Sensorless Control of Doubly-fed Asynchronous Machines for WECS Applications

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Abstract

This paper presents a rotor position estimation algorithm for a rotor current hysteresis control of a doubly-fed asynchronous generator in a variable-speed wind turbine system. The estimation scheme uses stator voltages and stator and rotor currents to calculate the position of the rotor. The system is simulated and compiled by a real-time toolbox. The results with and without position sensor are compared to confirm the good performance of the estimation algorithm.

Keywords: Wind energy, doubly-fed asynchronous generators, sensorless control, real-time systems.

1. Introduction

The most important advantages of variable speed wind turbines as compared with conventional constant speed systems are the improved dynamic behaviour and the increase of power capture [1]. One of the generation systems commercially available in the wind energy market currently is the doubly-fed induction generator (DFIG) with its stator winding directly connected to the grid and with its rotor winding connected to the grid through a frequency converter like in figure 1, [2]. One of the advantages of this system is that the rating of the power converter is a fraction of that of the generator. Control strategies and performance evaluation of doubly-fed induction generators have been widely discussed for operation below and above synchronous speed. If both speeds are to be achieved, two reversible DC/ AC power converters are required, as the rotor power flows from the rotor to the grid for supersynchronous speed and in the opposite direction for subsynchronous speed. A stator flux-oriented control with decoupled control of electrical torque and reactive power on wind energy applications is used in [3]. The rotor side converter usually is controlled through the projections of the rotor current phasor on the stator flux reference frame, the so-called field oriented control (FOC), [4]. This allows for decoupled control of the electrical torque and stator magnetizing current [5].

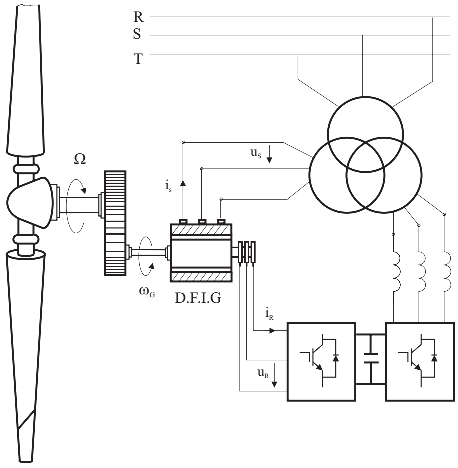

Figure 1: Variable speed wind turbine with a doubly-fed induction generator.

The aim of this paper is to avoid the use of a position sensor on the shaft of the generator while maintaining the good dynamic performance of the FOC of the rotor side converter. The influence of the estimation algorithm on the dynamic response of the controller is to be maintained so accurate as possible.

For vector-controlled doubly-fed asynchronous generators, sensorless operation is desirable because the use of a position encoder has several drawbacks in term of robustness, cost and maintenance, [3]. However, most of the works presented up to date have some limitations, e. g. at low speed operation, among others, [6],

[7]; and some other use complicated artificial intelligence based algorithms, that are very computation-time consuming and difficult to implement, [8]. Here, a position estimator based on the physical equations of the machine is introduced to enhance the performance of a doubly-fed asynchronous generator for a wind energy conversion system.

2. Machine model

The machine is represented by the well-known phasor equations, [5], expressed in a synchronous reference frame rotating at ω_s as:

$$\begin{aligned} u_{sd} &= \dot{\psi}_{sd} - \psi_{sq}\omega_s + R_s i_{sd} \\ u_{sq} &= \dot{\psi}_{sq} + \psi_{sd}\omega_s + R_s i_{sq} \\ u_{rd} &= \dot{\psi}_{rd} + R_r i_{rd} - \psi_{rq}(\omega_s - \omega_m) \\ u_{rq} &= \dot{\psi}_{rq} + R_r i_{rq} + \psi_{rd}(\omega_s - \omega_m) \\ t_e &= \frac{2}{3}p(\psi_{sd} i_{sq} - \psi_{sq} i_{sd}) \end{aligned} \tag{1}$$

where $\frac{\omega_m}{dt} = \frac{p}{J}(t_e - t_{load})$ is the mechanical equation. A classical stator-flux orientation is used for the rotor converter control, while for the estimation of the position the magnitudes are expressed in a reference frame rotating synchronuosly with the stator voltage phasor. The q-axis of this reference frame is aligned with the stator voltage phasor, so that $u_{sd} = 0$ and $u_{sq} = |U_s|$.

3. Estimation scheme

As the stator of the generator is directly connected to the grid, for the proposed method, measurements of stator voltages and stator and rotor currents are expressed in the reference frame of the stator voltage phasor in order to estimate the position of the rotor, being the position of the stator field fixed by the grid. This can be seen in equations 2, derived from equations 1 in steady state:

$$\begin{aligned} \psi_{sd} &= \frac{u_{sq} - R_s i_{sq}}{\omega_s} \\ \psi_{sq} &= \frac{R_s i_{sd}}{\omega_s} \end{aligned} \tag{2}$$

where the stator voltage vector is aligned with the q-axis of the synchronous reference frame, i.e. $u_{sd} = 0$. Thus, the position of rotor currents in the synchronous reference frame can then be obtained from stator quantities, as shown in equation 3:

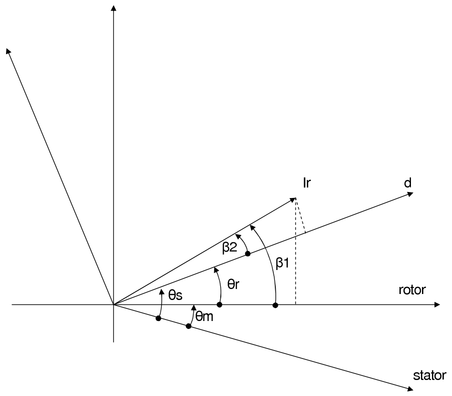

Figure 2: Angle description for the estimation algorithm.

$$\beta_2 = arctg\left(\frac{\frac{R_s i_{sd}}{\omega_s} - L_s i_{sq}}{\frac{u_{sq} - R_s i_{sq}}{\omega_s} - L_s i_{sd}}\right) \tag{3}$$

where the expression in brackets is derived from the expression of the estator flux in the synchronous reference frame. This angle is a constant value in steady state, as it is the ratio of the q component of the rotor current to the d component of the rotor current, that is rotating synchronously with the reference frame. In terms of the stator power, β_2 is positive when the machine is working as a generator and negative when the machine is working as a motor.

The angles between the different reference frames are shown in figure 2.

The position of the rotor currents in its own reference frame, β_1, is computed from direct measurement of rotor currents and the well known Clarke transformation, as follows:

$$\beta_1 = arctg\left(\frac{i_{r\beta}}{i_{r\alpha}}\right) \tag{4}$$

This angle varies between 0 and 2π around the dq axes at the slip speed $s\omega_s$, both in sub- and super-synchronous operation, but in opposite direction in each case. Substracting β_2 from β_1, equations 3 and 4 respectively, results in the estimated position of the rotor in the synchronous reference frame, $\hat{\theta}_r$:

$$\hat{\theta}_r = \beta_1 - \beta_2 \tag{5}$$

Subtracting $\hat{\theta}_r$ from θ_s yields the estimated electrical rotor position, $\hat{\theta}_m$:

$$\hat{\theta}_m = \theta_s - \hat{\theta}_r \tag{6}$$

For the desired mechanical rotor position, the number of pole pairs of the machine must be taken into

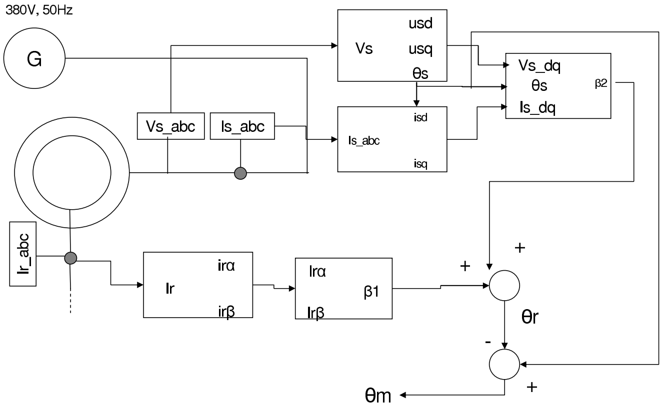

Figure 3: Estimation algorithm.

account. The whole sensorless control scheme is shown in figure 3. The mechanical speed is obtained from the positon and filtered before it is fed back to the speed controller.

4. Simulations and results

Figure 7 shows the scheme used in the simulations. Simulations have been carried out on a MATLAB/Simulink platform, by means of the toolboxes SimPowerSystems and Real Time Workshop. A wounded rotor asynchronous machine connected to the grid and driven by an inverter connected to its rotor windings is shown, as well as the control and estimation blocks.

Different kind of tests have been done to analize the performance of the system. Figure 4, shows the reactive power response for a step in the d-axis rotor current. A fast response is observed. The changes in β_1 and β_2 are shown in figures 5 and 6 respectively. Again, the response of the estimation algorith is very fast. In figure 5 the difference in β_1 between the estimation algorithm and the use of a sensor, is a consequence of the dynamic response of the controller to the noisy feedback signal from the estimation block, i.e. the speed has a small damping oscillation around the reference value, that causes this little drift between the signals. This effect disappears as soon as the transient fades away. This remarks the importance of tuning the controller and filtering the speed.

In figure 8 the generator accelerates fast from subsynchronous speed to supersynchronous speed. The phase-A rotor current is also shown to prove the smooth transition through synchronous speed. The estimated rotor angle in this test is shown in figure 9. The good accuracy of the estimation algorithm can be seen, as well as the influence of the estimation algorithm on the dynamics of the system, as previously

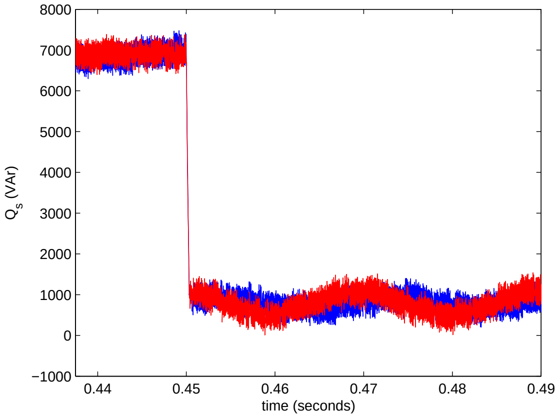

Figure 4: Reactive power step.

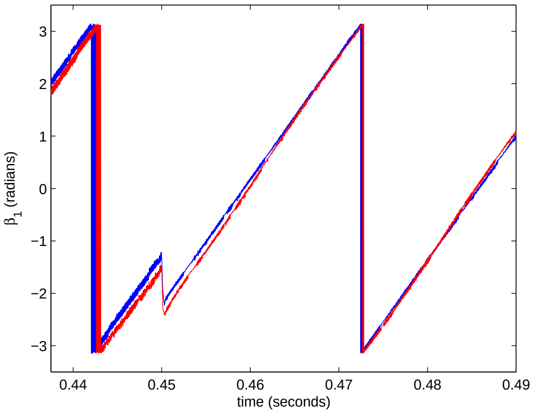

Figure 5: β_1 change under a reactive power step.

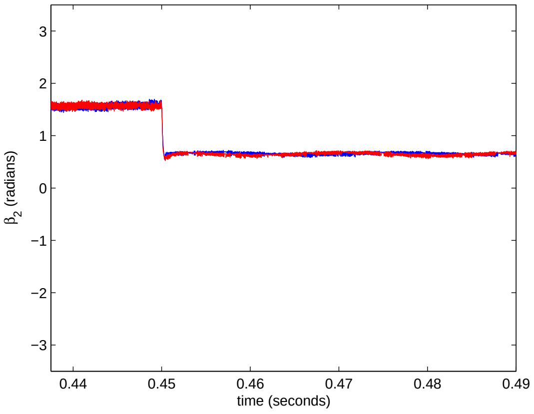

Figure 6: β_2 change under a reactive power step.

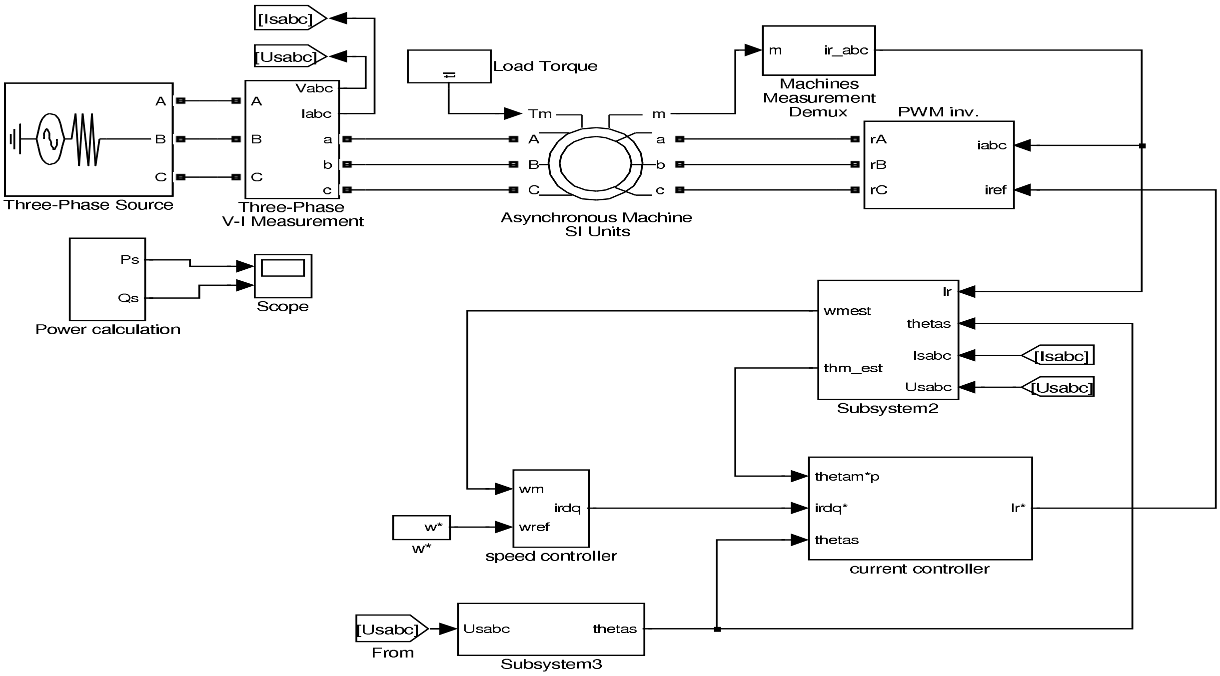

Figure 7: Sensorless control of DFIG.

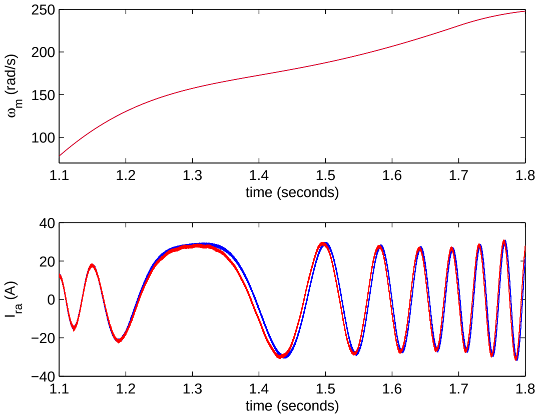

Figure 8: Speed and phase A rotor current during acceleration through synchronous speed.

mentioned. Again the drift fades away in a very short time.

At last, a rated load torque change is applied at zero speed reference. The machine moves from zero to a low speed and back to zero in a short time. This is shown in figure 10. Again, the estimated rotor angle convergence to the measured one depends on the dynamimc behaviour of the system with estimated feedback to the controllers.

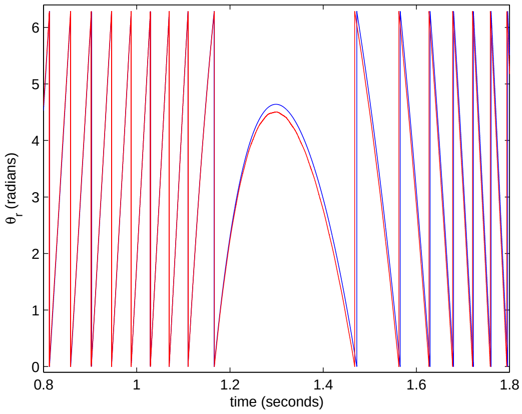

Figure 9: Estimated rotor position during acceleration through synchronous speed.

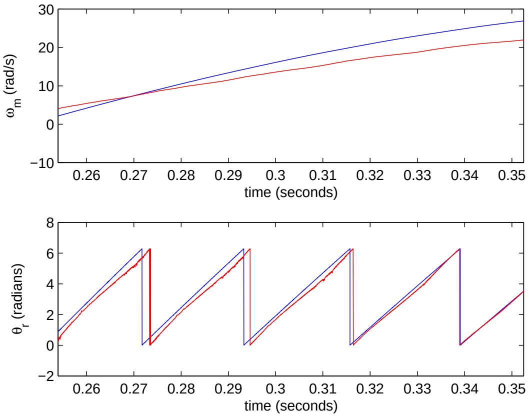

Figure 10: Speed and rotor angle for a torque step at zero speed.

5. Conclusions

A rotor position estimation scheme has been proposed for variable-speed wind turbines with doubly-fed asynchronous generators. Results show the accuracy of the proposed system for the good performance of the sensorless control. Responses to load and reactive power setpoints changes, and smooth transition through synchronous speed have been given, proving the good performance regardless the inherent noise due to the hysteresis current controllers and the estimated signals.

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