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Wind Farm Power System Model Development

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Wind Farm Power System Model Development

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***Abstract*—In some areas, wind power has reached a level where it begins to impact grid operation and the stability of local utilities. Utility system operators and engineers now want a better understanding of the impacts of large wind farms on grid stability before they are interconnected to the grid. They need wind farm electrical models that will help them analyze potential grid stability problems. Without the necessary tools and knowledge of large wind power plant behavior, utilities are reluctant to integrate more wind power into the grid.**

The operating characteristics of a single wind turbine are well known and models to simulate and predict dynamic characteristics under various wind and grid conditions are available. However, models that can simulate and predict the behavior of large wind power plants with hundreds of wind turbines and their impact on the power system operations have yet to be developed. In this paper, the model development for a large wind farm will be presented. Grid stability during electrical transients depends on generators providing voltage stability. Wind farm dynamic behavior and contribution to stability during transmission system faults will be examined.

***Index Terms*-- wind turbine, wind farm, wind energy, aggregation, power system, variable speed generation, renewable energy**

I. INTRODUCTION

WIND Power generation is a new type of generation introduced into the power system grid. In comparison, synchronous generator has been used for generation for more than one hundred years. There is a major different between conventional power plant and wind power plant. In a conventional generation, a prime mover is connected to a synchronous generator while in a wind power generation, the wind turbine is the prime mover and it is connected to an induction generator. There are two major types of induction generator used one is the so-called fixed-speed (squirrel cage induction generator) and the other one is the wound rotor induction generator. Although there other types of generators used (permanent magnet, synchronous generator etc.), in this paper only wound rotor induction generator will be discussed.

There are many types of wind turbine generator available on the market. In this paper we limit our scope to a typical wind turbine presently used in many wind farms in the US. We chose a variable speed wind turbine generator (VS-WTG at 1.5 MW) with pitch control, using a doubly fed induction generator (DFIG). Although there are so many aspects in a wind turbine (aerodynamic, fatigue, control systems, etc.), we focus this paper on the power system side of the equation. A typical block diagram describing a VS-WTG DFIG is shown in Figure 1.

In Figure 1 the block diagram of the real power, reactive power and pitch control is shown. The asterisk (*) used as superscript indicates that the variable is a commanded variable. Thus P* means the

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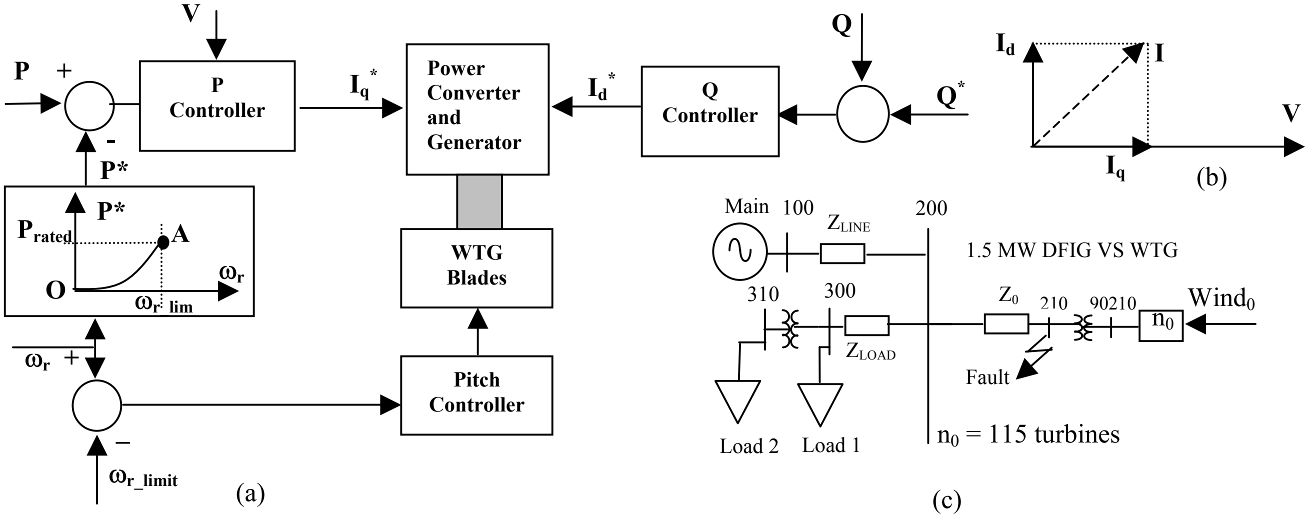

Figure 1. Block diagram of real power, reactive power and pitch control in a VS-WTG and single line diagram.

commanded power to be generated by the WTG. The pitch control is activated when the rotor speed reaches its limit. Thus, when the pitch blades are pitched to feather, the aerodynamic torque generated by the blades will be reduced significantly as such that the rotor speed will be limited. In the lower to medium wind speed, the rotor speed varies and the blade pitch angle is set to constant angle at its optimum angle. As shown in figure 1a, the power look up table will follow the solid line OA. The rotor speed will be limited by the pitch controller to ω_{r_lim} where the output power reaches its rated power P_{rated}.

In section II we will explore one type of wind turbine generator commonly used in modern wind farm. Section III will present the power systems aspects of wind power plant. In Section IV, the representation of a wind farm will be discussed. In Section IV, the results from the simulation will be presented for operational (normal) operation and for fault events. Section VI will summarize the paper.

A package program called Power System Simulation for Engineers (PSS/E) will be used throughout this study.

II. DOUBLY FED INDUCTION GENERATOR

Doubly fed induction generator (DFIG) is commonly used in wind turbine generator. It is a wound rotor induction machine with slip rings attached at the rotor and fed by power converter. With doubly fed induction generator, generation can be accomplished in variable speed ranging from below synchronous speed to above synchronous speed. The power converter feeding the rotor winding is usually controlled using current regulated pulse width modulation (CRPWM), thus the output current can be adjusted in magnitude and phase angle. The power converter output frequency is the slip frequency, and the power converter processed only the slip power. Thus if the DFIG is to be varied at ±30% slip, the rating of the power converter is only about 30% of the rated power of the wind turbine. The CRPWM power converter is able to control the output real power as well as the reactive power.

A. Real power controllability

In Figure 1a, the block diagram of the real power control is shown. The real power is control to be proportional to the cube function of rotor speed to achieve maximum performance coefficient (C_p), thus, optimizing the wind turbine aerodynamic characteristics. There is a look up table that can be used as such that at any rotor speed (ω_r) there is a corresponding power P* that must be generated to optimize the energy capture by the wind turbine. From the phasor diagram shown in Figure 1b, the current component generating real power Iq is adjusted according to the commanded power. Thus given the commanded power P* and divided by the terminal voltage V, the commanded current Iq* can be sent to the power converter so that the current component generating real output power (Iq) will produce output real power P = P*.

B. *Reactive power controllability*

The ability to control the output of reactive power out of a DFIG is a big advantage. In conventional wind turbines, a squirrel cage induction generator (SCIG) is used. By its nature, an SCIG always draws reactive power from the grid to which it is connected. This fact makes the terminal voltage at the generator is lower from the infinite bus because the voltage drop across the line impedance is as such that it reduces the voltage at the generator. Therefore, in practice, external capacitor compensation is used to compensate a squirrel cage induction generator. From Figure 1a, the block diagram shows that the reactive power can be commanded (Q^*) as such that the resulting output current will generate the necessary output $Q = Q^*$. The measured reactive power and the commanded reactive power will be subtracted and the error ΔQ_{err} will be fed to the Q controller block which will output the commanded current component I_d^*. This current command I_d^* will be fed to the power converter to generate the proper current I. Note that the commanded current I^* will be a phasor or vectorial summation of I_q^* and I_d^*. Thus the resulting current I will have the required component of I_q and I_d. This is a very convenient way to provide a decoupled command of real power and reactive power.

C. *Balance between real power and reactive power*

As shown above, the output of real and reactive power output can be controlled independently, however, there a limit in this ability. The limit is mostly due to the fact that we require a power converter to enjoy this benefit. Power converter is built out of power semiconductor switches that has current limit. Exceeding the current limit above the designed values will damage the power semiconductor. Manufacturers set this limit by indicating that the maximum reactive power that can be generated continuously at rated power is limited to power factor 0.95 (leading or lagging).

III. POWER SYSTEM ASPECT OF A WIND POWER PLANT GENERATION

In the previous section the basic of wind turbine is provided. In most cases a wind turbine is very seldom operated alone. It is usually operated as a group of wind turbines called wind power plant or wind farm connected to a power grid.

The subject of voltage and frequency stability is very critical to the customers at the receiving end of the electrical grid. Customers want to have a good power quality electricity from the grid namely constant voltage and constant frequency all the time. In practice, these two attributes cannot be maintained constant all the time. Variation in loads, generations, switching of auxiliary equipments (transformer taps, capacitors), circuit changes (planned and unplanned) happen all the time. Thus, there is always imbalance in the net real power (ΔP) and net reactive power (ΔQ). Small imbalances (wind fluctuations, small load changes etc.) create a degraded power quality of the available electrical energy, but larger imbalance (fault, loss of line, loss of generation etc.) threaten stability of the grid. If the net real power is zero ($\Delta P = 0$) there will be a stable and steady frequency, and similarly if the net reactive power is zero ($\Delta Q = 0$), there will be a stable and steady voltage on the grid. On the contrary, if the wind turbine generates more power ($\Delta P > 0$), additional frequency ($\Delta f > 0$) will be seen on the generator bus and vice versa. The same phenomenon is applicable for reactive power. If the generator generates more reactive power, a voltage rise will be seen on the generator terminals.

IV. SIMULATION RESULTS

In the next few sections, results from the simulations will be presented. Normal and abnormal condition will be investigated and the worst possible conditions will be used in the simulation. The grid simulated will be a weak grid, thus the voltage and frequency variation can be obviously seen on the traces of voltage and frequency. The fault condition chosen is the worst condition kind of fault, a three-phase short circuit to the ground. The worst scenario of wind farm aggregation is simulated, thus we assume that there is a large number of turbines operating at the same wind speed feeding the same line. Figure 2 shows the power systems simulated in this paper. The system consists of an infinite bus, a nearby load and a wind power plant.

A. Normal Operation

Let us consider the case for operation during low-medium wind speed as shown in Figure 2a. In this wind speeds region, the rotor speed of the turbine has not reached the maximum rotor speed limit. Thus the pitch blade is fixed at the optimum angle. The rotor speed is allowed to vary, thus the output power will vary accordingly (along line OA) as dictated by the look-up table P^*-ω_r shown in Figure 1a. Shown in Figure 2b, the terminal voltage and reactive power varies according to the power fluctuations as well. On the same Figure, the frequency variation shown as Δf, depends on the variation of power. It varies above and below nominal. Also we should keep in mind that the variation of the frequency is proportional to the derivatives of output power (thus, steeper fluctuations create higher Δf fluctuations).

The wind speed is then scaled by a factor of 130% to represent high wind speed (refer to Figure 3). At the high wind speed region, the rotor speed limit has been reached, thus the rotor speed will stay the same by the action of pitch control. The blade pitch angle will vary to keep the rotor speed constant. Once the rotor speed reaches its limit, the output power also reaches its limit and it stays there following the rotor speed condition. If there is a drop in wind speed, the rotor speed drops, and the output power also drops accordingly. The voltage is practically constant because this DFIG is controlled to keep its voltage constant. The frequency varies when there are some changes in output power. Note that in steady state the frequency always returns to its constant value. Therefore it is important that the rate of increment and the rate of decrement of output power determine the output frequency at the bus of the generator.

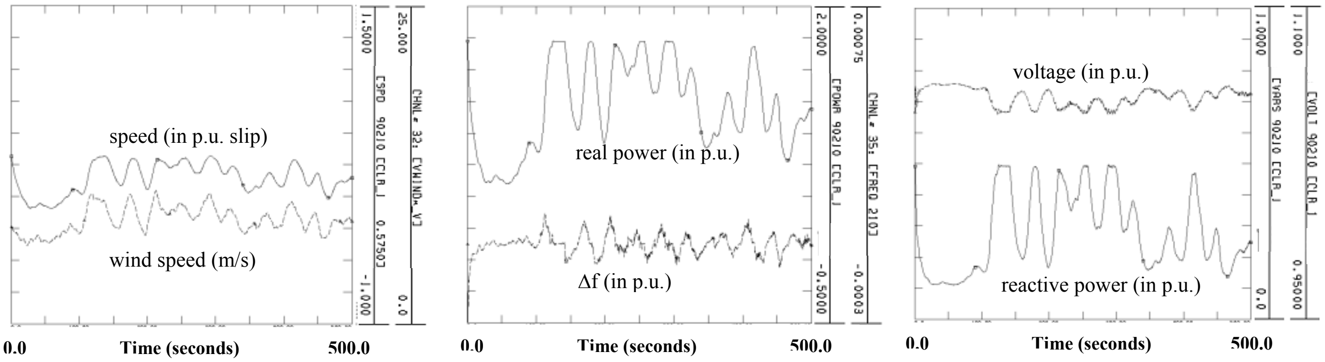

Fig. 2 a. Medium wind speed and rotor speed, b) Real power and frequency, c) Reactive power and voltage

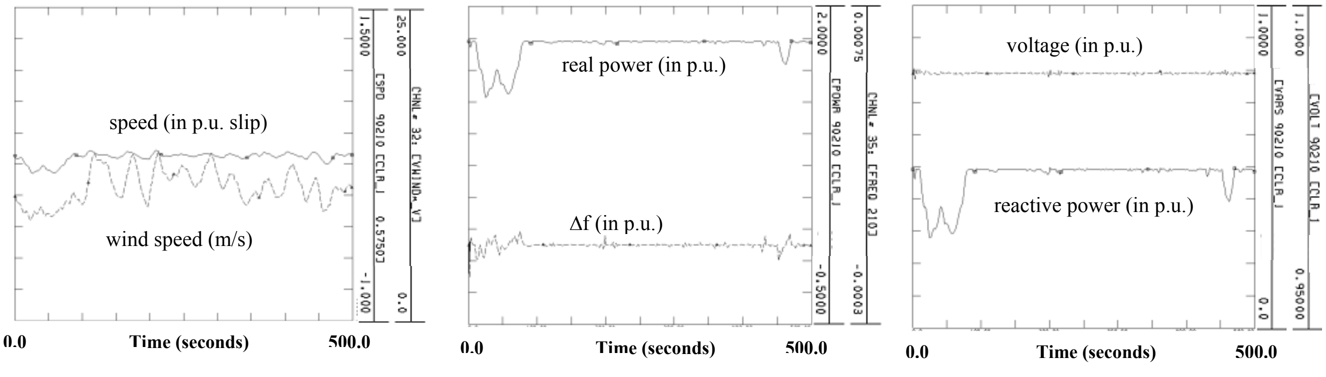

Fig. 3 a. High wind speed and rotor speed, b) Real power and frequency, c) Reactive power and voltage

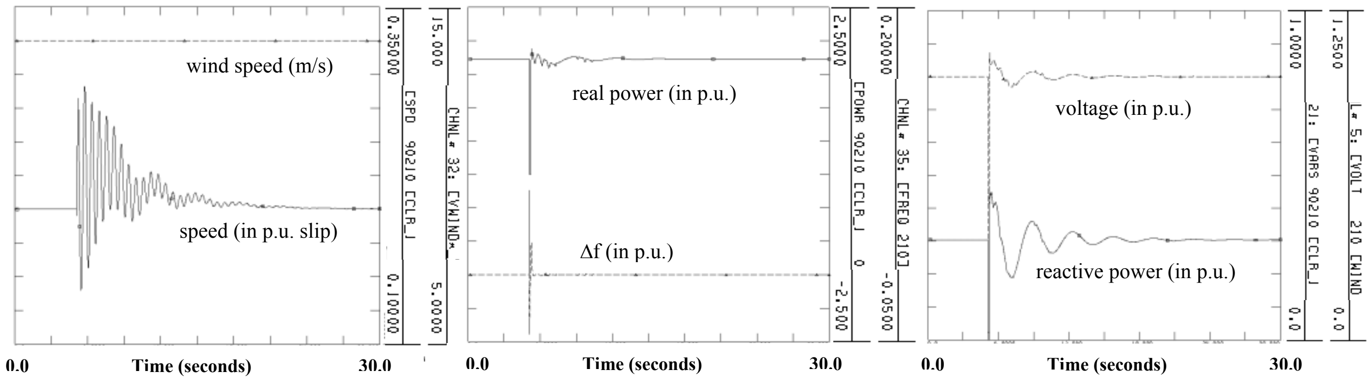

Fig. 4 a. Wind speed (14m/s) and rotor speed, b) Real power and frequency, c) Reactive power and voltage

B. *Abnormal Operation*

In this section, we consider a situation when the wind turbine is originally operated at normal condition, constant wind (14m/s) and all of a sudden there is a sudden fault at bus 210 for 8 cycles. The resulting voltage and frequency variation is shown in Figure 4. From the traces shown, it is shown that the system exposed to the fault survives the fault and return to normal operation after the fault is cleared.

V. CONCLUSION

This paper investigates the development of power system model for a wind farm. Normal and abnormal operations are investigated under two wind speed condition (low and high wind speeds). The worst case condition of the power system is simulated (i.e. weak grid, no aggregation effect). In summary, the wind turbine performs within acceptable criterion (voltage variations less than ± 3% and frequency variations less than ± 0.01%) under normal conditions (medium or high wind speeds). Under fault condition, the frequency varies $-4.5\% < \Delta f < 6.2\%$ and the voltage variation after the fault is –0.96 p.u. $< \Delta V <$ 1.09 p.u., which is way above the requirement listed in Ref. [3]. During fault, the rotor speed variation is decoupled from the frequency and real power variations, this is contrary to conventional power plant (synchronous generator) where stability is strongly affected by the rotor angle variation.

VI. ACKNOWLEDGMENT

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VII. REFERENCES

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In some areas, wind power has reached a level where it begins to impact grid operation and the stability of local utilities. In this paper, the model development for a large wind farm will be presented. Wind farm dynamic behavior and contribution to stability during transmission system faults will be examined.

15. SUBJECT TERMS

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