Capacity and Location Effects of Wind Turbine Energy Systems on Power Systems Stability

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Abstract- This paper presents a detailed analysis of the optimum location and rating of wind turbine for studying the voltage stability and transient stability of electric power system. The 9-bus IEEE system was used as the study case. The wind turbine used is a variable speed doubly-fed induction generator (DFIG). The wind turbine has been installed at different buses in order to get the best location. The wind power has been changed to obtain the optimum value. Finally, a fixed capacitor with different ratings has been connected with the wind turbine to obtain the best power factor (pf). The simulation analysis was established by PSAT/MATLAB, which gives access to an extensive library of grid components, and relevant wind turbine model.

Keywords - Wind turbine, voltage stability, transient stability.

I. INTRODUCTION

The growing importance of wind power, which can be observed in many European countries, the USA, Canada and also Australia requires detailed analysis of the impact of wind power on power system stability [1-14]. Therefore, some studies have been carried out recently and are currently carried out for identifying required network reinforcement, reserve requirements and the impact of wind power on power system stability [2]. These studies are dealing with different aspects related to wind power, such as the fluctuating nature of wind power, location of wind resources, various generator technologies and generator control.

There is no doubt that wind power will play a predominant role in adding clean and nonpolluting energy to the country’s grid. However, as more wind turbines are connected to the grid, their impact on the power quality of services populated with wind generation is becoming more evident, so it is important to analyze the voltage stability and transient stability of power system including wind power stations [3-10].

Meanwhile, as wind power generation is a relatively new technology in power system studies, unlike other conventional power plant technologies, no standardized model is available today. Many studies on various wind turbine technologies have been presented in literature. Most of these studies are more focused on detailed machine rather than its effect and applicability in power system studies. In many cases, it was found that the model provided is over simplified or the other way around, far too detailed with respect to power system stability studies [6]. An appropriate model for wind turbine is essential for power system stability studies. This model is accurately performed using PSAT/MATLAB [9].

Currently, three main wind turbine types are on the market namely, squirrel cage induction generator, doubly fed (wound rotor) induction generator (DFIG), and direct drive synchronous generator. The main differences between the three concepts are the generating system and the way in which the aerodynamic efficiency of the rotor is limited during high wind speeds [4].

This paper deals with the DFIG as it has more control possibilities and reactive power capabilities. The test system used is a 9-bus IEEE system. In the voltage stability analysis, PV curves, voltage profiles, and loading parameter are discussed. In the transient stability analysis, rotor angles of the synchronous generators and voltage magnitude of the faulted bus have been discussed. The best value of wind power and placement of wind turbine are stated for both voltage stability and transient stability analysis.

The organization of this paper is as follows: Section II describes the wind model and the test system, Section III describes the simulation results for the voltage stability and transient stability analysis, and Section IV presents the overall conclusion of the paper.

II. WIND MODEL AND TEST SYSTEM

A. Wind model:

DFIG is a wound rotor induction generator with a voltage source converter connected to the slip-rings of the rotor. The stator winding is coupled directly to the grid and the rotor winding is connected to the grid via a power electronic converter. The typical configuration of a wind turbine based on a DFIG is shown in Figure 1. The rotor winding is supplied using a back-to-back voltage source converter [5]. In high wind speeds the power extracted from the wind is limited by pitching the rotor blades. The reactive power exchanged between the machine and the network can be controlled up to certain limits.

For power system stability studies, modeling of DFIG should be considered for steady state analysis as well as for large disturbance dynamic analysis. As DFIG units have reactive power capability, the wind farm is modeled in a way similar to the conventional generator for steady state analysis and is represented as either PV bus with appropriate VAR limits or PQ bus with constant power factor [8]. In this paper, DFIG has been modelled as PQ generator for steady state analysis.
For power system dynamic simulations, the wind farm is modeled as a single equivalent machine. Several components that contribute to the dynamic behavior of DFIG are included. These components are: turbine aerodynamics, shaft dynamics, generator electrical characteristics, and electrical controls. Details of the steady state and transient stability analysis are found in [11-12].

### B. Test system:

The IEEE 9-bus system is used for this study. Single line diagram of the system is illustrated in Figure 2. The system data is found in [6-7]. A modification from the original system is that the loads were doubled. This modification was done in order to make the system weak and hence the voltage stability problem becomes clear.

![Figure 2: 9-Bus IEEE system](image)

### III. SIMULATION RESULTS

#### A. Voltage Stability Analysis:

In this analysis we determined the optimum location and rating of wind turbine which achieve the maximum loading parameter ($\lambda_{\text{max}}$) of the system. Figure 3 shows the PV curves for buses 5, 6, and 8 without wind power. $\lambda_{\text{max}}$ was equal to 1.27 pu. The figure shows that Bus 5 is the worst bus as it contains the largest load.

The wind turbine was connected to the system at buses 5, 6, and 8 (i.e., load buses). Figure 4 shows the variation of $\lambda_{\text{max}}$ with both the location of wind turbine and the value of the wind power. The wind power was assumed to have unity power factor. $\lambda_{\text{max}}$ increases with increasing wind power at the three locations. However, Bus 5 exhibits the greatest values of $\lambda_{\text{max}}$. Results of Figures 3 and 4 coincide and show that to enhance the voltage stability, the best location of wind turbine is the weakest bus which contains the largest load. In this case, it is Bus 5. The optimum value of wind power at Bus 5 was 1.0 pu, after which $\lambda_{\text{max}}$ starts to decrease.

![Figure 3: P-V curves for load buses without wind power](image)

![Figure 4: Maximum loading parameter $\lambda_{\text{max}}$ with unity pf wind power](image)

Power factor of the wind power is also considered, as it has a great effect on the voltage stability. Power factor can be varied by connecting variable steps parallel capacitors with the wind turbine. Different cases are now discussed to explain the effect of the power factor of the wind power at Bus 5 on the PV curves of Bus 5 and the voltage profiles of the buses. These cases are:

- Case 1: Without wind power.
Case 2: With wind turbine at Bus 5, 1.0 pu wind power, and 0.9 pf lagging.

Case 3: With wind turbine at Bus 5, 1.0 p.u wind power, and unity pf

Case 4: With wind turbine at Bus 5, 1.0 pu wind power, and 0.9 pf leading.

Figure 5 shows the PV curves of Bus 5 for the above cases. It is clear that $\lambda_{\text{max}}$ increases at leading pf wind power. $\lambda_{\text{max}}$ values are 1.27, 1.18, 1.43, and 1.53 for Case 1 – 4, respectively. An increasing of 20% between lagging and leading pf can be obtained.

The voltages magnitude at Buses 4 – 9 for the above cases are shown in Figure 6. It is clearly shown that the leading pf wind power exhibits the best voltage profile. Figure 5 and Figure 6 show that for voltage stability enhancement, leading pf wind power is preferred.

B. Transient Voltage Analysis:

In this analysis we determined the optimum location and rating of wind turbine which achieve system stability and the least oscillations in power angles and voltage waveform of the faulted bus. We are confined to fault at Bus 7 at this is the worst case of this system [7]. To force the system to be unstable without wind power, 10-cycle fault at 60 Hz frequency was assumed at Line 5-7 very near to Bus 7. Table 1 shows the events sequence of the simulation. Power angles and voltage of Bus 7 were displayed.

Figure 7 shows the voltage of Bus 7 at unity pf for different wind powers when the wind turbine is located at Bus 5. The figure shows that 1.7 pu wind power is reasonable choice. Below 1.2 pu and more than 2.0 pu wind power the system was unstable and the voltage failed to build up. Power angles for 1.7 pu wind power is shown in Figure 8.

![Figure 5: Voltage at Bus 5 as Function of Maximum Loading Parameter $\lambda_{\text{max}}$](image)

![Figure 6: Voltage profiles of Buses 4 – 9 Cases 1 – 4](image)

![Figure 7: Voltage of Bus 7 at unity pf for different wind powers when the wind turbine is located at Bus 5](image)

![Figure 8: Power angles at 1.7 pu and unity pf wind power when the wind turbine is located at Bus 5](image)

Table 1: Sequence of simulation events

<table>
<thead>
<tr>
<th>Step</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1</td>
<td>Steady state operating conditions</td>
</tr>
<tr>
<td>Step 2</td>
<td>1s later, 3-phase to ground fault near Bus 7 at Line 5-7</td>
</tr>
<tr>
<td>Step 3</td>
<td>10-cycle later a circuit breaker was opened to remove Line 5-7</td>
</tr>
<tr>
<td>Step 4</td>
<td>12-cycle later the circuit breaker closed again to return back Line 5-7</td>
</tr>
</tbody>
</table>
Figure 9 shows the voltage of Bus 7 at unity pf for different wind powers when the wind turbine is located at Bus 6. The figure shows that 1.7 pu wind power is reasonable choice. Below 1.0 pu and more than 2.0 pu wind power the system was unstable and the voltage failed to build up. Power angles for 1.7 pu wind power is shown in Figure 10. Angle oscillations in Figure 10 are greater than those in Figure 8. Between Figures 7 and 13 shows that the voltage at Bus 7 is greater with unity pf wind power that with leading pf one. Power angles for 1.7 pu wind power is shown in Figure 14. A comparison between Figures 8 and 14 shows that the oscillation of power angles is smaller with unity pf wind power that with leading pf one. Figures 7, 8, 13, and 14 shows that leading pf wind power is not preferred from the point of view of transient stability, however, it is preferred from the point of view of voltage stability. Because the two types of stability are required, unity pf wind power is the best choice.

Figure 11 shows the voltage of Bus 7 at unity pf for different wind powers when the wind turbine is located at Bus 8. The figure shows that 1.2 pu wind power is reasonable choice. It is clear from Figure 11 that the voltage of Bus 7 is smaller than that of Figures 7 and 9. Below 1.0 pu and more than 1.4 pu wind power the system was unstable and the voltage failed to build up. Power angles for 1.2 pu wind power is shown in Figure 12. Angle oscillations in Figure 12 are greater than those in Figure 8. Figure 11 and Figure 12 show that Bus 8 is not practical location for wind turbine.

The effect of leading pf is now considered. Figure 13 shows the voltage of Bus 7 at 0.9 pu leading and 1.7 pu wind power when the wind turbine is located at Bus 5. A comparison between Figures 7 and 13 shows that the voltage at Bus 7 is greater with unity pf wind power that with leading pf one. Power angles for 1.7 pu wind power is shown in Figure 14. A comparison between Figures 8 and 14 shows that the oscillation of power angles is smaller with unity pf wind power that with leading pf one. Figures 7, 8, 13, and 14 shows that leading pf wind power is not preferred from the point of view of transient stability, however, it is preferred from the point of view of voltage stability. Because the two types of stability are required, unity pf wind power is the best choice.
Finally, although 1.0 pu wind power at Bus 5 is the best choice for voltage stability, higher values of wind power are required for transient stability of system. These higher values of wind power adversely affect the voltage stability. To enhance both the voltage stability and the transient stability of the studied system, 1.7 pu wind power at unity pf located at Bus 6 is required.

VI. CONCLUSION

This paper presents a detailed analysis of the optimum location and rating of wind power for voltage stability and transient stability of 9-Bus IEEE system. Different locations and rating are tested with interconnect DFIG wind turbine at load buses (5, 6, and 8). Effect of changing power factor of wind power is also considered. Simulations show that:

• There is an optimum value of wind power for both voltage stability and transient stability,
• The optimum value of wind power and location of wind power for voltage stability may not be the ones for transient stability,
• Leading pf of wind power is preferred for voltage stability, however it adversely affects the transient stability,
• Location of wind turbine at Bus 8 is not practical for either voltage stability or transient stability,
• Location of wind turbine at Bus 6 is preferred for voltage stability but not for transient stability, and
• Location of wind turbine at Bus 5 with 1.7 pu wind power and unity pf is the optimum choice for both voltage stability and transient stability.

REFERENCES