Doubly Fed Induction Generator Model for Power System Simulation Tools

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Abstract— **The present paper describes a proposed model of a doubly fed induction generator (DFIG) with its controllers. The model has been implemented in the power system simulation tool PSS/E, and test simulations have been performed to validate the model. Analysis of these simulation results are described in this paper.**

In addition it is shown how a stabilizer can be implemented to damp 3p fluctuations

Index Terms—**Doubly Fed Induction Generator, Power electronic converters, PSS/E, Wind Turbine**

I. NOMENCLATURE

The variables/constants are in pu-values, unless other units explicitly are specified.

v_{qs} – The q-axis voltage on the stator terminals
v_{ds} – The d-axis voltage on the stator terminals
i_{qs} – The q-axis current flowing from the stator terminals and into the external network
i_{ds} – The d-axis current flowing from the stator terminals and into the external network
v_{qr} – The injected q-axis voltage in the rotor circuit
v_{dr} – The injected d-axis voltage in the rotor circuit
i_{qr} – The q-axis current in the rotor circuit
i_{dr} – The d-axis current in the rotor circuit
i_{dc} – The d-axis current flowing through the net side converter
i_{qc} – The q-axis current flowing through the net side converter
ψ_{qs} – The q-axis stator flux
ψ_{ds} – The d-axis stator flux
ψ_{qr} – The q-axis rotor flux
ψ_{dr} – The d-axis rotor flux
ω_N – The rated speed of the generator[rad/s]
ω_s – The synchronous speed
ω_r – The rotor speed of the generator
r_s – The stator resistance
r_r – The rotor resistance
$x_{s\sigma}$ – The leakage reactance in the stator
x_m – The magnetizing inductance
x_s – The stator reactance, $(x_m+x_{s\sigma})$
$x_{r\sigma}$ – The leakage reactance in the rotor
x_r – The rotor reactance, $(x_m+x_{r\sigma})$
x' – The transient rotor reactance, $(x_s-(x_m^2/x_r))$
T_0' – The rotor circuit short circuit constant, $(x_r/(r_r\omega_N))$ [s]
T_{ag} – The air gap torque
T_{gen} – The mechanical torque on the generator shaft

H – The inertia constant of the generator [s]
V_s – The phasor voltage on the stator terminals $(v_{ds}+j\ v_{qs})$
$V\ '$ – The phasor voltage behind the transient impedance of the induction generator
P_c – The active power delivered by the net side converter to the grid
Q_c – The reactive power delivered by the net side converter to the grid
P_{net} – The total active power delivered to the grid
Q_{net} – The total reactive power delivered to the grid

II. INTRODUCTION

The use of doubly fed induction generators (DFIGs) is becoming increasingly important in wind power applications. Compared with conventional asynchronous generators they enable variable speed operation. Advantages from this are reduction of the mechanical stresses on the wind turbines, reduced noise, reduced requirements for the pitch angle controllers, and with low losses in the power electronic converters the overall efficiency of the wind turbine may be improved [1]. In addition, the power electronic converters may provide a significant degree of control of the reactive power flowing between the DFIGs and the grid.

To study the impact from DFIGs on the power system it is important to have good models and simulation tools. It is also vital to control the DFIGs in a proper way. This paper describes a doubly fed induction generator model with a proposed control system. The DFIG model has been implemented for use in the power system simulation tool PSS/E [2]. In the simulations a turbine model [3] was used to generate the mechanical torque of the DFIG. The turbine model accepts wind speed series as input, and it ensures that the dominant dynamics of the drive train are taken into consideration. It also includes a pitch angle controller.
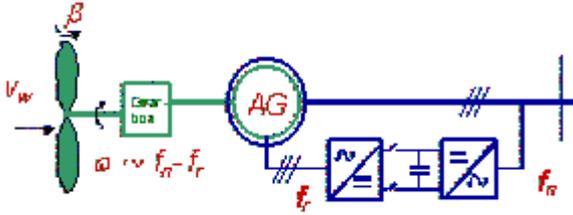
III. THE DFIG MODEL

Fig. 1. Wind turbine with a DFIG

In the present chapter the DFIG model implemented in PSS/E is described. For every time step the DFIG model injects a sum of two currents into the network model it is a part of. One of the current is injected through the stator of the induction generator, and the other through the net side converter. It is therefore convenient to describe the induction generator model and the model for calculating the current through the net side converter separately.

A. The induction generator

A third order model of the induction generator has been used. Thus, the stator flux dynamics have been neglected. For studying of power system stability in the context of PSS/E, this is considered to be sufficient as the stator flux has a very short time constant. In cases where it is desirable to find for instance the peak value of the current through the stator during short-circuit, the fifth order model should be used.

The stator terminal voltages are given by :

$$v_{ds} = -r_s i_{ds} + \omega_s \psi_{qs} \tag{1}$$

$$v_{qs} = -r_s i_{ds} - \omega_s \psi_{ds} \tag{2}$$

The rotor voltages are given by:

$$v_{dr} = r_r i_{dr} - (\omega_s - \omega_r)\psi_{qr} + \frac{1}{\omega_N}\dot{\psi}_{dr} \tag{3}$$

$$v_{qr} = r_r i_{qr} + (\omega_s - \omega_r)\psi_{dr} + \frac{1}{\omega_N}\dot{\psi}_{qr} \tag{4}$$

The rotor speed acceleration $\dot{\omega}_r$ is given by:

$$\dot{\omega}_r = \frac{1}{2H}(T_{ag} - T_{gen}) \tag{5}$$

Equations 3-5 are the state equations for the induction machine, and they comprise the third order model. Typically in power system simulation tools the induction machines are in every time step represented as a voltage source behind the transient impedance [4]. This way the machine appears as a current source for the network model.
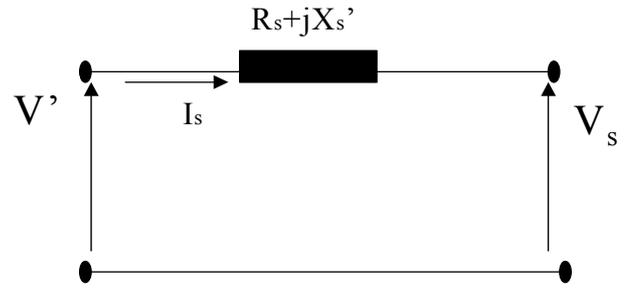

Fig. 2. Transient equivalent circuit of the induction generator

The voltage $V^{'}$ is derived in the following:

The stator fluxes are given by:

$$\psi_{qs} = (x_{s\sigma} + x_m)i_{qs} + x_m i_{qr} = x_s i_{qs} + x_m i_{qr} \tag{6}$$

$$\psi_{ds} = x_s i_{ds} + x_m i_{dr} \tag{7}$$

The rotor fluxes are given by:

$$\psi_{qr} = (x_{r\sigma} + x_m)i_{qr} + x_m i_{qs} = x_r i_{qr} + x_m i_{qs} \tag{8}$$

$$\psi_{dr} = x_r i_{dr} + x_m i_{ds} \tag{9}$$

From Equations 8-9, the rotor currents can be written as:

$$i_{dr} = \frac{\psi_{dr} - x_m i_{ds}}{x_r} \tag{10}$$

$$i_{qr} = \frac{\psi_{qr} - x_m i_{qs}}{x_r} \tag{11}$$

Inserting 10-11 into 6 and 7 gives:

$$\psi_{ds} = \frac{x_m}{x_r}\psi_{dr} + (x_s - \frac{x_m^2}{x_r})i_{ds} = \frac{x_m}{x_r}\psi_{dr} + x^{'} i_{ds} \tag{12}$$

$$\psi_{qs} = \frac{x_m}{x_r}\psi_{qr} + x^{'} i_{qs} \tag{13}$$

The stator terminal voltages can now be expressed as:

$$v_{ds} = -r_s i_{ds} + x^{'} i_{qs} + \omega_s \frac{x_m}{x_r}\psi_{qr} \tag{14}$$

$$v_{qs} = -r_s i_{qs} - x^{'} i_{ds} - \omega_s \frac{x_m}{x_r}\psi_{dr} \tag{15}$$

From 14 and 15 the voltage $V^{'}$ is defined:

$$V' = v'_q + jv'_d \tag{16}$$

where $v'_q = -\omega_s \dfrac{x_m}{x_r} \psi_{dr}$ and $v'_d = \omega_s \dfrac{x_m}{x_r} \psi_{qr}$.

It is desirable to have a direct coupling between the state equations and the current injection model shown in Figure 2. This is achieved by eliminating the rotor currents in Equations 3-4 and expressing the rotor fluxes in terms of v'_d and v'_q.

$$\dot{v}'_d = \frac{\omega_s}{T'_0}\left(\frac{-v'_d}{\omega_s} + \frac{x_m^2}{x_r}i_{qs}\right) + (\omega_s - \omega_r)\omega_N v'_q$$
$$+ \omega_s \omega_N \frac{x_m}{x_r} v_{qr} \tag{17}$$

$$\dot{v}'_q = -\frac{\omega_s}{T'_0}\left(\frac{v'_q}{\omega_s} + \frac{x_m^2}{x_r}i_{ds}\right) - (\omega_s - \omega_r)\omega_N v'_d$$
$$- \omega_s \omega_N \frac{x_m}{x_r} v_{dr} \tag{18}$$

B. The current injection through the net side converter

The active and reactive power flowing through the net side converter is determined by the chosen control strategy. The current component that is injected into the network model from the net side converter is simply given by:

$$i_{dc} + ji_{qc} = \frac{(P_c + jQ_c)^*}{V_s^*} \tag{19}$$

IV. THE PROPOSED CONTROL STRATEGY

The control strategy of a DFIG is a matter of choice, and little information is usually available about practical implementations. It is nevertheless important to model the control system such that it can represent the real system performance as close as possible. In the present paper the chosen control strategy of the DFIG is based on four criteria:

1. Run the wind turbine at optimum efficiency
2. Provide a desired reactive exchange between the stator and the grid
3. Use the net side converter to control the terminal voltage of the DFIG
4. Keep the DC-link voltage constant

To achieve criteria 1-2 it is the rotor voltages v_{dr} and v_{qr} that are controlled. The control of the net side converter makes it possible to achieve criteria 3 and 4. For the proposed control strategy of the DFIG, the model should only be connected with a wind turbine model with a pitch angle controller to limit the output power.

A. Control of the rotor side converter

The power electronic converter is on the rotor side modelled as a controlled voltage source. The d-axis rotor voltage v_{dr} is controlling the torque of the generator (this component causes the speed to vary), and the q-axis rotor voltage is mainly controlling the reactive power flow in the stator of the generator. The control systems for rotor side converters are shown in Figure 3 and Figure 4, respectively. The maximum and minimum size of v_{dr} and v_{qr} are dependent on the size of the rotor side converter.
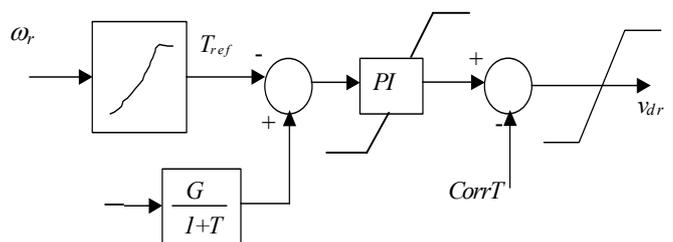

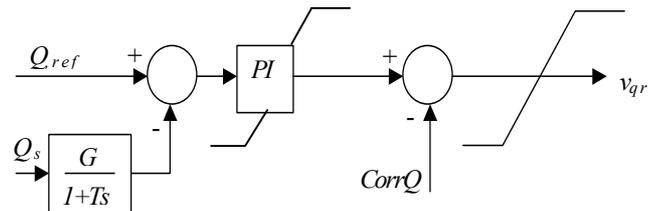Fig. 3. Control system for the generator torque

Fig. 4. Control system for the reactive power flow in the stator

The reference torque T_{ref} follows a constant times the square of the rotor speed i.e. $T_{ref} = K\omega_r^2$. This ensures that the turbine runs with optimal efficiency. However, in cases where the speed is close to the cut-in speed of the machine or to the maximum speed limit of the machine this relation is no longer valid. A pitch angle controller may be used to limit the speed of the generator. At low speeds there is chosen a linear relation between speed and torque [5].

The correction terms *CorrT* and *CorrQ* (see Figures 3-4) are necessary to take into consideration the fact that a current in the q-axis creates a voltage component both in the d-axis and the q-axis, and vice versa. Thus, they are necessary to decouple the control loops. More detailed information about correction terms in DFIG control loops can be found in [6].

B. Control of the net side converter

The net side converter also has two main control loops. One loop is for control of active power and the other loop is for control of reactive power or the terminal voltage.

The active power through the net side converter is controlled in such a way that it delivers or draws the same active power from the grid as the rotor side converter delivers or draws from the rotor circuit. This can be achieved by controlling the DC side voltage of the converter. In the model it is assumed that there are no losses in the converter, and that the control is so fast that it can be assumed to be instantaneous. This corresponds to a constant DC side voltage in the model.

The voltage control or the reactive power flow control of the net side converter is shown in Figure 5.

One control strategy can be to keep the terminal voltage of the DFIG at constant or at a certain level depending on the reactive power flow. In this case V_{ref} is compared with $|V_s|$. The constant Cc is in this case zero or small.

Alternatively, the control strategy can be to control the amount of reactive power delivered from the wind turbine to the grid. In this case the filter constant $G=0.0$ and the constant $Cc=1.0$.
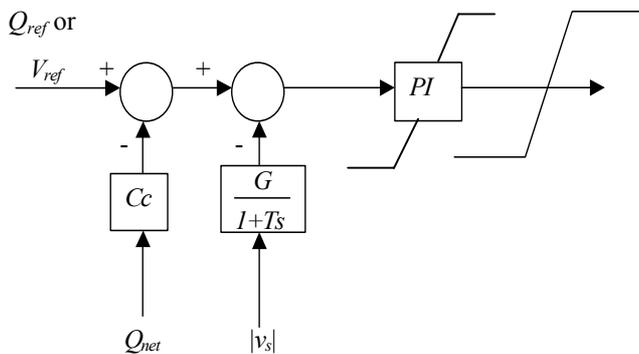
Fig. 5. Voltage control of the net side converter

V. TEST SIMULATIONS

A. Response to a wind series

A wind turbine is connected to a grid through a transformer and line. This is illustrated in Figure 6. The rated voltage of the asynchronous machine of the wind turbine is 0.69 kV, and the rated power of the asynchronous machine is 2.5 MVA. The shaft dynamics in the wind turbine have been modeled to take into the account the fact that the shaft is not stiff. The short-circuit rating of the power grid at the connection point (border line in Figure 6) is 56 MVA.
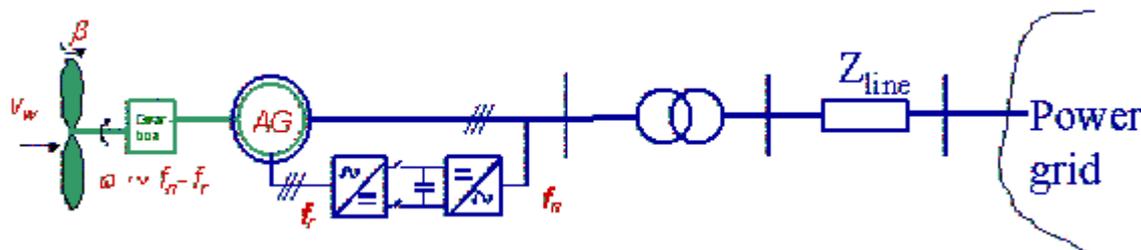
It is desired that the exchange of reactive power between the stator of the DFIG and the grid is 0.0 MVAr. Thus, Q_{ref} in Figure 4 is set to 0. Further, the rotor side converter of the DFIG is also controlled in such a way that the speed is adjusted after a Torque-speed characteristic. This ensures the optimum efficiency of the turbine-generator set as the wind speed varies. The speed range for achieving optimal efficiency is 0.7-1.3 pu. In this speed range the relation between the torque reference and the rotor speed is quadratic. The pitch controller is activated if the speed exceeds 1.3 pu. The cut-in speed of the turbine is 0.65 pu. For speeds between 0.65 pu and 0.7 pu the relation between the torque reference and the rotor speed is linear.

The net side converter is used for voltage control. The set point of the voltage is chosen to be the calculated voltage on the DFIG terminals from the initial load flow, and the compounding constant Cc is chosen to be 0 (see Figure 5).

A ten minutes wind series with average wind speed 7.9 m/s is used as input to the wind turbine. A wind field model ensures that the turbine also experience the 3p fluctuations. Below selected results from the simulation of this time series are shown. Among these is also the power spectral density (PSD) of the active power delivered from the wind turbine to the grid. The PSD reveal the 3p fluctuation and also how well this fluctuation is damped.
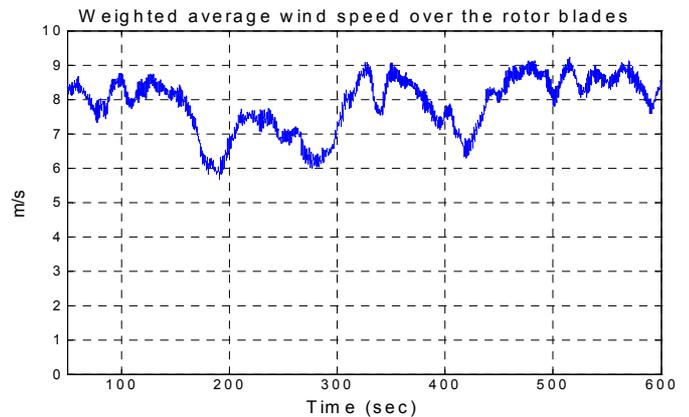
Fig. 7.   The weighted average wind speed over the rotor blades

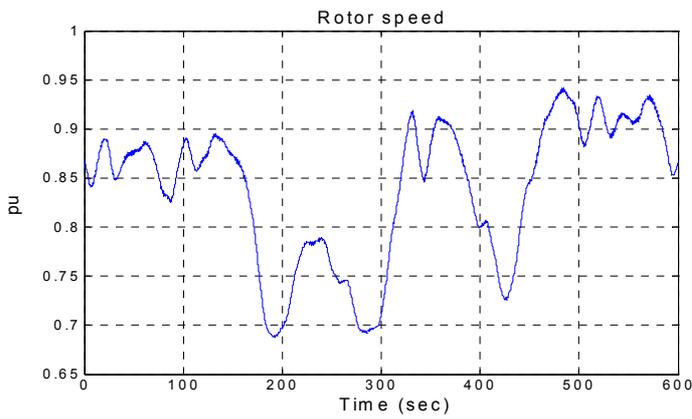Fig. 6.   The DFIG connected to a grid

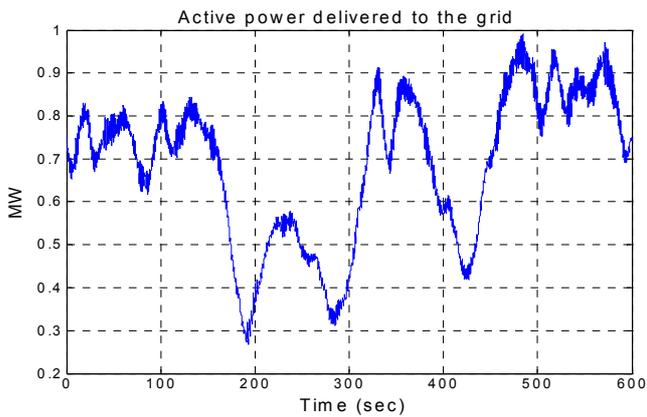Fig. 8.   The generator speed

Fig. 9.   The active power delivered to the grid
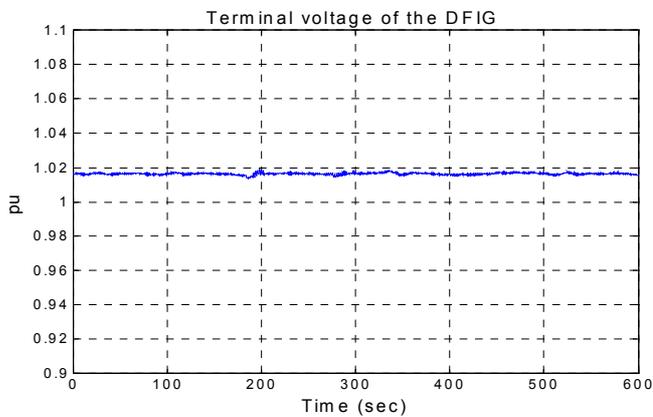

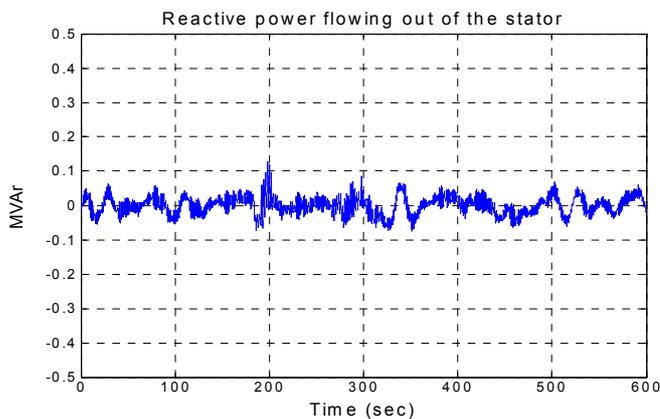Fig. 10.   The terminal voltage of the DFIG

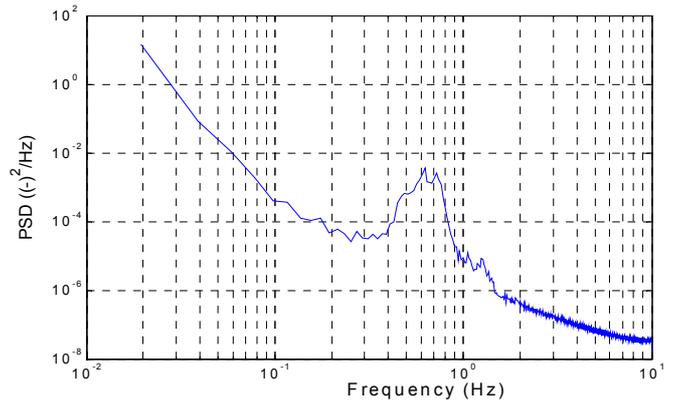Fig. 11.   The reactive power flowing out of the stator

Fig. 12.   The PSD of the active power delivered to the grid

From Figures 7-8 it is seen that the generator speed varies with the wind speed. This is expected as the turbine is operated in the variable speed area. The active power delivered to the grid does also reflect the variation in the wind speed.

Further it is seen from Figure 10 that the terminal voltage of the DFIG is kept constant during the whole simulation. This shows that the voltage controller is working properly.

Figure 11 shows that the controller for the reactive power flowing through the stator is also working properly.

As the generator is operated at variable speed the 3p frequency varies. This explains the wide range of the peak in Figure 12. For a conventional induction generator the 3p peak is normally narrower than in Figure 12, due to the constant rotor speed. Examples of this can be found in [7].

B. Stabilizer loop for damping of 3p fluctuations

The 3p fluctuations in the previous section were considerable. They are not desirable as they may cause disturbances for consumers or interact with components in the power system. Thus, there are good motives to eliminate them.

An advantage with the variable speed generator is that its control system relatively easy can be utilized to damp the 3p fluctuations. Figure 13 shows the principle of using a stabilizer loop in the generator torque control system to damp the 3p fluctuations.
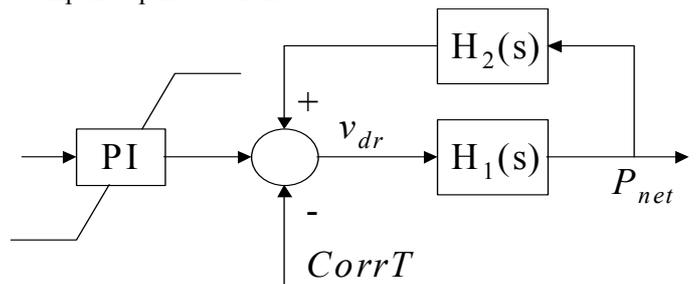

Fig. 13. Stabilizer loop from the active power output of the wind turbine to the d-axis rotor voltage reference

The idea is that $H_2(s)$ has the inverse gain and the negative phase angle of $H_1(s)$ for the frequencies of the 3p fluctuations. This way the stabilizing loop is opposing the 3p fluctuations. It is however, demanding to obtain the desirable gain-phase characteristic for $H_2(s)$ as the 3p fluctuations vary in frequency as the speed varies. Methods to deal with this problem may be parallel stabilizer loops that are activated depending on the rotor speed or an adaptive control adjusting the parameters in the transfer function for $H_2(s)$ as the rotor speed varies.

A stabilizer loop was designed and inserted in the control system for the generator torque as shown in Figure 13. Otherwise the case was identical with the one in the previous section. Figure 14 shows the PSD of the active power delivered to the grid for the cases with and without a stabilizer loop.
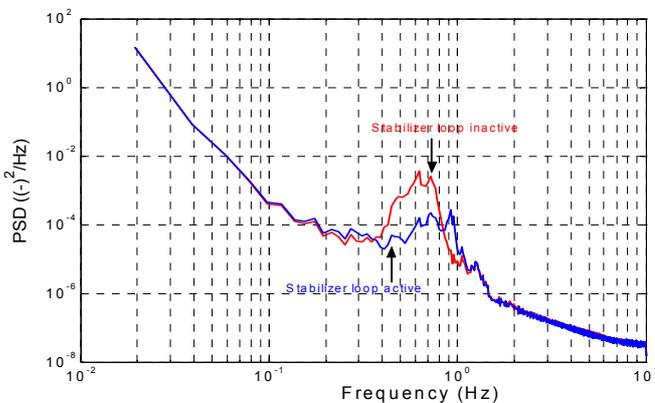

Fig. 14. PSDs of the active power delivered to the grid

It is seen from Figure 14 that the stabilizer loop have introduced considerable damping of the 3p pulsations that have frequency below 0.8 Hz. The pulsations corresponding to the peak in the simulation where the stabilizer loop was inactive is damped at least 10 times in the simulation where the stabilizer loop was active. The fact that the stabilizer loop provides poorer damping of 3p pulsations that are above 0.85 Hz is not of significance during this simulation as the maximum speed at 0.95 pu (see Figure 8) correspond to 3 pulsations with frequency 0.699 Hz. If the frequency of the 3p pulsations exceeds 0.8 Hz one may have to retune the stabilizer loop or activate a parallel loop that provides damping.

Figure 15 shows the time plot of a small section of the simulated output power from the wind turbine in both the case with and without the stabilizer loop. The effect of the stabilizer loop is obvious.
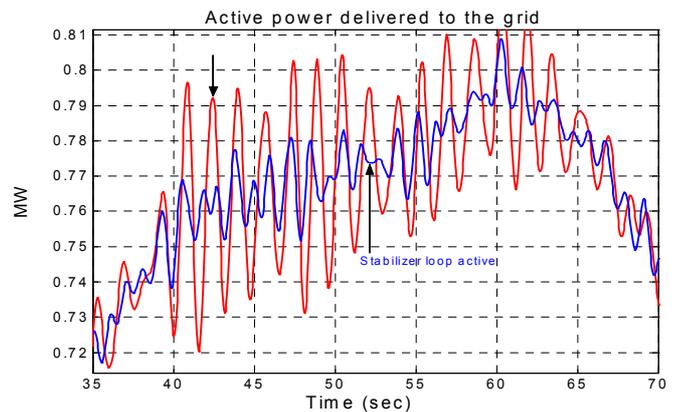

Fig. 15. A small section of the simulated active power delivered to the grid for the case with stabilizer loop and the case without stabilizer loop

VI. Conclusion

A model of a DFIG including its chosen control loops has been implemented in the power system simulation package PSS/E.

The initial simulations demonstrate how the model responds to an input wind series. The chosen control strategy works well, and it can by adding a stabilizer loop be utilized to damp 3p fluctuations in the output power of a wind turbine with DFIG.

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