Voltage Stability Analysis of the Wind Power System Using Power System Analysis Tools

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Abstract: In power systems, voltage stability is the main issue attracting worldwide attention. This research presents an implementation of a modified IEEE 14 bus system model in Power System Analysis Toolbox (PSAT) – free and open-source software. A newly developed Doubly Fed Induction Generator (DFIG) wind turbine model is modelled and connected to a modified IEEE 14 bus system. This paper investigates the impact of the Doubly Fed Induction Generator (DFIG) on the power system stability. Here considering wind generators, DFIG is variable speed. A small-signal stability study has been conducted on a modified IEEE 14 bus system with a DFIG wind turbine system, and their simulation results have been studied in this work.

Keywords: wind power, Wind speed, power quality, voltage stability, PSAT.

1. Introduction

In many countries, wind power expands and covers a gradually increasing part of these countries' power demand. From an environmental point of view, this is a favourable development, but some technical problems need to be addressed. Growing wind power impacts the power systems into which the wind turbines feed their power. Increasing wind power penetration in a power system means that wind turbines substitute the conventional power plants that traditionally control and stabilize the power system.

Wind power plants must provide the power quality required ensuring the reliability of the power system where it is connected and fulfilling the clients connected to the same grid. Understanding the sources of disturbances affecting the power quality [6]. Fixed speed and variable speed induction generators are used for wind power generation. Integration into the grid raises issues like voltage stability and transient stability problem. Power system stability depends on parameters belonging to turbines, generators, and governors. They affect both small-signal stability and transient stability. A transient short circuit fault is a widespread disturbance in a power system [1]. It upsets the rotating machines in the vicinity of the fault, causing the speeds of these machines and the power flows in the network to oscillate. When the short circuit is cleared by disconnecting the faulted line, the accelerated generators decelerate and come back into synchronism with the rest of the system. If they do not, and the system becomes unstable, there is a risk of widespread blackouts and mechanical damage to generators. So the critical clearing time (CCT) is the maximum time interval by which the fault must be cleared to preserve the system stability [2, 3]**.** Authors of [10] investigate the modelling and the transient stability analysis of the wind-integrated IEEE 14 test bus system. The investigation aims to enhance transient stability using a central area controller in a wind-integrated power system with storage. In [11], a comparison is made among three primary types of wind turbines such as constant speed wind turbine (CSWT), Doubly Fed Induction Generator (DFIG), Direct Drive Synchronous Generator (DDSG) and their steady and transient characteristics was analyzed and simulated, respectively. The nordic grid model implemented using Power System Analysis Toolbox was also validated through time-domain simulation by applying small and large disturbances [12].

2. Wind Farm Modeling

For the studies carried out in this paper, all wind farms were based on the doubly-fed induction generator concepts. However, it can be shown that most conclusions are also valid for wind farms based on generators with fully-rated converters. Additionally, it is assumed that all wind farms are equipped with low-voltage ride-through capability and reactive current support according to the latest connection standards [5]. Even if most wind generators installed today do not comply with these requirements because they have been connected based on older grid code requirements, it is assumed that future wind generators fulfil these requirements so that problems related to low-voltage disconnection are just temporary. In order to analyze

the impact of large wind farms on the transient stability of power systems, the complete wind farm's transient behaviour must be modelled accurately. Especially when analyzing the wind farm's local stability, a detailed model of every single wind generator, including mechanical components and controller devices, must be considered. However, when investigating the farms' impact on the transmission system stability, the wind farm response at the point of common coupling (PCC) has to be modelled precisely. The complete wind farm model consists of many small wind turbines, resulting in rather long simulation times for a transmission system with several wind farms. Thus before starting the investigation of effects on the transient stability of large power systems, aggregation techniques for generator models are applied to model a complete wind farm by an aggregated wind park model representing an entire wind park by one equivalent wind generator [6].

2.1 The Doubly-Fed Induction Generator Model

In order to obtain the exact response of a doubly-fed induction generator (DFIG), all electrical components, the mechanical parts, and the controllers must be considered in the model. A doubly-fed induction machine is a standard wound rotor induction machine with a frequency-converter connected to the slip-rings of the rotor. Two PWM converters with an intermediate DC voltage circuit are set up in the converter. This paper uses a generator with an active power output of 1.5MW to build wind farms. The scheme of the DFIG is shown in Figure 1.
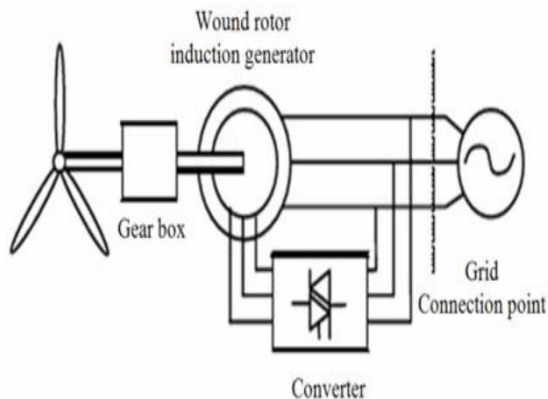

Fig.1 Doubly-Fed Induction Generator

The main components of the DFIG are • induction generator model with grid and generator side PWM converters • electrical control including low voltage ride through • mechanical parts, e.g. shaft and aerodynamics • pitch control Electrical Control An inner, fast control loop controls d- and q-axis currents by adjusting the pulse-width-modulation in dices and hence the AC-voltage of the rotor-side-and grid-side converters. The control operates sine voltage-oriented reference systems; hence, d-components correspond to active and reactive components correspond to reactive currents. An outer, slower control loop at the rotor-side converter regulates active and reactive power. DFIG Wind turbine modelling doubly-fed induction generator steady-state electrical equations are assumed, the flux dynamics of stator and rotor are fast compared to grid dynamics, and the generator decoupling from the grid can be done by the converter control mechanism. These assumptions lead to the following equations.

$$V_{sd} = R_s i_{sd} + \frac{d\Psi_{sd}}{dt} - \omega_d \Psi_{sq} \quad (1)$$

$$V_{sq} = R_s i_{sq} + \frac{d\Psi_{sq}}{dt} + \omega_s \Psi_{sd} \quad (2)$$

$$V_{rd} = R_r i_{rd} + \frac{d\Psi_{rd}}{dt} - (\omega_s - \omega)\Psi_{rq} \quad (3)$$

$$V_{rq} = R_r i_{rq} + \frac{d\Psi_{rq}}{dt} - (\omega_s - \omega)\Psi_{rd} \quad (4)$$

Where,

$$\Psi_{sd} = L_s i_{sd} + L_m i_{rd} \quad (5)$$

$$\Psi_{sq} = L_s i_{sq} + L_m i_{rq} \quad (6)$$

$$\Psi_{rd} = L_r i_{rd} + L_m i_{sd} \quad (7)$$

$$\Psi_{rq} = L_r i_{rq} + L_m i_{sq} \quad (8)$$

These are the voltage and flux equations for resistance and inductance currents. The ω_s represent the angular velocity at synchronous speed. Rotor angular velocity is given as

$$\omega_r = \omega_s - \omega \quad (9)$$

The torque is given as follows,

$$T_m = n(\Psi_{sq} i_{rd} - \Psi_{sd} i_{rq}) \quad (10)$$

4. TOOL USED

PSAT is a MATLAB toolbox for electric system analysis and control. PSAT includes power flow, optimal power flow, continuation power flow, small signal stability analysis and time-domain simulation. All operations can be evaluated through graphical user interfaces (GUI), and the Simulink-based library provides a user-friendly tool for network design. PSAT contains the power flow routine, which also takes care of state variable initialization. Once the power flow has been completed, other static and dynamic analyses can be executed [6]. These routines are:

1. Continuation power flow;
2. Optimal power flow;
3. Small signal stability analysis;
4. Time-domain simulations;
5. Phasor measurement unit (PMU) placement.

In the proposed solution, we are experimenting with the IEEE-14 bus system. For doing so, we use PSAT, a Matlab-based Simulink & Simulation tool for Power System Analysis.

5. Results and Discussions

Impact of Location

In order to assume the wind power's impact on the power system's angular stability, we included a three-phase symmetrical fault, and then we calculated the CCT corresponding to a case without a wind source and other cases where a wind source is connected to the test system by different Buses.
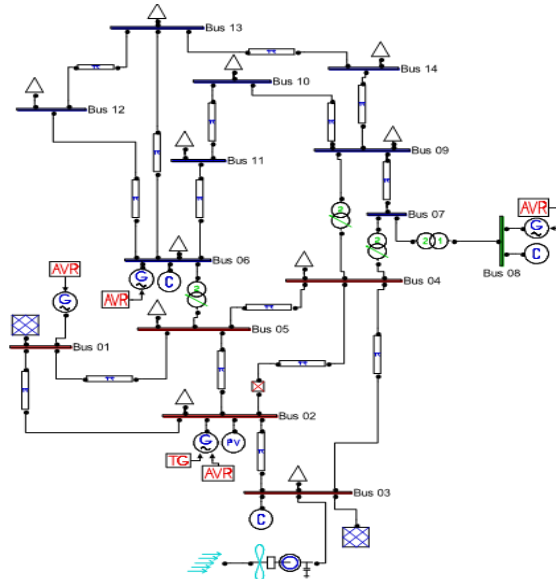

Fig.3. Simulation model of 14 IEEE bus systems

The proposed methodology has been tested on IEEE 14-bus modified test system, as shown in Figure 2. The wind farms have been connected to wind buses, and the loads have been scaled down to 50% from 100% initially to form the base case. Bus-2 is a PV bus, and 3, 6 and 8 are synchronous compensator buses. Loads were modelled as constant power loads (PQ load). The load sharing between the wind and system generators is through the initial power angle setting. The simulations use PSAT simulation software [9]. PSAT is power system analysis software with many features, including power flow and CPF. Using the CPF feature of PSAT, the voltage stability of the test system is investigated.
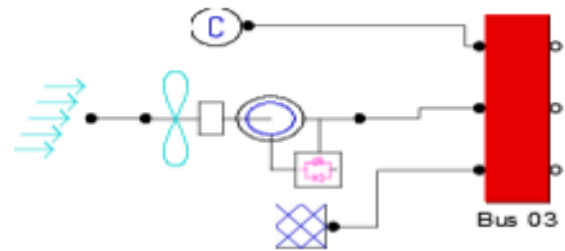

Fig. 3. DFIG connected to the modified IEEE14 bus system

The impact of wind turbines on power systems leads to a small signal stability problem. In DFIG based system, all poles lie entirely on the left-hand side, so the system is completely stable as small-signal stability is considered.

Without a Wind Source

The Base Case represents the system's normal operation without any wind power connected to the system. The critical fault clearing time (CCT) can be determined using transient simulations [3]. For this case, the result is CCT = 196 ms. Fig. 4 shows the speed generators compared to a fault clearing time close to the critical clearing time. In Fig.5, the fault introduced has a duration of t = 197 ms, so the time exceeds the stability limit of CCT.
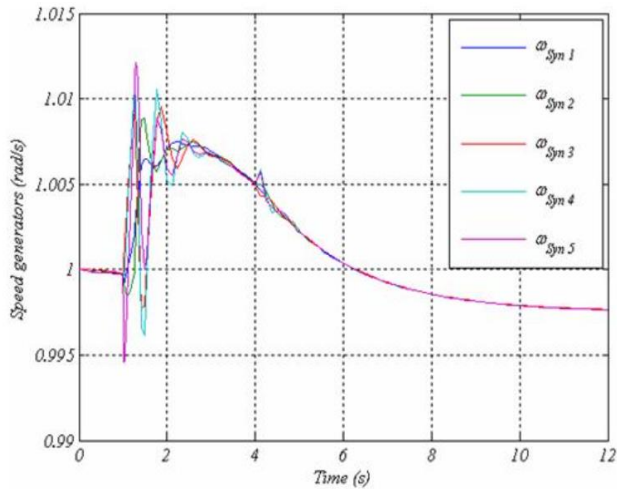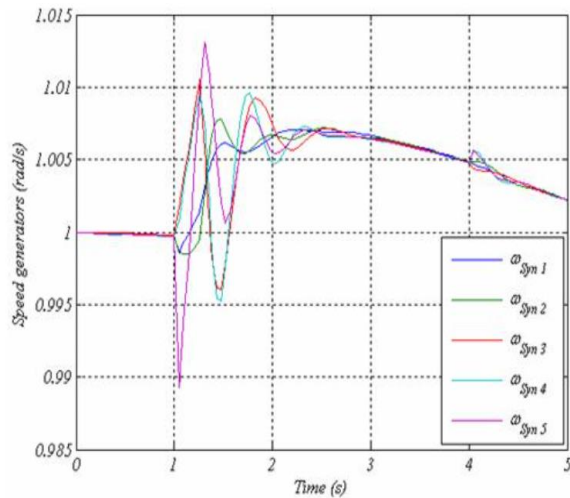
Fig.4. The rotor speed of all generators at t = 196 ms

Fig.5. The rotor speed of all generators at t=197 ms

With a Wind Source
After that, one wind turbine generator is connected to the system through a transmission line on different buses to evaluate their effect on the angular stability.

Table1. Results from the simulations for the angular stability in different locations

Bus Number	Bus 1	Bus 2	Bus 3	Bus 4
CCT(ms)	186	187	263	220

Compared to the previous case where any wind source was connected, the integration of the wind source had increased the transit stability when it was connected at BUS 8 or BUS 14, but on the contrary, for cases of BUS 1 and BUS 3, so there is no general

statement possible, if wind generation improves transient stability margins or if the impact is rather negative. The answer depends on the location of wind resources, and the problem has to be analyzed individually for each case.

Effect of Type of Generator Technology
In order to determine the effect of the type of generator technology on the transit behaviour of the grid, two types of generators are studied with keeping the same fault and the exact location of the wind source.

Case 1: Fixed Speed
The critical fault clearing time (CCT) can be determined using transient simulations. For this case, where the wind source is connected to Bus N°3, the result is CCT = 187 ms. Fig. 6 shows the speed rotor of all generators in comparison to a fault clearing time close to the critical clearing time.

Case 2: Variable Speed (DFIG Technology)
The fixed speed generator added to Bus 3 is now disconnected and substituted by a doubly-fed induction generator (DFIG) having the same power (2MW). Thus, the technology change can be considered and analyzed. The analysis of the CCT results in an increased stability limit compared to Case 1 with only fixed speed generators in service. The time increases to CCT = 216 ms, as shown in figure 7. The transient network stability is enhanced when DFIG is connected instead of a fixed speed generator.
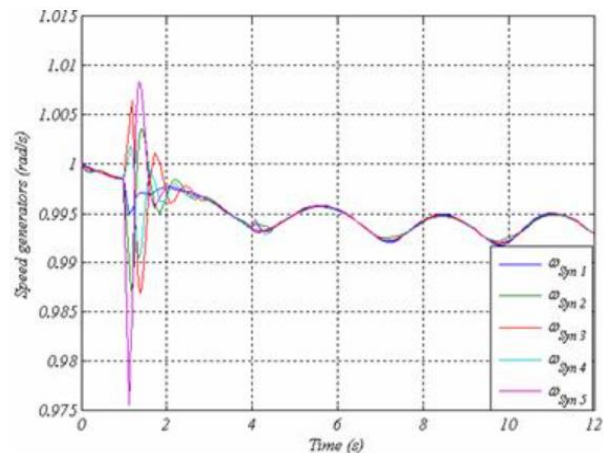

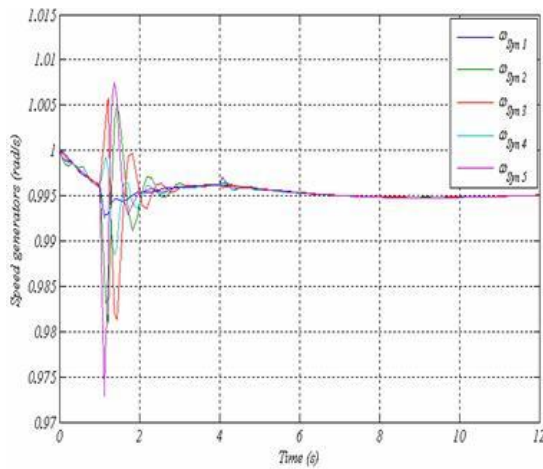Fig.6. The rotor speed of all generators at t=187 ms

Fig.7. The rotor speed of all generators at t=216 ms

According to the results, it is evident that the DFIG generator increases the critical clearing time; consequently, this type of generator presents the best performance than a squirrel cage induction generator concerning the angular stability of grid-connected to wind power. The Wind power generation with DFIG provides better angular stability after fault clearance due to its ability to control reactive power.

5. Conclusion

This work presents the IEEE 14 bus system model, a novelty in its implementation in free and open-source software, power system analysis Toolbox. This model considers detailed modelling of the dynamics, which play an essential role in assessing the systems' behaviour; in particular, the recently developed wind turbine and controller model implementation in this tool is significant. Simulation results show that the DFIG-based system is stable within a few seconds of the disturbances.

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