frequency (column 5) of modes of the cases with Type-A WPPs remained largely unaffected. The cases with type-C and type-D WPPs have higher participation factors than the case with type-A WPP. The high participation factors of the dominant modes depict the critical states of the system which have an overall detrimental effect on the test system.

VII. Conclusion

The deterioration of fossil fuels and the policy information on lessening greenhouse gases led to widespread power generation by wind power plants. This extensive development and implementation of WPPs raised several issues related to power system operation, dynamics and stability. Hence, it was crucial to study the effects of grid connecting the WPPs on the power system stability.

The adapted power system was the IEEE 14-bus system which was used for analysis by replacing the conventional round-rotor SGs by the Type–A, Type–C and Type–D WPPs of the same ratings as per the requirement of the cases. Depending on the configuration of the adapted power system and the wind power penetration level, the response of the system varied.

The higher the level of wind penetration is, the more the probability that the system becomes unstable. Hence, there is a need for small-signal stability analysis as the wind power penetration level increases due to the impending threat of the power system instability.

The replacement of the SGs affected the oscillation modes of the power system. The cases integrated with Type-A WPP indicated that the system was stable for small-signal stability. This was supported by [7]. With increased penetration of Type-A WPP, the oscillation modes improved as compared to Type-C WPP. Moreover, the Type-D WPP system improved the local oscillation damping related to the WPP. With the increased wind penetration the damping ratio reduced. This conclusion was supported by [6].

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