DOUBLY FED INDUCTION GENERATOR IN A WIND TURBINE

Hans Øverseth Røstøen
Norwegian University of Science and Technology (NTNU)

Tore M. Undeland
Norwegian University of Science and Technology (NTNU)

Terje Gjengedal
Statkraft

1 INTRODUCTION

In a wind power generating system, it is required that the generator tracks a prescribed torque-speed profile. Variable-speed operation is introduced to gain high efficiency in the generating system. Otherwise the generating system cannot capture the largest possible energy available from the wind and the blades of the wind turbine will subject to torsional stress and windage friction.

The mechanical efficiency in a wind turbine is dependent of the power coefficient. The power coefficient of the rotating wind turbine is given by [1] the Cp(λ,θ) curve, where λ is the tip speed ratio and θ is the pitch angle.

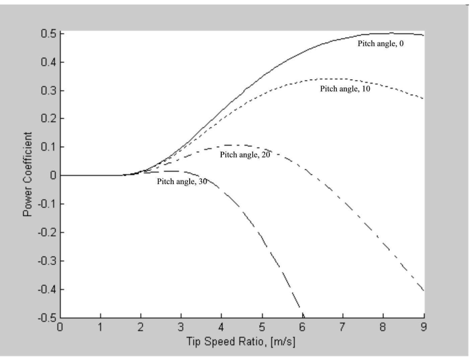

Figure 1 Power coefficient Cp(λ,θ) .

When converters in the rotor circuit provide the doubly fed induction generator the opportunity to realize adjustable speed, the maximal mechanical efficiency can be obtained and operation at the maximum power output can be realized over a wide power range.

2 TORSIONAL RESONANCE

The rotating shaft system in a wind turbine is divided into sections. The turbine itself is quite heavy and the machine rotor is light. The shaft, connecting the generator and the turbine cannot be assumed to be of infinite stiffness. The gearbox reduces the stiffness, therefore the shaft will twist as it transits torque from one end to the other. Typical value of the resonance frequency of such systems is in the range 1-2 Hz, and for a specific Danish windmill the resonance frequency is known to be 1.67 Hz [2].

A simple method for modeling the shaft system in MatLab is shown below. Because the mass of the shaft itself is very small, seen from the generator, it is reduced to zero. The inertia at the turbine gives a negative contribution to the torque when the generator is in generating mode.

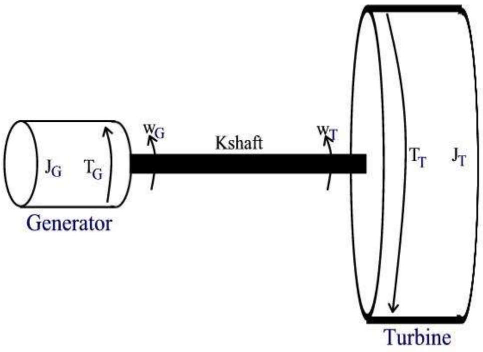

Figure 2 Generator and turbine torque interaction.

The torque T_{shaft} available to be transmitted by the shaft is

$$T_{shaft} = T_T + J_T \frac{d\omega_T}{dt}$$

The torque at the generator end seen from the shaft is,

$$T_{shaft} = T_G - J_G \frac{d\omega_G}{dt}$$

The twisting of the shaft depends on the shaft torsional or the compliance coefficient K_{shaft}:

$$(\theta_G - \theta_T) = \frac{T_{shaft}}{K_{shaft}}$$

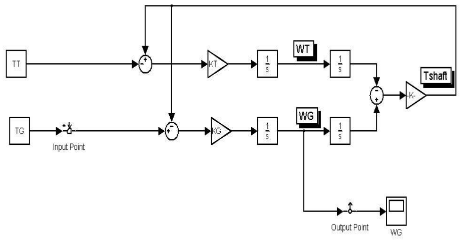

Figure 3 Simulation circuit of the torsional resonance, shaft model.

In Figure 3 a block diagram of the mechanical connection from the turbine to the generator through the shaft is shown. The constants K_T and K_G are $1/J_T$ and $1/J_G$ respectively.

$$H(s) = \frac{W_G(s)}{T_G(s)} = \frac{K_G \cdot s^2 + K_T \cdot K_{shaft}}{s^3 + (K_T \cdot K_{shaft} + K_G \cdot K_{shaft}) \cdot s}$$

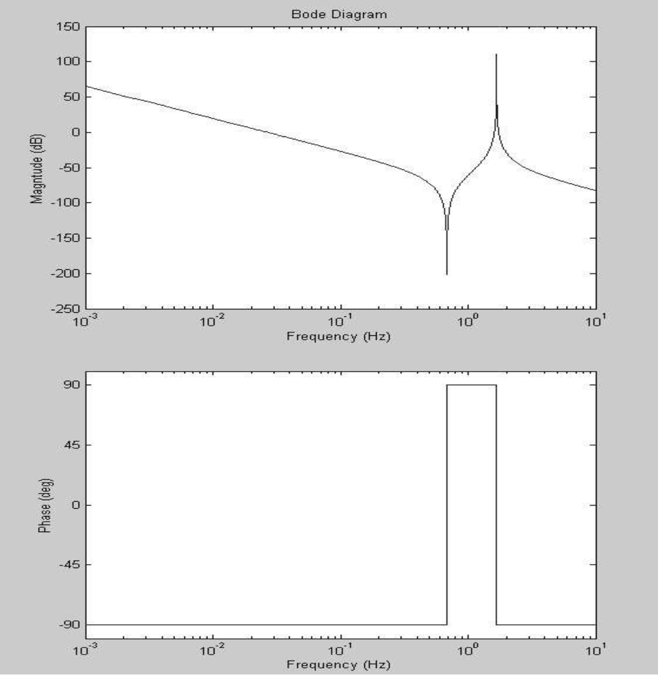

Figure 4 W_G/T_G Bode diagram.

Values for “a typical danish windmill” inertia constants are given in [2].

H_G=0.5 [s]

H_T=2.5 [s]

K_{shaft}= 0.35 [pu/rad]

The inertia constant, H, is defined as:

$$H = \frac{rotational\_energy\_at\_rated\_speed\_in\_watt-seconds}{rated\_apparent\_power\_in\_volt-amperes} = \frac{\frac{1}{2}J\omega_0^2}{S_N}$$

Where ω_0 corresponds to rated speed and J is the moment-of-inertia and expressed in [kg*m^2]. H is expressed in seconds.

3 DOUBLY FED INDUCTION GENERATOR

To construct a variable speed constant frequency system, an induction generator is considered attractive due to its flexible rotor speed characteristic with respect to the constant stator frequency. One solution to expand the speed range and reduce the slip power losses simultaneously is to doubly excite the stator and rotor windings. The power converters in the rotor circuit regenerate the majority of the slip power.

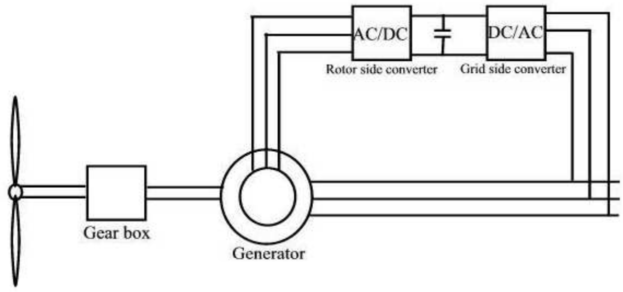

Figure 5 Doubly fed induction generator in a wind turbine.

A dynamic model of the doubly fed induction machine is needed to develop decoupled control of torque and reactive power. A model has been made in EMTDC/PSCAD. The model consists of a multi-mass model to represent the shaft system, a wound induction machine model, rotor- and grid-side converters and a grid model. The dynamic model vector-control use the Park Transformation. The transforming process of the voltage and current equations from a three-phase to two-phase components used in EMTDC/PSCAD are chosen so the turn-ratio n becomes equal to 2/3.

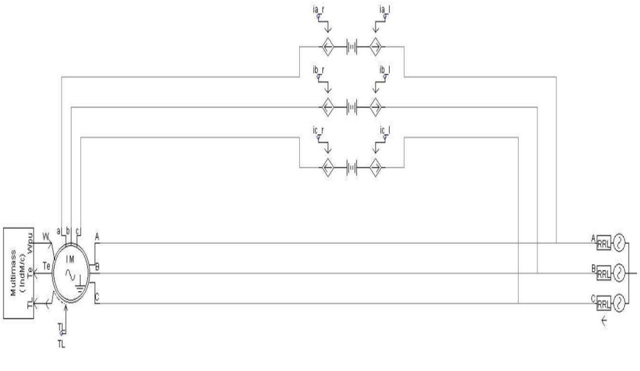

Figure 6 Doubly fed induction machine simulated in PSCAD/EMTDC.

In experimental systems [3] PWM converters are introduced in the rotor circuit. Here the converters are simulated as current sources.

4 THE ROTOR SIDE CONVERTER SIMULATED AS CURRENT SOURCES

The wound induction machine is controlled in a synchronously rotating dq axis frame, with the d-axis oriented along the stator flux vector position, via the rotor side converter.

Dynamic machine theory is presented in [4].

The machine model d-axis is aligned to the stator flux linkage, common to both the stator and the rotor. Therefore,

$$\lambda_{sq} = L_s i_{sq} + L_m i_{rq} = 0$$

Which gives,

$$i_{sq} = -\frac{L_m}{L_s} \cdot i_{rq}$$

The condition that the d-axis is always aligned with $\vec{\lambda}_s$ also results in d λ_{sq} /dt to be zero. An equivalent circuit is shown in Figure 7.

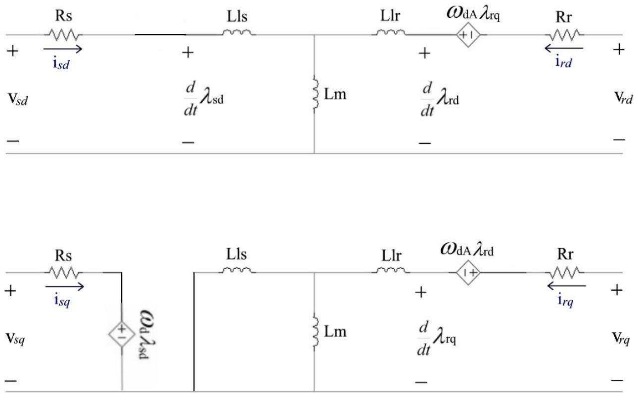

Figure 7 Dynamic circuits with the d-axis aligned with $\vec{\lambda}_s$

5 STEADY STATE VALUES

To calculate the currents in the rotor and the stator, input parameters are needed. These input parameters are:

- Voltages at the stator, v_{sd} and v_{sq}.
- Torque at the turbine, T_T.
- Reactive power desired out from the machine, Q_{ref}.
- Pole pairs, P
- Machine parameters at the stator side, R_s, L_s, L_m.

From the Figure 7 the v_{sq} voltage is,

$$v_{sq} = R_s \cdot i_{sq} + \omega_d \cdot \lambda_{sd}$$

When the motor model d-axis is aligned to the stator flux linkage then $\lambda_{sq} = 0$. The d-axis stator flux linkage and the q-axis current will create the electromagnetic torque, T_{em}. In steady state, without damping, the electromagnetic torque is equal to the torque at the turbine, T_T.

$$T_T = T_{em} = \frac{3}{2} \cdot P \cdot \lambda_{sd} \cdot i_{sq}$$

gives,

$$\omega_d \cdot \lambda_{sd}{}^2 - v_{sq} \cdot \lambda_{sd} + \frac{2 \cdot T_{em}}{3 \cdot P} \cdot R_s = 0$$

Where ω_d is the synchronous speed in electrical radians.

When the d-axis stator flux linkage is found, the q-axis currents can be calculated.

$$i_{sq,\,ref} = \frac{2 \cdot T_{em}}{3 \cdot P \cdot \lambda_{sd}}$$

$$i_{rq,\,ref} = -\frac{L_s}{L_m} \cdot \frac{2 \cdot T_{em}}{3 \cdot P \cdot \lambda_{sd}}$$

The d-axis rotor current controls the reactive power. From the reactive power equation and the d-axis stator flux linkage equation the d-axis current can be found.

$$Q_{stator,\,ref} = 3\left(v_{sd} \cdot i_{sq} - v_{sq} \cdot i_{sd}\right)$$

$$\lambda_{sd} = i_{sd} \cdot L_s + i_{rd} \cdot L_m$$

$$i_{sd,\,ref} = \frac{v_{sd} \cdot i_{sq,\,ref} - \frac{Q_{stator,\,ref}}{3}}{v_{sq}}$$

$$i_{rd,\,ref} = \frac{\lambda_{sd} - i_{sd,\,ref} \cdot L_s}{L_m}$$

6 CONTROL-LOOP DESIGN

Control of the reactive power and torque are made in to decoupled closed loop controllers. The reactive power control-loop compares the reactive power at the stator and the reactive power reference value, before sending the deviation signal to a proportional plus integral controller. The output signal of the proportional plus integral controller is the d-axis rotor current. The torque control-loop consists of a cascade speed and torque control-loop. The inner loop is the torque control that compares the electric torque and the output signal from the speed proportional plus integral controller. The speed controller compares the actual rotor speed and the reference rotor speed. The output signal from the cascade controllers is the q-axis rotor current. The d- and q-axis rotor currents are transformed to three phase currents before applied to the rotor side converter

The stator magnetizing current and the flux linkage can be considered constant when the stator is connected to the grid and the influence of the stator resistance is small. When a change occurs in the d-axis rotor current, i_{rd}, the current at the stator, i_{sd}, will change. Because the flux linkage can be considered constant, the d-axis stator current, i_{sd}, is dependent of the rotor currents and the impedances L_s and L_m.

$$isd = \frac{\lambda sd - ird \cdot Lm}{Ls}$$

The inductance L_m is strictly property to the magnetic circuit (i.e, the core material, the geometry, and the number of turns), provided that the operation is in the linear range of the magnetic material. In larger machine the L_m [p.u.] normally increases because of smaller air gap length.

Reactive power at the stator will change when the stator currents changes.

$$Q_{stator} = 3\left(v_{sd} \cdot i_{sq} - v_{sq} \cdot i_{sd}\right)$$

The control-loops in EMTDC/PSCAD is:

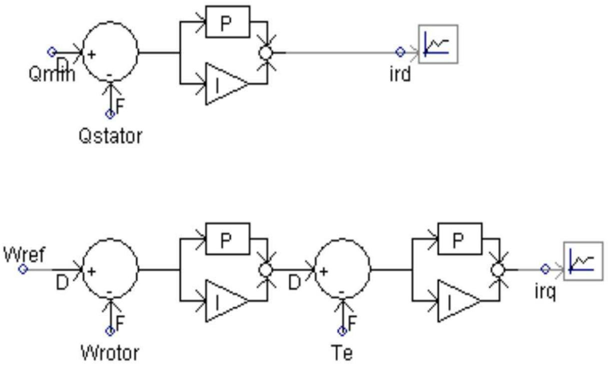

Figure 7 Reactive effect and torque control.

The current i_{sq} are generated by cascaded torque and speed control loops shown in Figure 7. The rotor speed, W_G, is measured and the W_{rotor} input is the electrical speed at the rotor given by the rotor speed and poles in the machine.

From the speed controller comes the torque reference value. The input signal T_e is a measurement of the electric torque given by the machine model. In practical life the electrical torque must be calculated.

7 PROPORTIONAL PLUS INTEGRAL CONTROLLERS

There are two ways to control the reactive power in a doubly fed induction generator. The grid side converter can work as a STATCOM and the rotor side converter can control the reactive power at the stator through the i_{rd}-axis current. Normally the d-axis rotor current will regulate the reactive power to a minimum power loss in the wound machine. Then only the grid side converter will control the reactive power from the wind turbine.

The currents in the rotor circuit are a limiting factor at the controller in the reactive power control-loop. A fast controller will give large overshot in the rotor currents. The Ziegler-Nichols methods is used to find the parameters in the control-loop.
To establish a proper control system for the torque- and speed-loops, the mechanical system is one factor. The other factors are electric system stability, power quality, mechanical stresses in the shaft system, transients in wind turbine blades and vortex tower interaction.

There should not be extra gain at the shaft systems resonance frequency. Under this condition the speed of the PI controllers must be less that the resonance frequency. Since the shaft systems resonance frequency is 1-2 [Hz] the response of the system will be slow compared to normal induction machines used in pump systems.
When there are torque pulsations in the shaft system, mechanical stresses may occur in the gearbox. To prevent breakdowns in the gearbox, torque control can damp the mechanical stresses.

Each time when a rotor blade is passing the tower the phenomenon of tower interaction occurs. What produce this interaction will not be discussed here. However, in a three bladed wind turbine a resonance three times the rotor-blade speed occurs, called the 3P effect. This can produce flicker in the voltage. With proper control this sub-harmonic frequencies can be limited.

The shaft system itself acts as a low pass filter; see Figure 4. However, a PI-controller in the speed loop will increase even more the gain at low frequencies.
The controller in the torque loop can bee designed to damp the mechanical stresses. Instead of a fast acting PI-controller, a slow controller can store the energy, from fast mechanical oscillations, in the shaft system. This control will also reduce mechanical stresses in the gearbox.

8 THE GRID SIDE CONVERTER SIMULATED AS A CURRENT SOURCES

The objective of the network side converter is to keep the DC-link voltage constant regardless of the magnitude and direction of the rotor power. A vector control approach is used, with a reference frame oriented along the stator voltage vector position.

$$P = 3\left(u_d \cdot i_d + u_q \cdot i_q\right)$$

and

$$Q = 3\left(u_d \cdot i_q - u_q \cdot i_d\right)$$

Aligning the d-axis of the reference frame along the stator voltage position gives u_{sq} to zero. If the amplitude of the stator voltage is constant the active and reactive power will be proportional to i_{sd} and i_{sq}, respectively.
To ensure stability of the system, the power into the rotor side converter should be the same as the power out of the network side converter.
The reactive power required by the network is commanding the reactive power control in the network side converter.

9 RESULTS

Different time-constants in the torque controller have been carried out in simulations shown in Figure 8. The response of a step in torque at the turbine will change with different time-constants in the electrical system. A step from 0 [pu] to -0.3 [pu] in the torque at the turbine is applied at 20 [s].

When the time-constant in the torque control-loop is infinite the PI-controller will work like a P-controller. Then the response in the speed, W_G, and the electromagnetic torque, T_G, at the generator side, is slow. A torque T_{shaft}, which is the torque transmitted in the shaft, has got a slow acting response as well. When a smaller time-constant is implemented in the PI-controller at the torque control-loop, the response will act faster. The faster response gives larger oscillations.

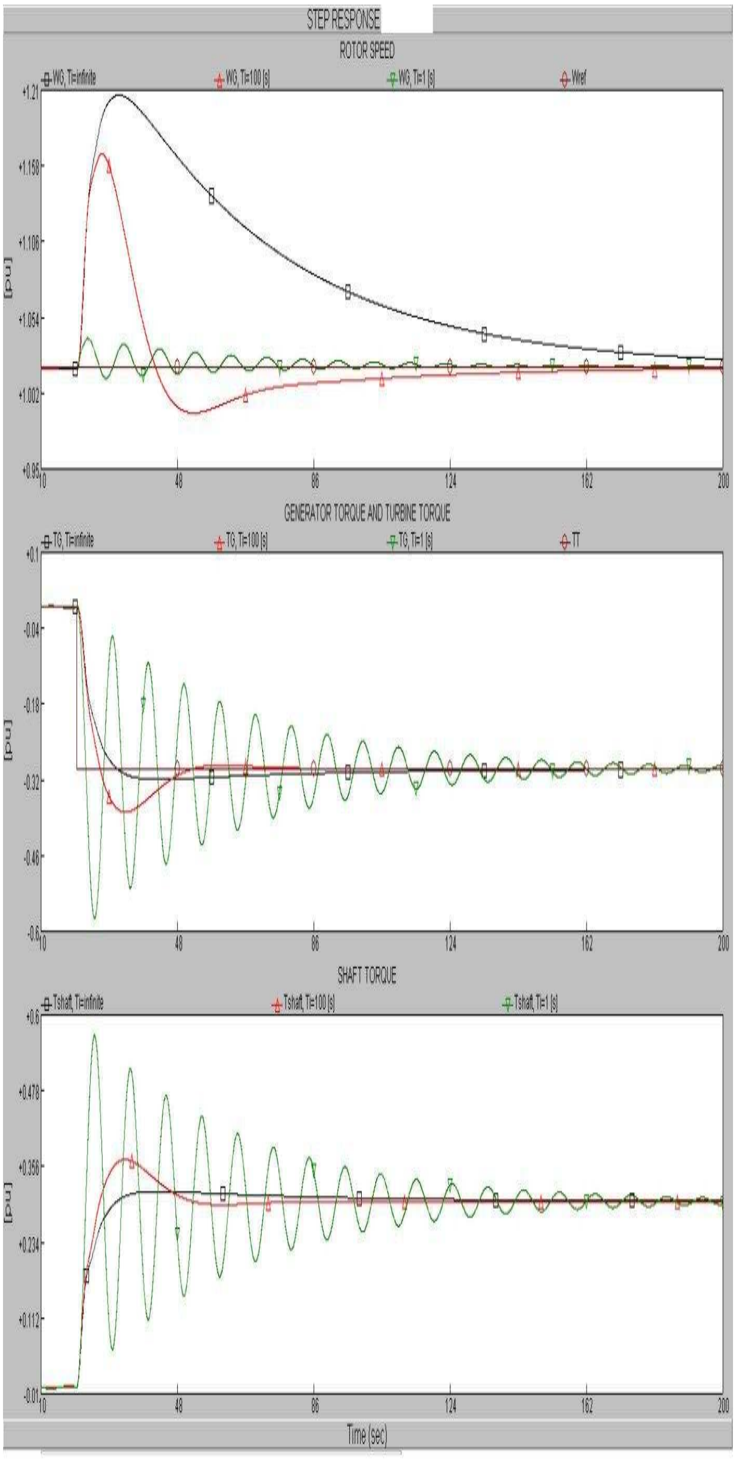

Figure 8 Step in the torque at the turbine.

These three simulations are all using the same control parameter except the time-constant in the torque control-loop. The overshoot may have been lower with different proportional gain constants. In these simulations the importance of the time-constants have been examined.

With a fast acting control system the torque transmitted in the shaft will contain larger oscillations than in slow acting control system. Slow control system means that the time-constant is large.

A ripple with magnitude 0.1 [pu] is applied to the torque at the turbine, T_T, in Figure 9. The frequency of the ripple applied in the torque is the same as the resonance frequency in the shaft. The reference speed at the rotor is 1.02 [pu]. Two simulations with different gain constants in the speed control-loop have been carried out.

A small gain constant in the speed control-loop gives large ripple amplitude in the rotor speed. When the gain constant increases the damping is growing and the amplitude in the speed ripple becomes less. The opposite happens in the electromagnetic torque. If the gain constant in the speed control-loop is increased, the oscillations in the reference value at the torque control-loop are rising. This gives increased amplitude in the electromagntic torque ripple, T_G.

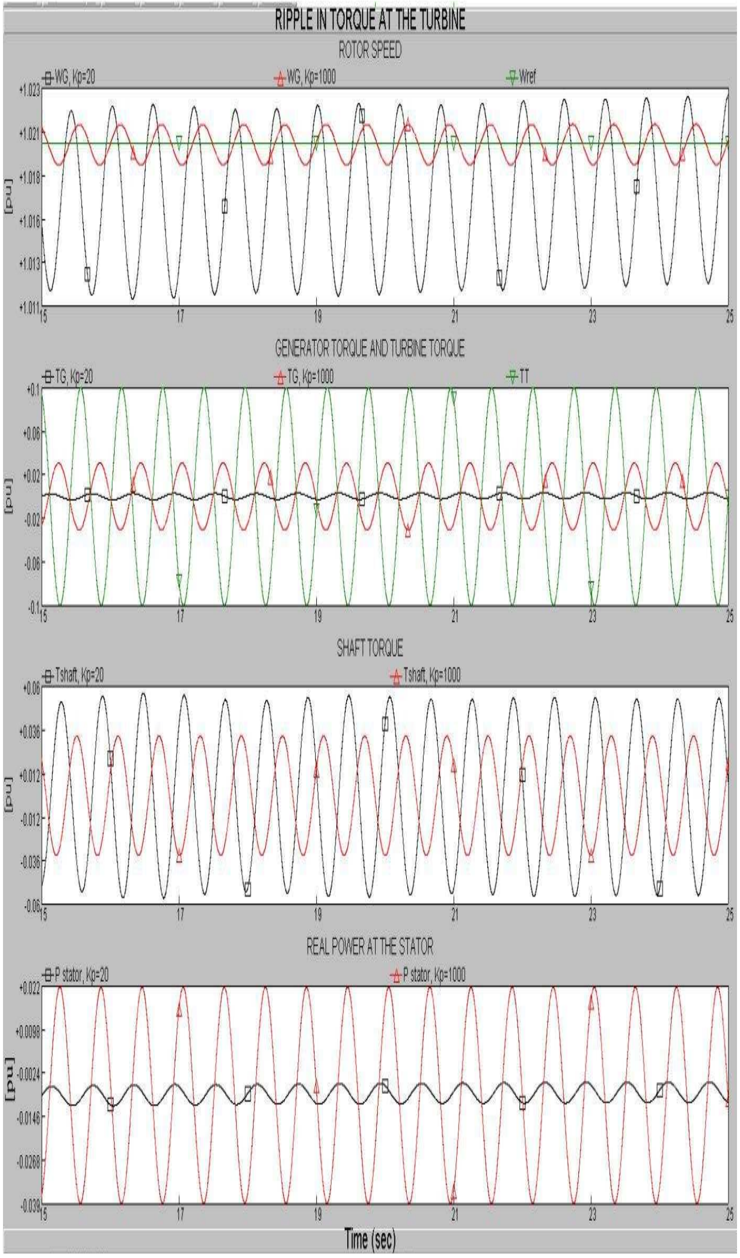

Figure 9 Ripple in the torque at the turbine.

When the ripple in the torque at the generator is getting larger and starts tracking the torque at the turbine, T_T, the ripple amplitude at the torque transmitted in the shaft, Tshaft, will reduce. As a result of larger ripple in the electrical torque, the ripple in the real power will increase.

Simulations in Figure 9 shows that increasing gain constants at the speed controller gives smaller ripple in the torque transmitted in the shaft. The problem is that the ripple in the real power increases.

10 CONCLUSION

The mechanical efficiency in a wind turbine is dependent of the power coefficient. The power coefficient of a rotating wind turbine is given by the pitch angle and the tip speed ratio. Adjustable speed will improve the system efficiency since the turbine speed can be adjusted as a function of wind speed to maximize output power.

To develop adjustable speed one possible solution is a doubly fed induction generator. A dynamic model is needed. The construction of a dynamic model of a doubly fed induction generator is similar to a wound rotor induction machine.

It is necessary to consider several factors when designing the control system in a wind turbine. These factors are electric system stability, power quality, mechanical stresses in the shaft system, wind turbine blade transients, vortex tower interaction and the converter currents.

The torque transmitted in the shaft varies with different speed of control. The proportional plus integral controller has two parameters, the proportional gain constant and the integral time constant. A large proportional constant gives large gain and a small integral time constant gives fast control. Simulations show that fast control of the electric torque gives oscillations in the torque that transmits through the shaft when a change in torque at the turbine occurs. If there are mechanical reasons to avoid oscillations in the torque transmitted through the shaft, a control with large time constant will help avoiding the oscillations that take place.

Torque pulsation from the mechanical system may take place. In simulations it can be seen that the torque transmitted in the shaft system will contain these pulsations. The pulsations will be damped with a large proportional gain constant in the speed controller. A large gain constant in the speed controller makes the electromagnetic torque to vary more and it starts tracking the torque pulsations from the turbine. When the electromagnetic torque has pulsations the power will contain the same pulsations. When choosing the gain constant in the speed controller a choice between pulsations in the torque transmitted in the shaft or pulsations in the power from the generator must be done.
To avoid unnecessary oscillations, the gain at the resonance frequency in the shaft system should be small.

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