Sliding Mode Control of a Doubly Fed Induction Generator in Real Time Wind Turbines

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Abstract:

This study details a real-time sliding mode control strategy for a wind turbine with a variable-speed double-feed induction generator. In this layout, the so-called vector control theory is used to reduce the complexity of the electrical equations governing the system. In real-time applications, the suggested control strategy may be implemented using a modestly priced Digital Signal Processor (DSP). Using Lyapunov stability theory, we analyse the suggested sliding mode controller's stability in the face of disturbances and parameter uncertainty. To examine how well the suggested controller works in practice, a brand-new experimental platform was built. The experimental validation performed on the experimental platform concludes that, on the one hand, the proposed controller provides high-performance dynamic characteristics, and, on the other, that this scheme is robust with respect to the uncertainties that typically appear in the real systems.

Keywords:

Nonlinear systems, variable structure controls, and real-time control of wind turbine systems.

Introduction

The worldwide use of wind power has exploded since the late 1990s. This rapid expansion of wind power capacity may be attributed to falling prices and new public government subsidies in many countries, both of which are tied to initiatives to boost the usage of renewable power generation and decrease CO2 emissions. 2013 had an annual growth in global wind capacity of 35.47 GW, much less than 2012's rise of 44.56 GW. Considering the capacity factor of wind power plants, the world energy demand may be met by 318.14 GW of installed wind capacity by the end of 2013 [1]. The wind industry throughout the globe has had a rough year in 2013 due to the shrinking size of the market. As a result of this development, the price of wind turbines has dropped, making renewable energy sources more competitive in terms of price [1]. Even though we are now facing certain obstacles, we are still positive about the future growth of wind power since we believe that the predicted decline in new installations is mostly attributable to the anomalous circumstances owing to the funding crisis. Although there is a need to strengthen national and international policies and to accelerate the deployment of wind power, it is clear that appetite for investment in wind power is strong and that many projects are in the pipeline, suggesting that the global wind markets will be able to recover from the 2013 decrease and set a new record in 2014. According to the WWEA, wind power will continue to expand rapidly in the years to come. Although short-term projections are impossible owing to the effects of the present financial crisis, it is projected that wind energy would rather attract more investments in the mid-term due to its low-risk nature and the demand for clean, dependable energy sources. Governments increasingly recognize the numerous advantages of wind power and are enacting supportive policies, such as those that encourage decentralized investment by independent power producers, small and medium-sized businesses, and community-based projects. Particularly promising regions for future expansion include China, India, Europe, and North America. Several nations in Latin America, especially Brazil, as well as emerging economies in Asia and Eastern Europe, are predicted to have rapid economic expansion in the near future. Major investment will be made in many African nations in the middle of the next decade, most notably in northern Africa but also in South Africa. The WWEA has revised its projections for the future expansion of global wind capacity in light of several insecurity concerns and current development rates. In 2016, the world's capacity may reach 500 GW. By the end of 2020, the world should have at least 1000 GW of installed capacity.

Simulating Systems

The amount of power that can be extracted from a wind turbine depends on three key factors: the available wind power, the power curve of the machine, and the machine's capacity to adapt to wind fluctuations. In [15], we have the term for wind power:

$$P_m(v) = \frac{1}{2} C_p(\lambda, \beta)\rho\pi R^2 v^3$$

where ρ is the air density; R is the radius of turbine blades; v is the wind speed; Cp denotes the power coefficient of the wind turbine; λ is the tip-speed ratio and β represents the pitch angle. The tip-speed ratio is defined as:

$$\lambda = \frac{R w_m}{v}$$

Wm represents the turbine's rotor speed. Therefore, if the rotor speed is kept the same, the power coefficient Cp and the quantity of power generated by the wind turbine will change. The system's power output may be optimized by changing the rotor speed in response to variations in wind velocity. Consequently, the ratio of tip speed to overall speed will remain same.

At its core, the WTS is an aero turbine that converts wind energy into mechanical energy; from there, a gearbox boosts speed and reduces torque, and a generator converts mechanical energy into electrical power. With an input wind torque of Tm, the wind turbine's rotor spins at a speed of wm. To produce electrical torque Te at the angular velocity w of the generator, electrical generators need this mechanical torque as input. It's important to remember that the gearbox often results in a speed differential between the turbine and the generator. The gear ratio defines the connection between the wm angular velocity of the turbine and the w angular velocity of the generator.

Methodology for Controlling Wind Generators

The rotor side converter (RSC) and grid side converter (GSC) are controlled by the variable frequency converter (VFC), which enables the DFIG to be handled. The RSC's principal role is to enable the stator's independent management of active and reactive powers. While the rotor power's amplitude and direction may fluctuate, the GSC's objective is to keep the dc-link voltage constant. The reactive power and stator terminal voltage of the DFIG may be controlled through the GSC control system. Figure 1 shows a common design for a DFIG-powered wind turbine.

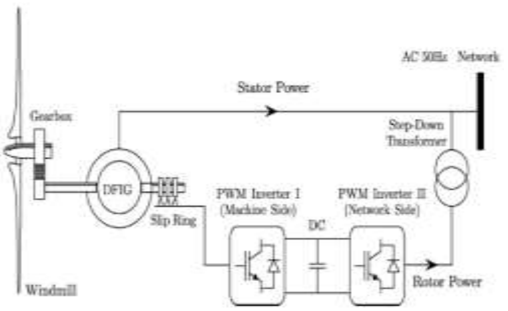

Figure 1. Scheme of a wind turbine system with a DFIG

When the WTS operates in the variable-speed mode, in order to extract the maximum active power from the wind, the shaft speed of the WTG must be adjusted to achieve an optimal tip-speed ratio λopt, which yields the maximum power coefficient Cpmax , and therefore the maximum power [18]. In other words, given a particular wind speed, there is a unique wind turbine speed command to achieve the goal of maximum wind power extraction. The value of the λopt can be calculated from the maximum of the power coefficient curves versus tip-speed ratio. The power coefficient Cp, can be approximated by Equation (20) [19]:

$$C_p(\lambda, \beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{\frac{-c_5}{\lambda_i}} + c_6\lambda$$

where the coefficients c1 to c6 depends on the wind turbine design characteristics, and λi is defined as

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}$$

The value of λopt can be obtained from Equation (20) calculating the λ value that maximizes the power coefficient. Then, based on the wind speed, the corresponding optimal generator speed command for maximum wind power extraction is determined by:

$$w_m^* = \frac{\lambda_{opt} \cdot v}{R}$$

Wind Turbine Speed Control

The objective of the maximum wind power extraction can be achieved using an adequate speed controller that regulates the wind turbine speed in order to get the reference speed w ∗ m that gives the optimal tip-speed ratio λopt. In the DFIG based wind generation system, this objective is commonlyachieved by means of the rotor current regulation in the electrical generator. This current regulation is usually performed by the RSC control, using the stator-flux oriented reference frame in order to simplify the DFIG dynamic equations. In the stator-flux oriented reference frame, the d-axis is aligned with the stator flux linkage vector ψs , and then, ψds = ψs and ψqs = 0 . This yields the following relationships [20]:

$$
\begin{aligned}
i_{qs} &= -\frac{L_m i_{qr}}{L_s} \\
i_{ds} &= \frac{L_m(i_{ms} - i_{dr})}{L_s} \\
i_{ms} &= \frac{v_{qs} - r_s i_{qs}}{w_s L_m} \\
T_e &= -\frac{3p}{4}\frac{L_m^2 i_{ms} i_{qr}}{L_s} \\
Q_s &= \frac{3}{2}\frac{w_s L_m^2 i_{ms}(i_{ms} - i_{dr})}{L_s} \\
v_{dr} &= r_r i_{dr} + \sigma L_r \frac{di_{qr}}{dt} - sw_s \sigma L_r i_{qr} \\
v_{qr} &= r_r i_{qr} + \sigma L_r \frac{di_{qr}}{dt} + sw_s\left(\sigma L_r i_{dr} + \frac{L_m^2 i_{ms}}{L_s}\right)
\end{aligned}
$$

Where

$$\sigma = 1 - \frac{L_m^2}{L_s L_r}$$

LsLr Since the stator is connected to the grid, and the influence of the stator resistance is small, the stator magnetizing current (ims) can be considered constant [16]. Therefore, the electromagnetic torque can be defined as follows:

$$T_e = -K_T i_{qr}$$

where KT is a torque constant, and is defined as follows:

$$K_T = \frac{L_m i_{ms}}{L_s}$$

From the previous Equations (4) and (30) it is obtained that regulating the q-component of the rotor current (iqr), the wind turbine speed can be controlled.

DC Link Voltage Control

The dc link voltage of the inverter should be maintained constant regardless of the direction of rotor power flow. In order to achieve this objective, a vector control approach is employed using a reference frame oriented along the stator (or grid) voltage vector position. In such a scheme, the direct axis current is controlled in order to keep the dc link voltage constant. In the stator voltage oriented reference frame, the d-axis is aligned with the grid voltage phasor Vs , and then vd = Vs and vq = 0. Hence, the powers between the grid side converter and the grid are:

$$
\begin{aligned}
P &= \frac{3}{2}(v_d i_d + v_q i_q) = \frac{3}{2} v_d i_d \\
Q &= \frac{3}{2}(v_q i_d - v_d i_q) = -\frac{3}{2} v_d i_q
\end{aligned}
$$

where vd and vq are the direct and quadrature components of the supply voltages, and id and iq are the direct and quadrature components of the grid side converter input currents.

From the previous equations it is observed that the active and reactive power flow between grid side converter and the grid, will be proportional to id and iq respectively. The dc power change has to be equal to the active power flowing between the grid and the grid side converter. Thus,

$$
\begin{aligned}
E i_{0s} &= \frac{3}{2} v_d i_d \\
C\frac{dE}{dt} &= i_{0s} - i_{0r}
\end{aligned}
$$

where E is the dc link voltage; i0r is the current between the dc link and the rotor and i0s is the current between the dc link and the grid. From Equations (48) and (49) it is obtained:

$$
\begin{aligned}
\dot{E} &= \frac{1}{C}\left(\frac{3}{2}\frac{v_d}{E} i_d - i_{0r}\right) \\
&= g(t) i_d - \frac{1}{C} i_{0r}
\end{aligned}
$$

where the function g(t) is defined as:

$$g(t) = \frac{1}{C}\frac{3}{2}\frac{v_d}{E}$$

The function g(t) can be split up into two parts:

$$g(t) = g_0 + \Delta g(t)$$

$$g_0 = \frac{1}{C}\frac{3}{2}\frac{v_d}{E^*}$$

Simulation and Experimental

Results In this section the performance of the proposed adaptive sliding mode controller is analyzed. The experimental validation has been carried out in the experimental platform shown in Figure 3 that we have designed and constructed. The photography of this experimental platform is shown in Figure 4.

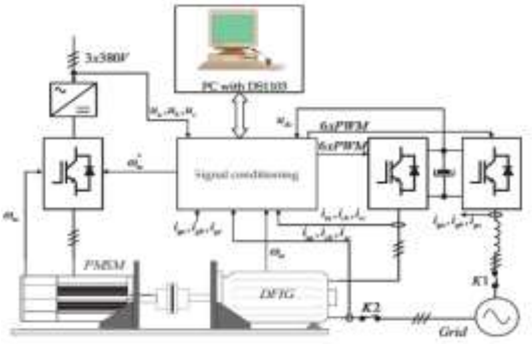

Figure 3. Block diagram of the DFIG wind turbine experimental platform.

Figure 4. Photography of the DFIG wind turbine experimental platform

The control platform is formed by a PC with MatLab7/Simulink R2007a, dsControl 3.2.1 and the DS1103 Controller Board real time interface of dSpace, with a floating-point PowerPC processor to 1 GHz. The electric machine used to implement the proposed controller is a commercial machine of Leroy Sommer of 7.5 kW, 1447 rpm, double feed induction machine (Table 1), connected to the grid through the rotor in a Back-to-Back configuration with two voltage source inverters. The wind profiles are generated by a 10.6 kW 190U2 Unimotor synchronous AC servo motor. The mechanical speed is measured using the servo motor incremental encoder of 4096 square impulses per revolution using the frequency measurement method. The rotor and stator currents are limited to the nominal values in order to protect the machine against over currents. All the sensors to measure the currents, voltages and speed are adapted and connected t

o the DS1103 Controller Board.

Table 1. Ratings and parameters of the DFIG (Leroy Sommer).

Ratings and parameters	Values
Stator Voltage	380 V
Rotor Voltage	190 V
Rated stator current	18 A
Rated rotor current	24 A
Rated speed	1447 r.p.m.@ 50 Hz
Rated torque	50 Nm
Stator resistance	0.325 Ω
Rotor resistance	0.275 Ω
Magnetizing inductance	0.0664 H
Stator leakage inductance	0.00264 H
Rotor leakage inductance	0.00372 H
Inertia moment	0.07 Kg.m^2

Both SVPWM (space vector pulse width modulation) inverter generators are managed by the DS1103 Controller Board. For 7 kHz SVPWM, a sample time of 143 s has been established. The inverters in this research have a dead time of 1.5 s, which may be adjusted through software and hardware. Charging the DC bus used by the rotor and grid converters is the first step in connecting the DFIG to the grid. After the DC bus has been charged and the grid side reference system has been aligned with the grid voltage, the grid side converter is linked through contactor K1, and DC bus regulation to a set value may then commence. There are two prerequisites that must be met before the stator may be connected to the grid. To begin, the stator voltage must be synchronized with the grid voltage, and then the encoder offset relative to the stator flux must be detected. When everything is in place, the stator will be wired into the grid through contactor K2, and active and reactive power regulation will commence. Grid voltage synchronization is achieved by measurement of grid voltage and implementation of a PLL (Phase Locked Loop).

Conclusions

This study details the design and implementation of a sliding mode vector control technique for a dual fed induction generator drive in variable speed wind power production. In order to prevent the second derivative of the error signal, which is common in traditional sliding mode control schemes, a variable structure control that has an integral sliding surface is developed. This control technique is resilient to uncertainties that often manifest in actual systems because of the inherent characteristics of sliding control. For fluctuating wind speeds, the suggested control approach provides for maximum power extraction by keeping the wind turbine working at peak power efficiency. The speed controller attempts to maximize power at wind speeds below the specified wind speed by following the maximum of the power coefficient curve. Thus, the modest fluctuation in wind speed is mirrored in the generator's speed. Using Lyapunov stability theory, we show that the provided design is stable in the closed loop.

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