Rotor Speed Stability Analysis of Constant Speed Wind Turbine Generators

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Abstract—This paper presents an analysis of rotor speed stability of a constant speed wind turbine generator with active stall control. To analyze the rotor speed stability, a 3-phase short circuit fault on a sample system with a constant speed WTG has been simulated using DiGILENT software package. From the simulation results, it has been shown that the operating point of wind turbine generator has influence on rotor speed stability. Using this phenomenon, how a constant speed wind turbine generator with active stall controls the operating point has been reported. Negative pitch control strategy of active stall controlled wind turbine generator to enhance rotor speed stability has been described with the help of simulation results.

Index Terms—active stall control, constant speed (squirrel cage) induction generators, power system stability, wind turbine generator (WTG).

I. INTRODUCTION

Among all renewable resources, wind power is the most booming renewable technology all over the world. India ranks fourth in the world with total installed capacity of more than 5,000 MW [1]. Most of the wind turbine generators (WTGs) installed in India are constant speed (squirrel cage) induction generators. This is because of their robustness, mechanical simplicity and low price. However, a constant speed WTG always demands reactive power, hence reactive power compensation is needed.

During grid disturbance near to a WTG, severe voltage sag in the connecting network may cause a significant reduction in active power generation and rise in rotor speed. After voltage recovery, the rotor speed of the induction generator may be so high that it does not return to the pre-fault value. This may lead to rotor speed stability problem [2].

As the penetration level of constant speed WTGs increases, it is very much important to maintain the rotor speed stability during low voltage at point of common coupling (PCC). This is referred as low voltage ride through (LVRT) capability of a WTG. Normally, LVRT requirements are stringent in regions with high penetration of the wind power. The specific requirements like voltage level and duration of fault differ from country to country [3], [4].

A controlled constant speed WTG consumes reactive power, and this consumption ramps up drastically during faults. Therefore, such a WTG does not possess LVRT capability. Consequently, it has to be disconnected from the grid due to rotor speed instability. The rotor speed stability of a constant speed WTG can be improved by active stall control. In transient condition, active stall controller controls the pitch angle ($\beta$) in negative direction to reduce turbine torque, this action helps to reduce acceleration in the rotor speed, and improves the rotor speed stability.

In [5]–[8] efforts have been put to model the WTGs, and to understand the behavior of constant speed WTGs. Pitch controller of wind turbine for optimum generation control has been explained in [9]. Application of the pitch control mechanism of a WTG for voltage recovery, subsequent to a short-circuit fault has been explained in [10]. Comparative study of active stall control with pitch control strategies for constant speed WTGs are discussed in [5], [11]. Transient stability of a fixed speed wind turbines has been evaluated in [12], [13].

This paper evaluates the rotor speed stability of a constant speed WTG with active stall connected to a sample system. The system has been simulated using DiGILENT PowerFactory, which is a computer aided engineering tool for the analysis of industrial, utility, and commercial electrical power systems [14]. Using negative pitch control strategy of active stall controlled WTG, the enhancement of the rotor speed stability has been demonstrated for the sample system.

The organization of the paper is as follows. In the section II, the phenomenon of rotor speed stability has been described. Negative pitch control strategy of active stall control based constant speed WTG is described in section III. Validation of 1.3 MW squirrel cage induction generator model of DiGILENT is detailed in section IV. Simulation of a squirrel cage induction generator with capacitor bank connected to the sample system, and effect of negative pitch control strategy on rotor speed stability are discussed in section V. Section VI concludes the paper.

II. ROTOR SPEED STABILITY OF A SQUIRREL CAGE INDUCTION GENERATOR

When a grid connected induction generator is subjected to a nearby fault, due to severe voltage sag, its rotor may accelerate to very high speed far from the system frequency. This phenomenon is related to the power system stability, but it is not covered in conventional stability concepts, such as, rotor angle stability, voltage stability and frequency stability [2]. Because of induction generator, stability of a WTG cannot
be classified under rotor angle stability phenomenon. After fault clearance, the system voltage may be recovered to a new allowable value, but the speed of induction generator may rise to unaccepted value. Hence, this cannot be classified under the voltage stability phenomenon. The frequency of the system after fault clearance may be acceptable, so it cannot be classified under frequency stability phenomenon. Thus, this kind of stability phenomenon is referred as rotor speed stability.

According to [2], Rotor speed stability refers to the ability of an induction (asynchronous) machine to remain connected to the electric power system and running at a mechanical speed close to the speed corresponding to the actual system frequency after being subjected to a disturbance.

The rotor speed stability of a constant speed WTG depends on the several factors such as, machine operating point, short-circuit power at PCC, distance from the fault location, rotor inertia etc [12]. Out of these factors, active power output (operating point) can be controlled by pitching wind turbine blades. By reducing output power of a constant speed WTG, reactive power drawn by the WTG reduces (due to reduction in slip). And, hence it may improve rotor speed stability margin of the WTG. Using this phenomenon, enhancement of the rotor speed stability of a constant speed WTG with active stall is explained in the next section.

III. ACTIVE STALL CONTROL OF A CONSTANT SPEED WTG

The active stall control based constant speed WTG (referred as Type-A2 wind turbine technology) has control of pitch in the negative direction (i.e. between $-90^\circ$ to $0^\circ$) with respect to pitch control based WTG (Type-A1). The rate of negative pitch control is normally less than $5^\circ$ per second. Although the pitch rate may exceed $10^\circ$ per second during emergencies [5].

Fig. 1 shows the difference in the direction of blade rotation between the pitch controlled and the active stall controlled constant speed WTGs. In the figure, the chord line is the straight line connecting the leading and trailing edges of an airfoil. The plane of rotation is the plane in which the blade tips lie as they rotate. The pitch angle ($\beta$) is the angle between the chord line of the blade and the plane of rotation. And, the angle of attack ($\alpha$), is the angle between the chord line of the blade and the relative wind or the effective direction of air flow.

In active stall control, at low wind speeds, the machine is usually controlled to pitch their blades similar to a pitch controlled machine. When the machine reaches its rated power value, the blades are pitched in the direction opposite from what a pitch controlled machine does, in order to control output power. This needs pitch angle $\beta$ to be decreased typically by a small amount only. Hence, the rating of pitch drives is less for active stall control, as compare to pitch control [11]. Therefore, the cost and complexity are less for active stall control, comparatively.

A. Negative pitch control strategy for constant speed WTGs

If a fault occurs close to a constant speed WTG, the voltage at the generator terminals of the wind turbine drops, which results in the reduction of active power. If a wind turbine controller does not attempt to reduce the mechanical power input, the turbine accelerates during the fault. If a wind turbine has no means of controlling its power, then critical clearing time will be very short [12]. Hence, an active stall controlled WTG has to change the pitch angle as quickly as possible. This will eventually change $\alpha$. By increasing $\alpha$, the active power generation can be reduced. In a constant speed WTG, the reactive power demand depends on the active power generation also. Consequently, the rotor speed and reactive power reduce, which enhances the rotor speed stability.

In this paper, negative pitch control strategy has been simulated using DiSILENT based built-in torque controller, to analyze the improvement in the rotor speed stability of a constant speed WTG. According to this strategy, during the fault, the turbine torque reduces as the $\beta$ increases in negative direction. This will reduce the rate of rise of the rotor speed. Hence, the rotor speed stability of a constant speed WTG can be maintained, and WTG remains connected to the grid. After fault clearance, if rotor speed is not recovered to its nominal value, then negative pitch angle does not return to its pre-fault (initial) value.

IV. VALIDATION OF AN INDUCTION MACHINE MODEL OF DSILENT SOFTWARE

DiSILENT PowerFactory is optimized to handle large amount of data, e.g., very large systems with thousands of buses/machines, appropriate initialization of models, etc. DiSILENT PowerFactory is using A-stable integration methods with optionally adaptive, error controlled step-length. For RMS simulations, steps length may vary between ms and minutes with precise event handling. For EMT simulations, variable step length my vary between a couple of $\mu$s and some ms [14].
A. Modeling of a squirrel cage induction generator in MATLAB

The equations used for squirrel cage induction generator modeling are described as follows [5]:

**Stator Equations:**

\[ V_{qs} = -i_{qs}R_s + \omega_s\Psi_{ds} + \frac{d}{dt}\Psi_{qs} \] (1)

\[ V_{ds} = -i_{ds}R_s - \omega_s\Psi_{qs} + \frac{d}{dt}\Psi_{ds} \] (2)

**Rotor Equations:**

\[ V_{qr} = 0 = -i_{qr}R_r + S\omega_s\Psi_{dr} + \frac{d}{dt}\Psi_{qr} \] (3)

\[ V_{dr} = 0 = -i_{dr}R_r - S\omega_s\Psi_{qr} + \frac{d}{dt}\Psi_{dr} \] (4)

**Flux Linkage are:**

\[ \Psi_{qs} = -(L_{s\sigma} + L_m)i_{qs} - L_m i_{qr} \] (5)

\[ \Psi_{ds} = -(L_{s\sigma} + L_m)i_{ds} - L_m i_{dr} \] (6)

\[ \Psi_{qr} = -(L_{r\sigma} + L_m)i_{qr} - L_m i_{qs} \] (7)

\[ \Psi_{dr} = -(L_{r\sigma} + L_m)i_{dr} - L_m i_{ds} \] (8)

**Electrical Torque equation is:**

\[ T_e = \Psi_{qr} i_{dr} - \Psi_{dr} i_{qr} \] (9)

The equation of motion of the generator is:

\[ \frac{d\omega_r}{dt} = \frac{T_{mech} - T_{elect}}{2H_m} \] (10)

where, \( V \) is the voltage, \( i \) is the current, \( R \) is the resistance, \( S \) is the slip, \( L \) is the inductance, and \( \Psi \) is the flux linkage. The subscripts \( d \) and \( q \) stand for direct and quadrature component, respectively. And, the subscripts \( r \) and \( s \) stand for rotor and stator, respectively. The indices \( m \) and \( \sigma \) are mutual and leakage, respectively.

These equations have been simulated using MATLAB software package. In both the softwares induction generator model has been executed for motor start-up condition. However, induction generator model available in the DIgSILENT does not have exact similar rating of the model simulated in MATLAB. Hence, the validation of the DIgSILENT result has been done qualitatively, as shown in Fig. 2 and Fig. 3.

![Fig. 2. Waveforms of active power, speed and reactive power of induction generator from the MATLAB.](image1)

![Fig. 3. Waveforms of active power, speed and reactive power of induction generator from the DIgSILENT.](image2)

V. SIMULATION OF A GRID CONNECTED WTG WITH ACTIVE STALL CONTROL

As shown in Fig. 4, a 1.3 MW constant speed WTG has been connected to a medium voltage (MV) distribution network. Modeling of WTG with capacitor bank connected to a sample system has been simulated using DIgSILENT PowerFactory. For rotor speed stability analysis, a 3-phase severe fault has been created on the line-1 at 3 seconds. The fault has been cleared by removing that line from the system at 3.12 seconds. To analyze the behavior of the WTG during this grid disturbance, the quantities of induction generator, such as active power generation (in MW), rotor speed (in p.u.), reactive power generation (in Mvar), and generator terminal voltage (in p.u.) are plotted. The effect of operating point and negative pitch control on rotor speed stability is illustrated in next sub-section.
A. Effect of operating point on the rotor speed stability

As mentioned earlier, as the power output of a constant speed WTG decreases, its rotor speed stability increases. It can be deduced from Fig. 5 and Fig. 6, if power output of the WTG reduces from 1.3 MW to 1 MW (due to low wind velocity), the rotor speed stability of a constant speed WTG increases. That is because, the reactive power drawn by the induction generator is proportional to the active power generation, rotor speed and terminal voltage. Fig. 6 show that 1.3 MW power output of WTG draws more reactive power, as compared to 1 MW power output. Hence, when the fault is created at 3 sec, the instantaneous reactive power drawn at 1.3 MW power generation is 6.5 Mvar, as compare to 4.5 Mvar at 1.0 MW. When the fault is cleared at 3.13 seconds, and at 1.3 MW power generation continue to draw large amount of reactive power due to very high rotor speed. This will reduce active power generation to zero, as shown in Fig. 5 and Fig. 6. Consequently, the generator protection system isolates the WTG from the system.

B. Effect of negative pitch control on the rotor speed stability

With the help of negative pitch control, the mechanical torque of a constant speed WTG can be reduced. During the grid disturbance, system voltage sags, and hence active power supplied by WTG decreases. Because of that, rotor speed increases and WTG draws very high reactive power, as shown in Fig. 7 and Fig. 8. In this case, the WTG power output is 1.3 MW (at constant rated speed). Critical clearing time 3.12 sec for this WTG is obtained by executing the simulation several times. Using negative pitch control strategy, the WTG will remain stable, eventhough fault is cleared after 3.12 sec. That is because, the active power generated is reduced from 1.3 MW to 1.2 MW till 3.2 sec, by controlling pitch angle $\beta$ in negative direction (as explained in section III). Consequently, the speed, and hence the reactive power drawn reduces, this improves the rotor speed stability of a constant speed WTG as shown in Fig. 7 and Fig. 8.

VI. CONCLUSIONS

The rotor speed stability margin of constant speed WTG is higher at lower active power operating point. With negative pitch control strategy, the operating point can be controlled...
under faulty conditions, thus, helping to maintain stability as shown in the result section. However, such control will be limited by the severity of the fault and ramping rate of pitch control. The work can be extended to coordinate the control with FACTS devices.

REFERENCES


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