MODELLING AND SIMULATION OF A WIND TURBINE WITH DOUBLY FED INDUCTION GENERATOR IN FULL LOAD OPERATION

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ABSTRACT

The paper focuses on modelling and simulation of a 5 MW wind turbine with doubly fed induction generator (DFIG) in full load operation. The wind turbine model is described mathematically and presented in simulation blocks. Through a computer simulation, the wind turbine behavior in full load operation is investigated. A speed controller is used to adjust the pitch angle of a rotor blade in high wind speed to limit the wind energy captured by the turbine to the nominal power value. By adjusting the pitch angle to 18.26° at wind speed 20 m/s, the wind turbine is protected from mechanical damage due to torque and power limitation. The simulation results obtained can be used as references for future optimization for the variable speed wind turbine operation.

Keywords: variable speed wind turbine, full load operation, pitch angle.

INTRODUCTION

A modern wind turbine consists of a rotor, a gearbox and a generator. Rotor, which has three blades, is used to capture wind energy and converts it into mechanical energy. In modern wind turbines, the blade pitch is controlled in the rotor. As mentioned in [4] the rotor speed and thus the performance of the wind turbine is limited by pitch control. Figure-1 indicates the simplified diagram of a wind turbine with doubly fed induction generator (DFIG). DFIG is a variable speed generator. It is often used in wind turbines with output power more than 1.5 MW.

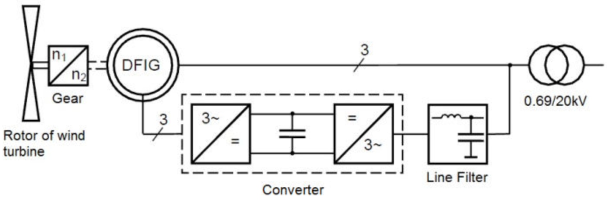

Figure-1. Simplified diagram of a wind turbine with DFIG.

As mentioned in [1] a variable speed, a pitch controlled wind turbine has four main operation modes with respect to the wind speed. The operation modes of variable speed, pitch controlled wind turbine is illustrated in Figure-2. The first operation mode is the idle mode. The cut-in wind speed for the wind turbine to start up is 3.5 m/s. Zone 1 is a partial load operation of the wind turbine. The wind speed range in partial load operation is between 4 m/s and 13 m/s while the pitch angle is 0° as shown by Figure-2. The rotor speed of the wind turbine must be adjusted to capture the maximum wind energy in this zone. For a given wind speed, the power coefficient must be maximized [10]. In zone 2, the wind turbine is operated in full load operation. The wind speed range is between 13 m/s and 25 m/s. In this zone, where the wind speed exceeds its rated value, the wind turbine must limit the capture of the wind power to prevent from any mechanical damage. Here, a controller must be used to adjust the pitch angle to limit the torque as well as the power for the wind turbine [10]. In zone 2, the values of the pitch angle are between 0° and 25°.

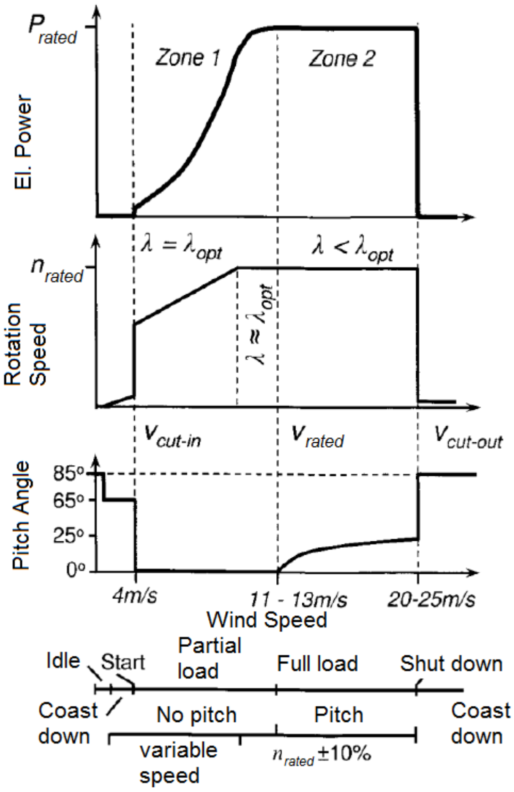

Figure-2. Operating zone of variable speed, pitch controlled wind turbine [1].

Dynamic behavior analysis of the wind turbine in full load operation is very crucial to protect the wind turbine from mechanical overload. Hence, a 5 MW wind turbine is modelled and simulated using MATLAB/Simulink to investigate its behavior in full load operation. A speed controller is then used for further investigation of the model behavior. The paper is organized as follows. The modelling of the wind turbine is presented in section 2. In section 3, the simulation results of the wind turbine in full load operation are discussed.

MODELLING OF WIND TURBINE

Rotor of wind turbine

A variable speed wind turbine has three main components namely the rotor of wind turbine, the gearbox and the DFIG. The formula for aerodynamic power captured by the rotor is:

$$P_R = \frac{1}{2} * \rho_{Luft} * \pi * R^2 * v_{wind}{}^3 * c_p(\lambda, \beta) \tag{1}$$

where ρ_{Luft} is air density and R the rotor radius. The power captured by the rotor, P_R, is proportional to the cube of wind speed v_{wind}. The power coefficient, c_p ,depends on the tip-speed ratio, λ, and the pitch angle, β . The formula for the tip-speed ratio is:

$$\lambda = \frac{\omega_R * R}{v_{wind}} \tag{2}$$

where ω_R is rotor speed. Figure-3 shows the behavior of power coefficient depending on the tip-speed ratio for different pitch angles. The tip-speed ratio is the most important parameter for the aerodynamic design of the rotor blades.

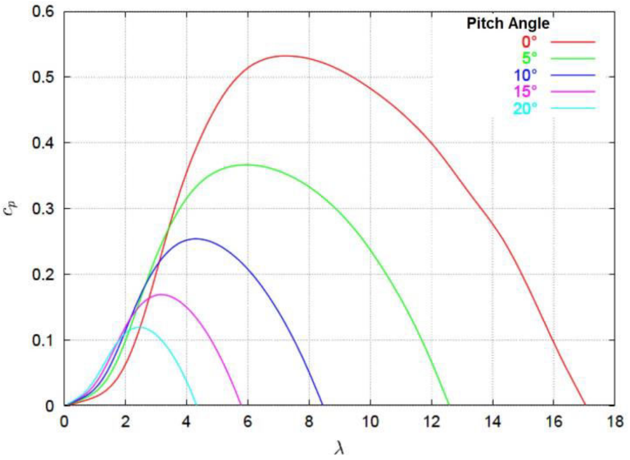

Figure-3. Power coefficient depending on tip-speed ratio [7].

The aerodynamic torque developed by the rotor can be determined by rotor speed and aerodynamic power of the rotor.

$$M_a = \frac{P_R}{\omega_R} \tag{3}$$

By introducing the torque coefficient, $c_m(\lambda, \beta) = c_p / \lambda$ [6] the aerodynamic torque can be expressed as following:

$$M_a = \frac{1}{2} * \rho_{Luft} * \pi * R^3 * v_{wind}{}^2 * c_m(\lambda, \beta) \tag{4}$$

Figure-4 illustrates the behavior of the torque coefficient depending on the tip-speed ratio for different pitch angles. The simulation model of the wind turbine rotor contains equations (2) and (4) [5].

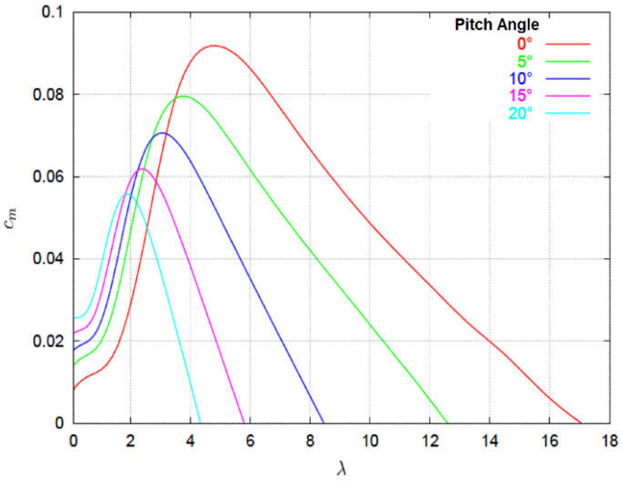

Figure-4. Torque coefficient depending on tip-speed ratio [7].

A radial segment of a rotor blade with thickness dr is considered (refer Figure-5). The aerodynamic forces acting on the segment consist of a lift force, dF_a, which is perpendicular to the local inflow direction, and a drag force, dF_w, which is parallel to the local inflow direction:

$$dF_a = \frac{1}{2} * \rho_{Luft} * t_b * c_a(\alpha) * v_{rel}{}^2 * dr \tag{5}$$

$$dF_w = \frac{1}{2} * \rho_{Luft} * t_b * c_w(\alpha) * v_{rel}{}^2 * dr$$
(6)

whereby t_b is denoted as chord length, c_a the lift coefficient, c_w the drag coefficient, α the angle of incidence or attack and v_{rel} the relative incoming wind speed. The vector of relative incoming wind speed depends on the local wind speed, $v_{wind,local}$, on the blade and on the tangential speed, $r\Omega_{Rotor}$, of the inspected blade segment.

Figure-6 shows the typical behavior of lift and drag coefficient of a blade profile. As mentioned in [10] “For small angle of attack, the laminar flow of the blade occurs, the lift force dominates. Basically, the tangential force, $dF_{\tan}$, which is in the rotational direction on the rotor, and the axial thrust force, dF_{ax}, which is parallel to the rotor axis, will be caused by the lift force. Meanwhile, greater angle of attack leads to stall. The tangential force is reduced with drop of lift force and significant increase of the drag force; hence the axial thrust force increases”.

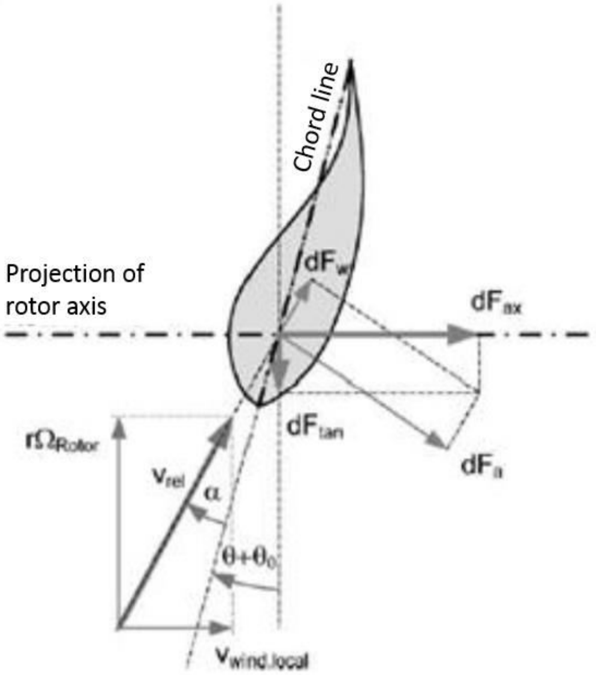

Figure-5. Incident flow and aerodynamic forces on a segment of a rotor blade [10].

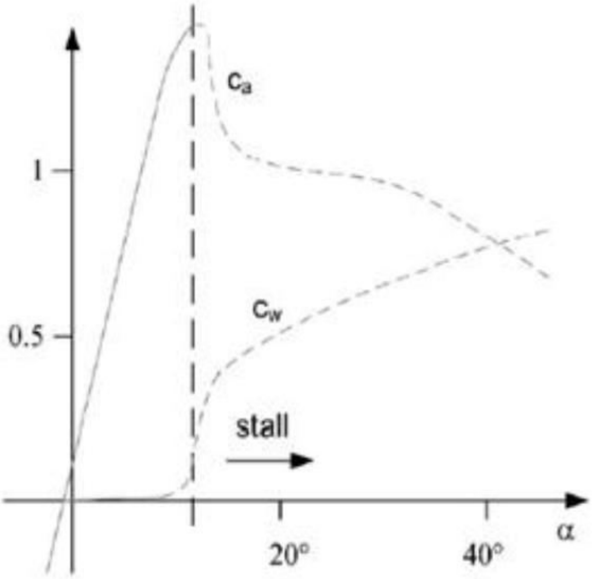

Figure-6. Typical behavior of lift and drag coefficient of a blade profile [10].

There are two possible ways to optimize the angle of attack:

- By changing the rotor speed, n_R
- By changing the pitch angle, β

The first option takes place in the partial load zone of a wind turbine, while the second option takes place in the full load zone of the wind turbine. As mentioned in [10] the power absorbed from the wind must be limited to the nominal value when wind turbine is in full load operation. In full load zone, the values of the pitch angle are between 0° and 25° and with a constant rotor speed, the tip-speed ratio is smaller than the optimum tip-speed ratio, λ_{opt}. The angle of attack becomes smaller as the pitch angle increases. This results in a reduction of aerodynamic forces as well as torque and thus the absorbed power.

Mechanical drive train

The mechanical drive train consists of the rotor, shaft, gear and generator. The energy conversion from aerodynamic-mechanical (primary) energyto the mechanical-electrical (secondary) energy takes place via the mechanical drive train. Figure-7 shows a two-mass model of a wind turbine. The mechanical behavior of the wind turbine can be described using this simple model.

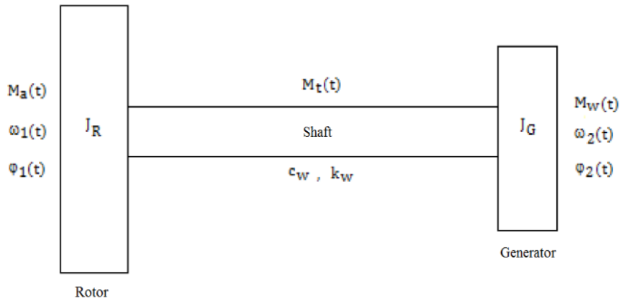

Figure-7. Two-mass model.

The accelerating torque on the rotor is the difference between the drive torque, M_a and shaft torque, M_{welle}:

$$J_R * \frac{d\omega_1}{dt} = M_a - M_{welle} \tag{7}$$

where ω_1 is rotor speed and J_R rotor moment of inertia. The generator is driven by shaft torque and braked by the generator torque, M_w:

$$J_G * \frac{d\omega_2}{dt} = M_{welle} - M_w \tag{8}$$

The shaft is described mathematically as a spring-damper system with the spring constant, c_w, and the damper constant, k_w [11]. Hence, the formula for the shaft torque is:

$$M_{welle} = M_t - M_D = c_w * (\varphi_1 - \varphi_2) + k_w * (\omega_1 - \omega_2) \tag{9}$$

whereby M_t is denoted as torsional moment, M_D damping torque, φ_1 shaft position angle at rotor, φ_2 shaft position angle at generator, ω_1 angular velocity of rotor and ω_2 angular velocity of generator.

If there is no relative movement between the two shaft ends i.e. $\omega_1 = \omega_2$, then it is sufficient to describe the model of the mechanical drive train as a one-mass model (refer Figure-8).

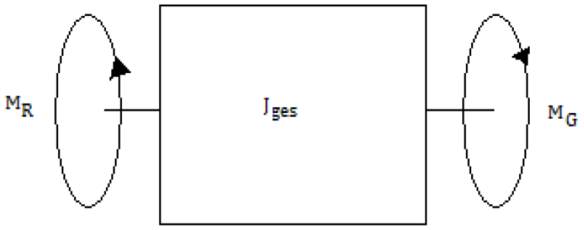

Figure-8. One-mass model.

The gear transmission ratio, i_G, can be defined as:

$$i_G = \frac{\omega_2}{\omega_1} = \frac{M_R}{M_G} \tag{10}$$

where M_R is rotor torque and M_G generator torque. The equation of motion for one-mass model is:

$$\frac{d\omega_2}{dt} = \frac{M_R{}' - M_G}{J_{ges}} \tag{11}$$

All variables in the equation of motion are transformed to the generator side. The total moment of inertia, J_{ges}, is calculated by adding up the moment of inertia of the generator and the moment of inertia of the rotor relative to the generator side, $J_R{}'$, where:

$$J_R{}' = \frac{\omega_1{}^2}{\omega_2{}^2} * J_R = \frac{1}{i_G{}^2} * J_R \tag{12}$$

The simulation model of the mechanical drive train based on the one-mass model can be referred to [5].

Doubly fed induction generator

The rotor speed of a wind turbine can be adjusted to obtain the maximum power at different wind speeds. For this purpose, a variable-speed generator principle is required. In this paper, a doubly fed induction generator (DFIG) is used. The wind turbine with DFIG operates on the superposition principle:

$$f_s = p * n + f_r \tag{13}$$

where f_s is stator frequency, f_r rotor frequency, p number of poles and n speed. When changing the speed, the rotor frequency must be set so that the desired stator frequency is maintained. In addition to the large speed range, the doubly fed asynchronous machine also offers the advantage that in generator mode, the active and reactive power can be regulated independently of each other and completely decoupled from the rotational speed by a rotor current component [9]. Here, not only the efficiency can be increased at an appropriate operation management, but also a neutral, even capacitive operation of the wind turbine is possible [8].The principle of field orientation is used for dynamic active and reactive power control.

The principle of field orientation is applied to simulate the behavior of the DFIG. The structure of a field-oriented drive with DFIG can be referred to [3]. Two circuits in Figure-9 are constructed using Sim Power Systems to simulate the DFIG. It is sufficient to build two circuits instead of three for three-phase machine. A current-fed power supply is also built in the simulation.

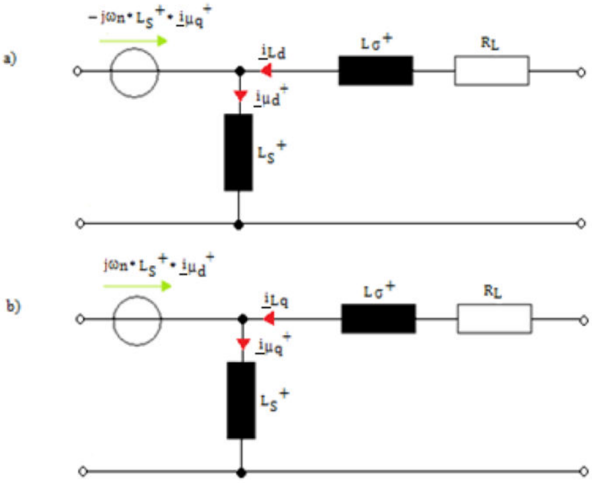

Figure-9. Circuits in doubly fed induction generator for three-phase machine [3].

SIMULATION RESULTS OF WIND TURBINE

Wind turbine behavior in full load operation has been investigated by simulating wind turbine model at a wind speed of 20 m/s. For the simulation of the wind turbine, it has been assumed that the wind speed is constant and the torque of generator is preset as set point value. Figure-10 shows the simulation results of the wind turbine behavior in full load operation. From Figure-10, the rotor of the wind turbine generated a driving torque M_{a_tur} of 172.8 kNm at the given wind speed ($v_{wind} = 20m/s$). In this case, the generator must have been driven above a synchronous speed. The generator could be maximum operated until a nominal speed ($n_N = 1170\,\text{min}^{-1}$). When the torque of the generator reached the value of the drive torque, the asynchronous generator was mechanically overloaded. In this case, the generator power exceeds its rated value ($P_{el,N} = 5000kW$).

The asynchronous generator must have been controlled to prevent this problem. The generator powerin full load operation could be limited by using a speed controller [2]. The pitch angle has been determined as a manipulated variable. By positively changing the pitch angle, the drive torque of the rotor and the rotational speed of the generator has been limited to their nominal values ($M_N = 4.081*10^4\,Nm$ and $n_N = 1170\min^{-1}$).

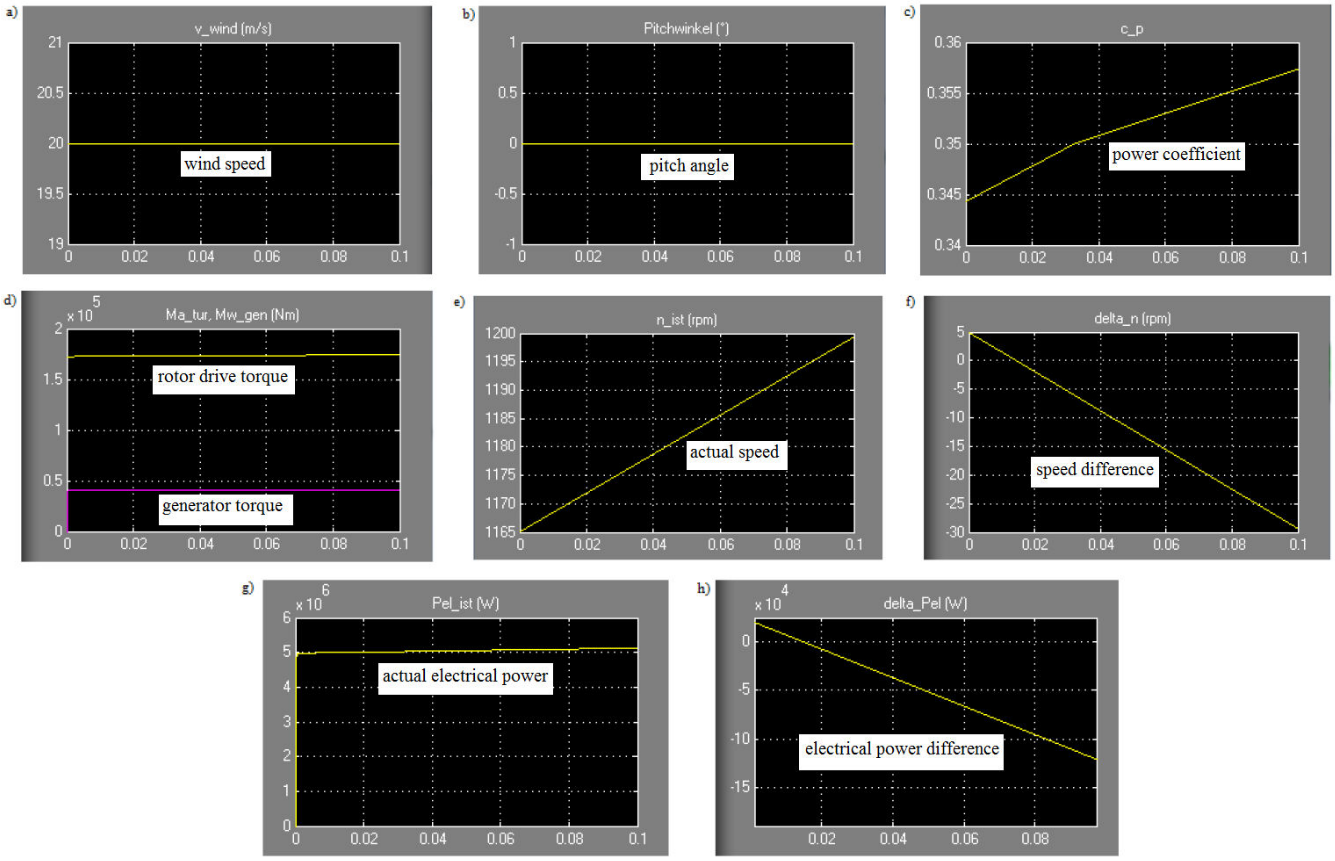

Figure-10. (a-h): Wind turbine behavior in full load operation.

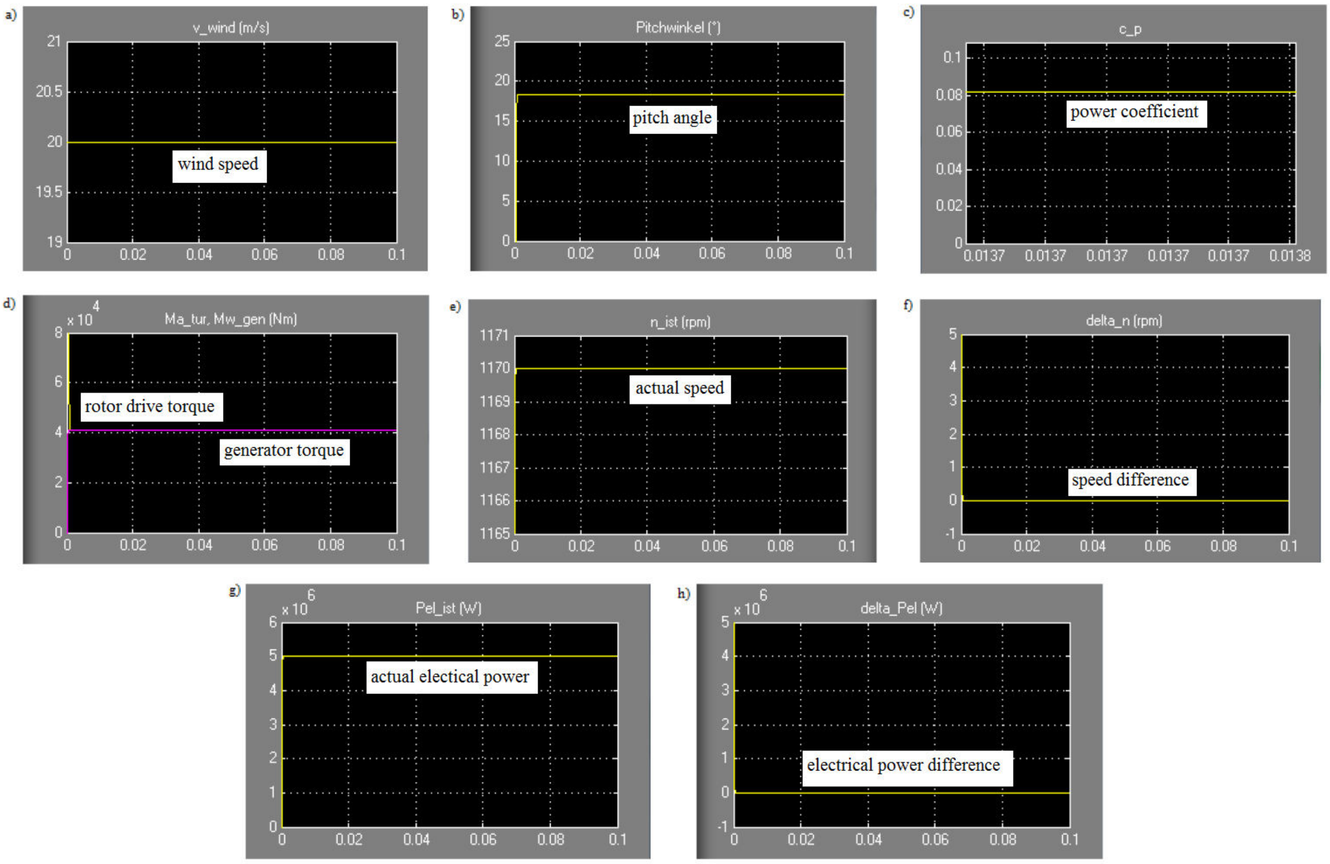

Figure-11. (a-h): Wind turbine behaviour with speed controller in full load operation.

The behavior of the wind turbine has been visualized and analyzed by simulating the wind turbine model with speed controller in full load operation. Figure-11 shows the simulation results of the wind turbine with a speed controller in full load operation. The limitation of the drive torque of the rotor and the rotational speed of the generator was due to a positive change in the pitch angle. At the wind speed of 20 m/s, the pitch angle was 18.26°. In addition, it could be easily seen that the electrical power has been limited to its nominal value when the generator speed has been kept constant. Finally, it could be determined that at a constant speed, the tip speed ratio decreased with a higher wind speed. The power coefficient is dependent on the tip speed ratio. As the tip speed ratio decreases, the power coefficient also decreases [7].

CONCLUSIONS

In this paper, the modelling and simulation of a wind turbine with DFIG is performed to study the behavior of the system in full load operation at a wind speed range between 13 m/s and 25 m/s. By keeping the generator torque constant, a speed controller is used to adjust the pitch angle of the rotor blade to limit the drive torque of the rotor and the generator power to their nominal values. The simulation results of the system behavior are presented in this paper. This research successfully showed that modelling and simulation of the variable speed wind turbine with DFIG can be implemented using MATLAB/Simulink. The proposed model should be used as reference to solve a part of the wind power system problem in full load operation.

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