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Effect of AVR and PSS on Power System Transient Stability with Different Wind Generation Technologies

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Abstract

In the last decade, wind generation has been the fastest growing energy source globally. However, higher penetration of wind energy into existing power networks raises concern for power system operators and regulators. In this paper, we investigate the effect of wind farms employing doubly-fed induction generators (DFIGs) on the transient stability of power systems. We carried out simulations to demonstrate and compare the transient performance of the standard 3-machine 9-bus system with and without wind power integration during a fault. We analyzed the generator technology mentioned, replacing one synchronous generator in the system. We also analyzed the mentioned system after introducing the automatic voltage regulators (AVR) and power system stabilizers (PSS) into the system. We simulated the system using DIgSILENT PowerFactory. Our results show that a better transient performance is achieved with the inclusion of DFIGs in the system. There is also a further improvement of the transient stability after including both the AVR and PSS in the simulations.

Keywords: Squirrel cage induction generators, Doubly-fed induction generators, Transient stability, Automatic Voltage Regulator, Power System Stabilizer.

1. Introduction

Wind power is not something new in the world. This is because it was in use even in the ancient times for applications such as: pumping water, grinding mills and propelling boats. The remarkable contribution in the electricity supply began in the mid 1980s and is now firmly established as one of the major technologies for electricity generation in the world. It is one of the fastest growing electricity generating technologies and features in energy plans across the world, both in the developed and the developing world. According to the World Wind Energy Association, over 239 GW of capacity is now installed worldwide, with China for instance having over 62 GW installed capacity [1]. In the same report it is evident that some countries have high penetration levels like Denmark where about 25% of the power demand is supplied from wind. It is also evident that the installed wind capacity has been increasing significantly around the world in the recent past. Wind power's rapid expansion has been driven by a combination of factors such as environmental benefits and various state and federal policies and incentives [2, 3].

2. Wind Generation Technologies

Induction generators are the most commonly used in wind turbines because they are cheap and widely available [4]. Two kinds of induction generators are normally used in wind turbines which are:

i. Squirrel cage induction generators (SCIGs).
ii. Doubly fed induction generator (DFIGs).

2.1 Squirrel Cage Induction Generators

Wind turbines based on this technology are directly coupled to the grid as shown in Figure 1 below.

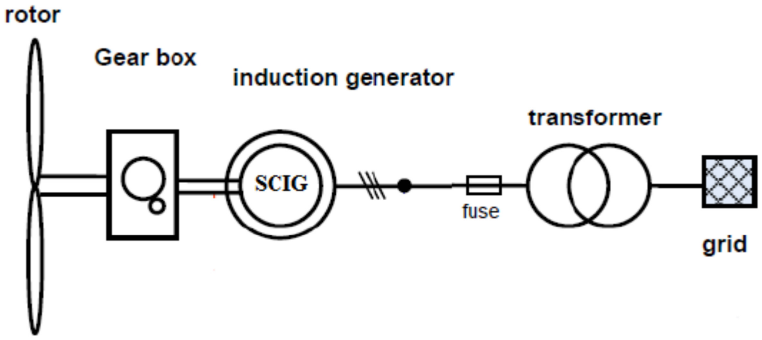

Figure. 1. Grid connected Squirrel cage induction generator.

The slip, and hence the rotor speed of a squirrel cage induction generator varies with the amount of power generated. These rotor speed variations are, however, very small, approximately 1 to 2 per cent. Therefore, this wind turbine type is normally referred to as a constant speed or fixed speed turbine. A squirrel cage induction generator always consumes reactive power. In most cases, this is undesirable, particularly in case of large turbines and weak grids. Reactive power consumption of the squirrel cage induction generator is nearly always partly or fully compensated by capacitors in order to achieve a power factor close to one [5].

The equivalent circuit of SCIG used in DIgSILENT is shown in Figure 2. The model is characterized by the stator winding resistance Rs, the stator leakage reactance Xs, the magnetizing reactance Xm, the rotor impedance Zrot, the stator terminal voltage U, and ring voltage of the rotor Ur. The dynamic model of the induction generator uses the steady state parameters defined in the equivalent diagram depicted in Figure 2.

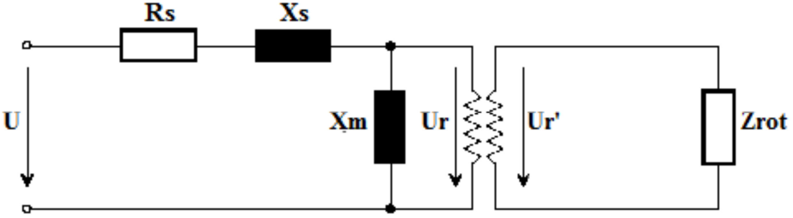

Figure. 2. Equivalent circuit of squirrel cage induction generator.

DIgSILENT provides a d-q model, expressed in the rotor reference frame:

$$u_s = R_s i_s + j\omega_{syn}\psi_s + \frac{d\psi_s}{dt}$$
$$0 = R_r i_r + j(\omega_{syn} - \omega_r)\psi_r + \frac{d\psi_r}{dt} \quad (1)$$

where μ, *i*, and ψ are space vectors for the voltage, current and flux, respectively. w_{syn} is the synchronous speed, while w_r is the angular speed of the rotor. As the rotor is short-circuited in the squirrel-cage induction generator, the rotor voltage is set to zero. The generator inertia is specified in the form of an acceleration time constant in the induction generator type. The dynamic model of the induction generator is completed by the mechanical equation [6].

$$J\dot{\omega}_r = T_e - T_m \quad (2)$$

where J is generator inertia, T_e is the electrical torque, T_m is the mechanical torque. The mechanical equation can be rated to the nominal torque:

$$T_n = \frac{P_n}{[\omega_n(1 - s_n)]} \quad (3)$$

and thus the acceleration time constant Tag can be expressed as:

$$T_{ag} = \frac{J(1 - s_n)\omega_n^2}{P_n} \quad (4)$$

where w_n is the nominal electrical frequency of the network, P_n is the nominal power and s_n is the nominal slip.

2.2 Doubly Fed Induction Generators

The DFIG is a wound rotor type of an induction machine, the three phase rotor terminals are connected to back-to-back PWM power converters. The power converters are then connected to the grid. The stator terminals are connected directly to the grid. This is illustrated in Figure 3.

In contrast to a conventional, squirrel cage induction generator, the electrical power of a doubly-fed induction machine is independent from the speed. Therefore, it is possible to realize a variable speed wind generator allowing adjusting the mechanical speed to the wind speed and hence operating the turbine at the aerodynamically optimal point for a certain wind speed range [7].

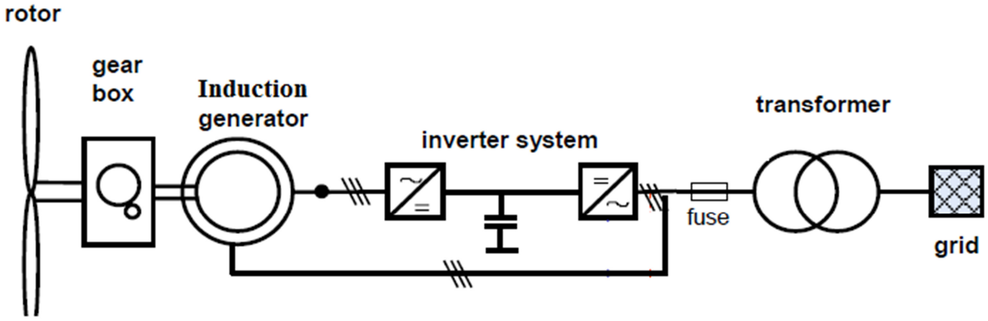

Figure 3. Grid connection of doubly fed induction generator.

The DFIG equivalent circuit is similar to that of a conventional generator except that the rotor circuit includes the power converters. The doubly-fed induction generator (DFIG) model in DIgSILENT equivalent circuit is as illustrated in the figure 4

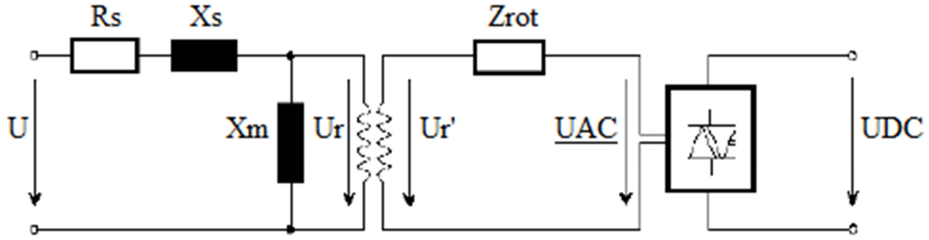

Figure. 4. Equivalent circuit model of DFIG

Where:

U is the stator terminal voltage. **Rs** Is the stator resistance.
Xs The stator reactance **Zrot** The impedance of the rotor circuit.
Ur The slip ring voltage of the rotor. **UAC** The ac rotor slip ring voltage.
UDC The dc voltage on the DC bus of the converter.

The doubly-fed induction generator (DFIG) model as shown above extends the usual squirrel cage induction generator by a PWM rotor side converter in series to the rotor impedance Zrot. The PWM converter inserted in the rotor circuit allows for a flexible and fast control of the machine by modifying the magnitude and phase angle of the generators AC voltage output UAC on the rotor side. This is done by modifying the modulation factor PWM. Based on the power balance between the AC and DC side of the converter, the DC voltage and DC current can be then calculated. The AC-DC relationship of the PWM converter is the following (the AC voltage is expressed as line-to-line voltage)

$$U_{ACr} = \frac{\sqrt{3}}{2\sqrt{2}}.PWM_r.U_{DC}$$
$$U_{ACi} = \frac{\sqrt{3}}{2\sqrt{2}}.PWM_i.U_{DC} \qquad (5)$$

Where *PWMr* and *PWMi* are the real and imaginary components of the modulation factor, respectively. U_{ACr} and U_{ACi} are the real and imaginary components of the AC voltage. It is assumed that a standard bridge consisting of six transistors builds the converter and that an ideal sinusoidal pulse width modulation is applied. The relationship between AC and DC currents can be found by assuming that the PWM converter is loss free:

$$P_{AC} = Re(U_{AC} I_{AC}^{*}) = U_{DC} I_{DC} = P_{DC} \qquad (6)$$

During time domain simulations the converter is controlled through the pulse width modulation factors PWMd and PWMq, which define the ratio between DC-voltage and the AC-voltage at the slip rings. The model equations of the doubly-fed machine can be derived from the normal squirrel cage induction machine equations by modifying the rotor-voltage equations:

$$\underline{u}_s = \underline{R}_s \underline{i}_s + j\frac{\omega_{syn}}{\omega_n}\underline{\psi}_s + \frac{1}{\omega_n}\frac{d\underline{\psi}_s}{dt}$$
$$\underline{u}_r e^{-j(\omega_{syn}-\omega_r)t} = \underline{R}_r \underline{i}_r + j\frac{(\omega_{syn}-\omega_r)}{\omega_n}\underline{\psi}_r + \frac{1}{\omega_n}\frac{d\underline{\psi}_r}{dt} \qquad (7)$$

The per unit rotor voltage that appears in the above equation is related to the DC- voltage as follows:

$$u_{rd} = \frac{\sqrt{3}}{2\sqrt{2}}.PWM_d.\frac{U_{DC}}{U_{rnom}} \qquad (8)$$

$$u_{rq} = \frac{\sqrt{3}}{2\sqrt{2}}.PWM_q.\frac{U_{DC}}{U_{rnom}}$$

where *Urnom* is the nominal rotor voltage.

3. Case Study

The standard 9 bus system shown in Figure 5 was considered in carrying out our analysis [8].

In our study synchronous generator G3 which generates about 20% of the system installed capacity is replaced with a wind farm. All the operating conditions are given provided in the appendix. The wind farms were based SCIGs and DFIGs. An assumption was made that wind speed is constant and the wind turbines were producing their maximum rated power. A three phase short circuit was applied on the transmission line connecting buses 7 and 8 at 5% distance from bus 7. The fault was cleared by tripping the line 7-8 at both ends. Analysis on each of the above generator technologies was carried out separately. G2 was the nearest to the fault location and therefore was the most affected. For this reason we considered its post fault behavior in our analysis. We first carried out analysis without any excitation control system. In the second case we analysed the system with AVR only and finaly with both the AVR and PSS. The controllers and generator data are also given in the appendix.

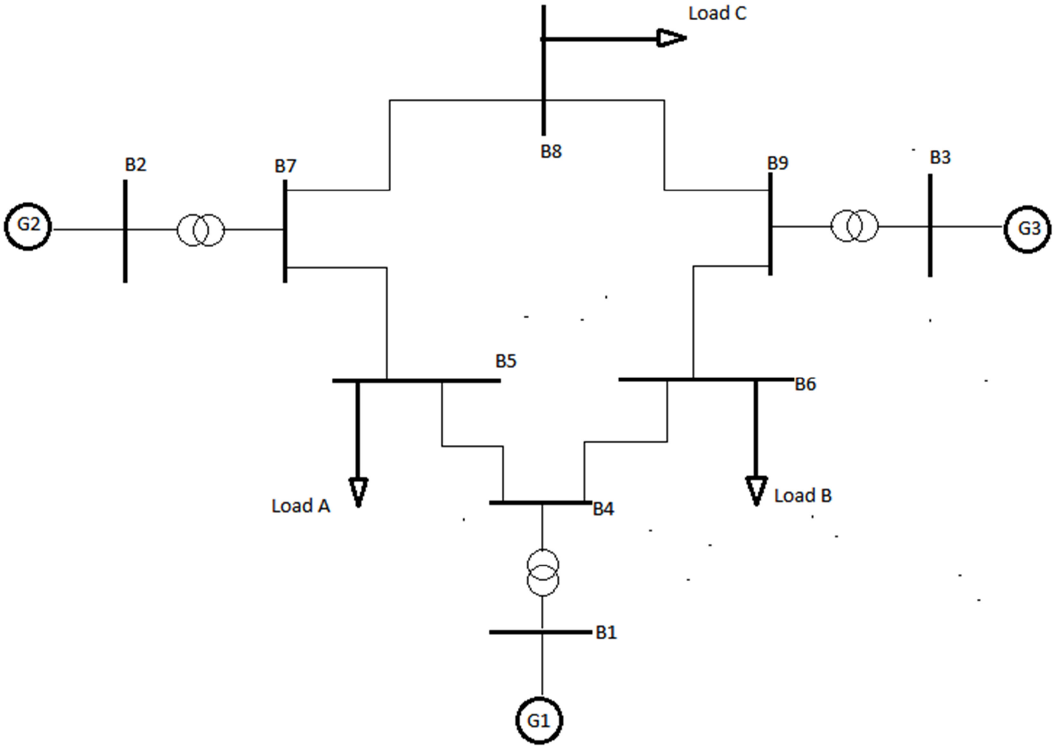

Figure 5. IEEE standard 9 bus system.

4. Simulation Results and Discussion

4.1 Without AVR and PSS.

For this case the excitation control was not included in the simulation. It is evident that the for DFIG the rotor angle settles faster compared to SCIG.

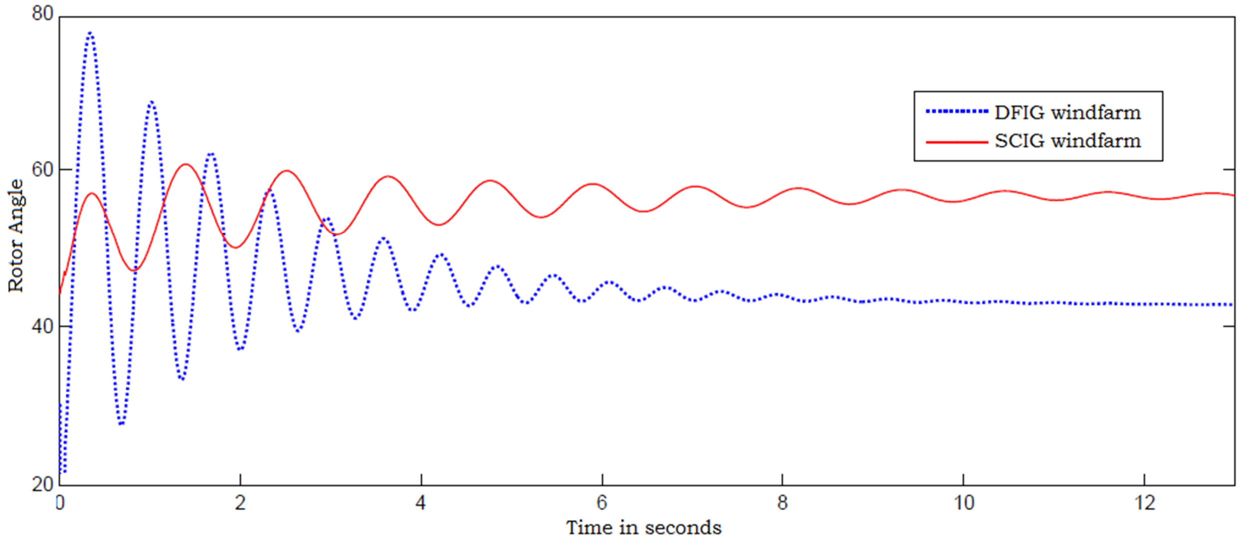

Figure 6. G2 Rotor angle with no excitation control.

4.2 With AVR only.

Here we only modelled the automatic voltage controller (AVR). This as it can be seen has a negative damping effect to the system.

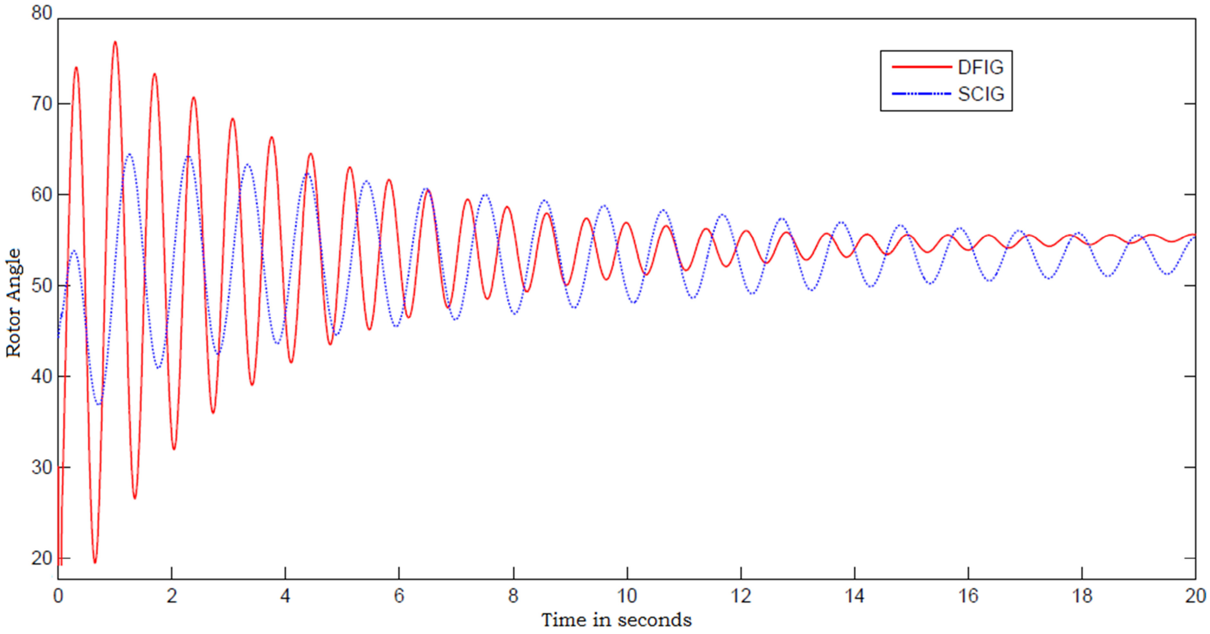

Figure 7. G2 Rotor angle with AVR only

4.3 With both AVR and PSS

Both the AVR and PSS were included in this case and from the results it can be seen that the rotor oscillations are very well damped.

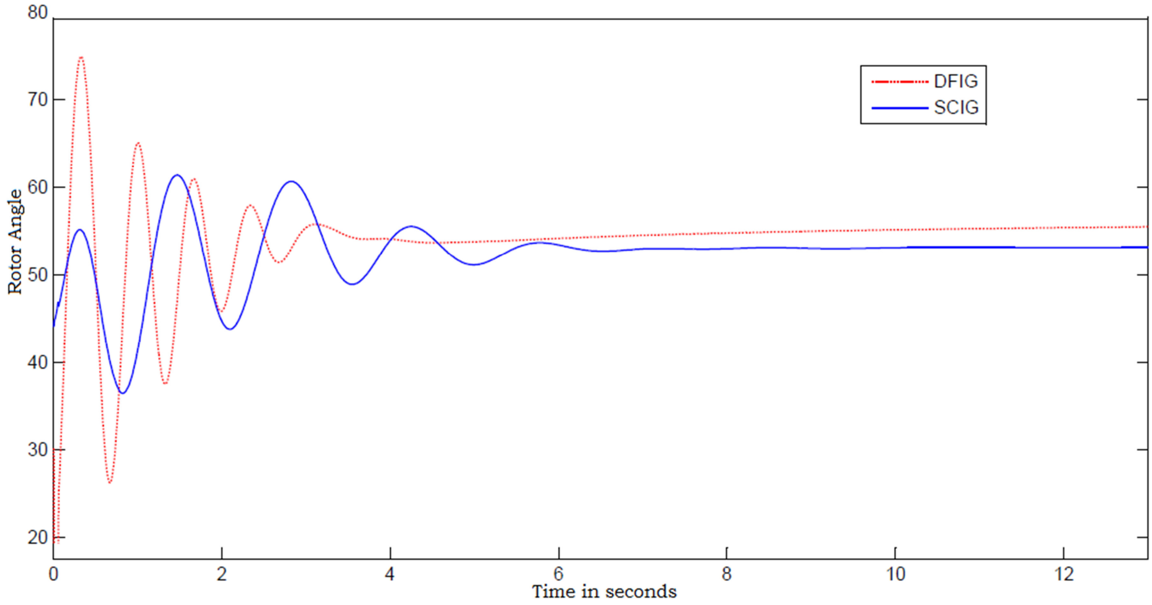

Figure 8. G2 Rotor angle with both AVR and PSS.

5. Conclusion

This paper investigated an efficient method of analyzing the of excitation control system on transient stability performance of a power system with different wind generation technologies. The standard IEEE 9-bus system with 3 synchronous generators was used in this study. The performance of the system without any excitation control was studied first. Furthermore, the impact of power from wind considering two generator technologies was investigated one at a time. The results show that with DFIG based wind power integration transient stability improves. Our results agree with other published works for instance in Ch. Eping et al [9]'s work they came with the same conclusion. Also our results have shown that the inclusion of PSS along with AVR damps out the rotor angle oscillations therefore further improving the transient stability.

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