Backstepping Control of a Wind Turbine-Driven Doubly-Fed Induction Generator

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***Abstract*— The purpose of this paper is to design a nonlinear backstepping controller for double-fed induction generators (DFIG) employed in wind energy conversion systems (WECS). DFIGs have the singularity of the stator being connected directly to the power grid, while the rotor employs a back to back converter to link it to the grid. Design of the controller will be divided in two parts. The first part of the design focus on the modeling of the DFIG and its controlling parameters, using a nonlinear dynamic model to describe the relationship between the power output and voltages across the stator and rotor. To facilitate the controller implementation, model variables are decomposed in their direct and quadrature components. The proposed controller is designed in the second part by defining the error variables to control active and reactive power, selecting a suitable Lyapunov Function Candidate (LFC) and assessing the stability of the system. MATLAB/Simulink simulation is used for validation and verification of controller functionality.**

I. INTRODUCTION

In the last decade, there has been an increasing interest in using renewable resources of energy for electrical generation. Traditionally the main renewable resource utilized for this purpose has been water, however technological advances in the last 30 years led to significant increases in wind turbine power and productivity [1]. The increased efficiency, along with a drop in price of wind-generated electricity has made wind energy an essential participant in power generation industry.

Moreover, the continuing growth of the wind industry in the U.S. and the significant portion it represents of newly installed generating capacity demonstrates how wind energy is and will continue to be a fundamental component of the next era of energy projects that connect to the electricity grid [2].

Basically, there are four types of generators in wind power generation, which are doubly-fed induction generators (DFIG), squirrel cage induction generators (SCIG) wound-rotor synchronous generators (WRSG) and permanent magnet synchronous generators (PMSG) [3]. DFIGs are one of the most extensively used generators in the wind energy industry [3], thus this will be the generator type we will focus on this document.

DFIG control systems are traditionally based on stator field oriented control or stator voltage control [4]. The design of the proposed backstepping controller will make use of the latter one.

II. SYSTEM MODELING

A. DFIG Model

The dynamic voltages equations for the stator and rotor of the DFIG in the synchronous d-q reference frame are given by [5]:

$$V_{sd} = R_s I_{sd} + d\phi_{sd}/dt - \omega_s \phi_{sq}, \quad (1)$$

$$V_{sq} = R_s I_{sq} + d\phi_{sq}/dt - \omega_s \phi_{sd}, \quad (2)$$

$$V_{rd} = R_r I_{rd} + d\phi_{rd}/dt - \omega_r \phi_{rq}, \quad (3)$$

$$V_{rq} = R_r I_{rq} + d\phi_{rq}/dt - \omega_r \phi_{rd}. \quad (4)$$

Where:

V_{sd}, V_{sq}, V_{rd}, and V_{rq} are the stator and rotor voltage in d-q frame reference respectively.

I_{sd}, I_{sq}, I_{rd}, and I_{rq} are the stator and rotor currents in d-q frame reference respectively.

ϕ_{sd}, ϕ_{sq}, ϕ_{rd}, and ϕ_{rq} are the stator and rotor flux in d-q frame reference respectively.

ω_s and ω_r are the stator and rotor angular velocities.

R_s and R_r are the stator and rotor resistances.

Flux equations of the DFIG are expressed by:

$$\phi_{sd} = L_s I_{sd} + L_m I_{rd}, \quad (5)$$

$$\phi_{sq} = L_s I_{sq} + L_m I_{rq}, \quad (6)$$

$$\phi_{rd} = L_r I_{rd} + L_m I_{sd}, \quad (7)$$
$$\phi_{rq} = L_r I_{rq} + L_m I_{sq}. \quad (8)$$

Where:
L_s, L_r and L_m are the stator, rotor and mutual inductances.

And the rotor angular velocity is:
$$\omega_r = \omega_s - p\Omega. \quad (9)$$

With:
$$\omega_s = 2\pi f. \quad (10)$$

For p equal to the number of pole pairs and f equal to the nominal electrical frequency of the machine.

Finally, for the stator active and reactive power we have the following relationship:
$$P_s = V_{sd} I_{sd} + V_{sq} I_{sq}, \quad (11)$$
$$Q_s = V_{sq} I_{sd} + V_{sd} I_{sq}. \quad (12)$$

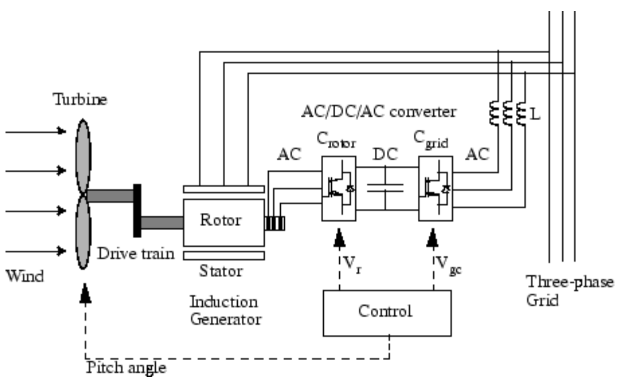

Figure 1. Operating Principle of the Wind Turbine Doubly-Fed Induction Generator [6].

B. Control Strategy

To provide a separate control for active and reactive power we apply the stator Field Oriented Control (FOC) technique using direct and quadrature voltages and currents. This technique is also known as Vector Control and is very common in electrical drives for induction motors [7].

The basic principle of SFOC consists in aligning the stator flux with the d axis, which translates in [8]:

$$\phi_{sd} = \phi_s, \ \phi_{sq} = 0, \quad (13)$$

Steady-state operation is considered and resistance of the stator is neglected, obtaining:

$$V_{sd} = 0, \ V_{sq} = \omega_s \phi_s = V_s, \quad (14)$$

Based on (7), (8) and (13) we rewrite equation (3) and (4) as:

$$V_{rd} = R_r I_{rd} + \sigma L_r dI_{rd}/dt - g\sigma L_r \omega_s I_{rq}, \quad (15)$$
$$V_{rq} = R_r I_{rq} + \sigma L_r dI_{rq}/dt + g\sigma L_r \omega_s I_{rd} + gV_s L_m/L_s. \quad (16)$$

With:
$$\sigma = 1 - L_m{}^\wedge 2/(L_s L_r), \ g = (\omega_s - \omega_r)/\ \omega_s. \quad (17)$$

Equations (11) and (12) can be simplified too, resulting in:

$$P_s = -V_s L_m I_{rq}/L_s, \quad (18)$$
$$Q_s = -V_s L_m I_{rd}/L_s + V_s{}^\wedge 2/(\omega_s L_s). \quad (19)$$

III. Backstepping Controller

A. Active Power Control

Active power of the stator is defined as the output of the system, then we define the tracker and the error dynamics which for this simplified system are of order one [9]:

$$y = P_s = -V_s L_m I_{rq}/L_s, \quad (20)$$
$$dy/dt = dP_s/dt = -\xi\,(V_{rq} - R_r I_{rq} - g\sigma L_r \omega_s I_{rd} - gV_s L_m/L_s), \quad (21)$$

with:
$$\xi = V_s L_m/(\sigma L_r/L_s), \quad (22)$$

The tracker and error dynamics are:

$$e_1 = P_{ref} - P_s, \quad (23)$$
$$de_1/dt = dP_{ref}/dt - dP_s/dt. \quad (24)$$

After this we proceed to find a suitable control input to stabilize the system and decrease the error.

We pick the following as our Lyapunov Candidate Function:

$$V_1 = ½(e_1{}^\wedge 2), \quad (25)$$

with its derivative equal to:
$$dV_1/dt = e_1(de_1/dt), \quad (26)$$

Replacing the error dynamics in (26) we get:
$$dV_1/dt = e_1(dP_{ref}/dt + \xi\,(V_{rq} - R_r I_{rq} - g\sigma L_r \omega_s I_{rd} - gV_s L_m/L_s)), \quad (27)$$

To stabilize the system the system we pick de_1/dt to be equal to $-k_1e_1$ which leads to:

$$dP_{ref}/dt + \xi(V_{rq} - R_rI_{rq} - g\sigma L_r\omega_sI_{rd} - gV_sL_m/L_s) = -k_1e_1, \quad (28)$$

If we want to maintain a simple approach in the control of P_s, and keep it decoupled from Q_s, we need to pick a variable that only affects P_s and not Q_s. The only variable that complies with this criterion is V_{rq}. Thus from (28) we can derive an expression for V_{rq}:

$$V_{rq} = -1/\xi\,(dP_{ref}/dt + k_1e_1) + R_rI_{rq} + g\sigma L_r\omega_sI_{rd} + gV_sL_m/L_s \quad (29)$$

And:

$$dV_1/dt = -k_1e_1\text{^}2. \quad (30)$$

B. Reactive Power Control

Now reactive power of the stator is defined as the output of the system, and then we define the tracker and the error dynamics for this new assumption [9]:

$$y = Q_s = -V_sL_mI_{rd}/L_s + (Vs\text{^}2)/(\omega_sL_s), \quad (31)$$
$$dy/dt = dQ_s/dt = -\xi\,(V_{rd} - R_rI_{rd} + g\sigma L_r\omega_sI_{rq}). \quad (32)$$

The tracker and error dynamics are:

$$e_2 = Q_{ref} - Q_s, \quad (33)$$
$$de_2/dt = dQ_{ref}/dt - dQ_s/dt. \quad (34)$$

As before, we proceed to find a suitable control input to stabilize the system and decrease the error.

We pick the following as our Lyapunov Candidate Function:

$$V_2 = ½(e_2\text{^}2), \quad (35)$$

With its derivative equal to:

$$dV_2/dt = e_2(de_2/dt), \quad (36)$$

Replacing the error dynamics in (36) we get:

$$dV_2/dt = e_2(dQ_{ref}/dt + \xi\,(V_{rd} - R_rI_{rd} + g\sigma L_r\omega_sI_{rq})), \quad (37)$$

To stabilize the system the system we pick de_2/dt to be equal to $-k_2e_2$ which leads to:

$$dQ_{ref}/dt + \xi(V_{rd} - R_rI_{rd} + g\sigma L_r\omega_sI_{rq}) = -k_2e_2, \quad (38)$$

Using the same approach as for active power control, to keep Q_s decoupled from P_s, we need to pick a variable that only affects Q_s and not P_s. The only variable that complies with this criterion is V_{rd}. Thus from (38) we can derive an expression for V_{rq}:

$$V_{rd} = -1/\xi\,(dQ_{ref}/dt + k_2e_2) + R_rI_{rd} - g\sigma L_r\omega_sI_{rq} \quad (39)$$

And:

$$dV_2/dt = -k_2e_2\text{^}2. \quad (40)$$

Finally, to assess the whole system stability we pick a global Lyapunov function:

$$V = ½(e_1\text{^}2) + ½(e_2\text{^}2), \quad (41)$$

With its derivative equal to:

$$dV/dt = e_1(de_1/dt) + e_2(de_2/dt), \quad (42)$$

From our previous calculations, we conclude:

$$dV/dt = -k_1e_1\text{^}2 - k_2e_2\text{^}2. \quad (43)$$

Which demonstrates that the whole system is stable.

Figure 2 shows the general idea of the backstepping controller.

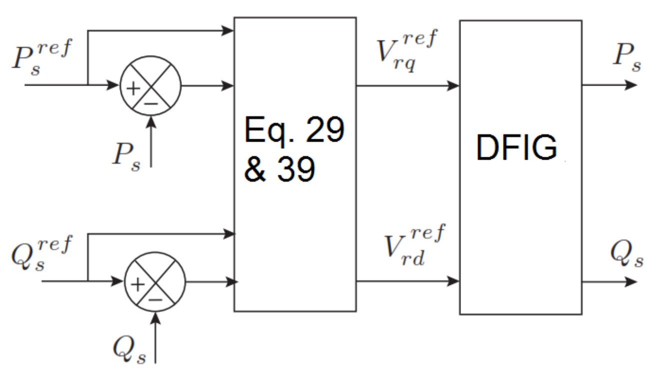

Figure 2. Block diagram of the power control using backstepping [5].

IV. SIMULATION RESULTS

MATLAB/Simulink was used to simulate the behavior of the controller for a small 800 VA wind generator. We assumed the voltage of the grid to be under normal conditions and that the system has a steady state operation, meaning that we do not have harmonics or any fault during the simulation.

The main parameters used in the simulation are:

Vs = 320 V
f = 50 Hz
P_G = 800 VA
p = 1 pair of poles

Lm=1.7303 p.u.
Ls=0.1200[p.u.
Lr=0.2216 p.u.
Rs=0.0758 p.u.
Rr=0.0836 p.u.
Zb=128 ohm

For the first part of the simulation, we tested the behavior of stator & rotor voltages and currents for different power inputs, checking their stability and desired waveform shape. Figures 3,4,5 and 6 illustrate this verification.

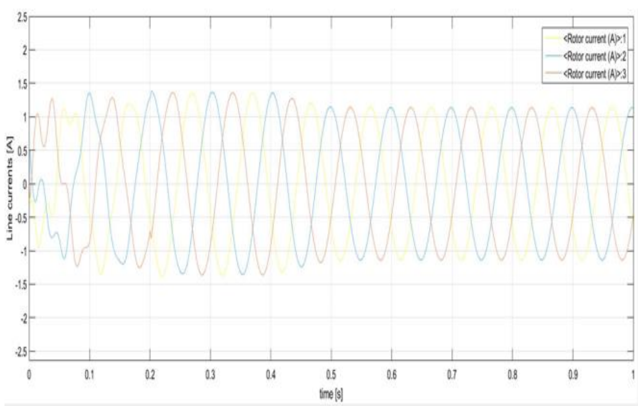

Figure 3. Rotor Line Currents.

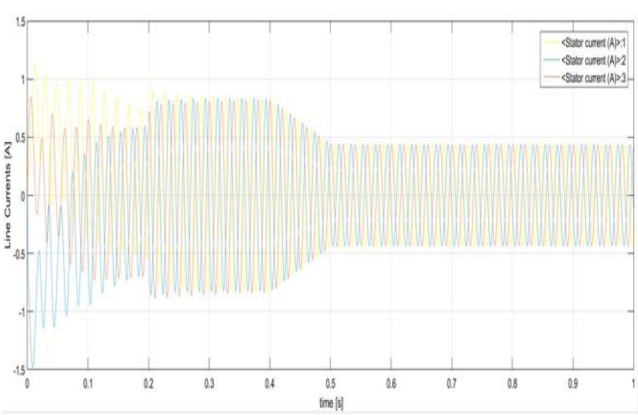

Figure 4. Stator Line Currents.

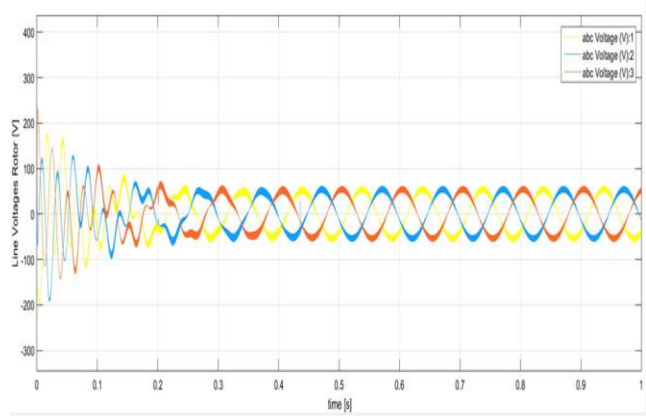

Figure 5. Rotor Line Voltages.

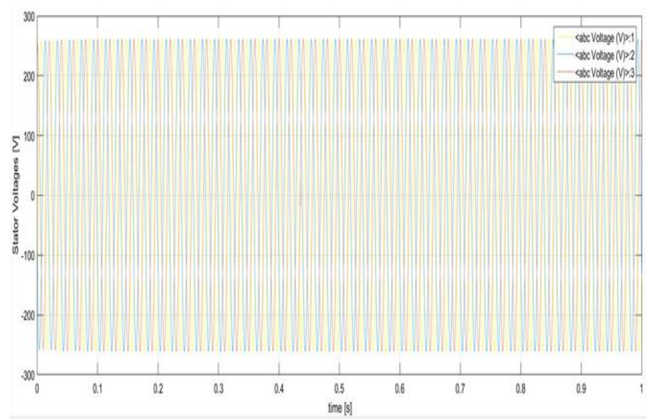

Figure 6. Stator Line Voltages.

After reviewing the electrical parameters of the generator, we proceeded with the simulation of active and reactive power of the machine. The main purpose of this last simulation was to evaluate how well did the actual values of active and reactive power followed the desired values of power. This also showed the controller capabilities and how effective it was in reducing the tracking errors.

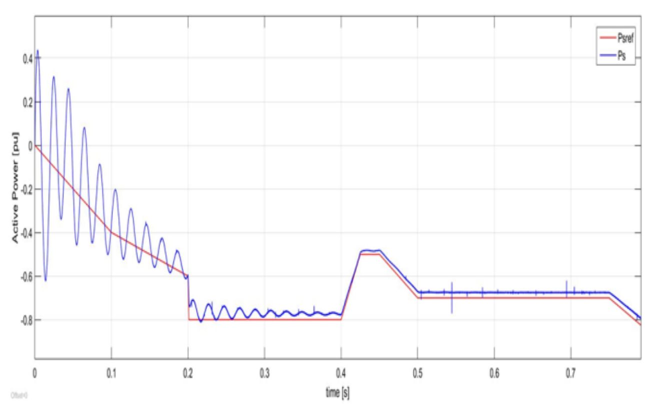

Figure 7. Output Active Power.

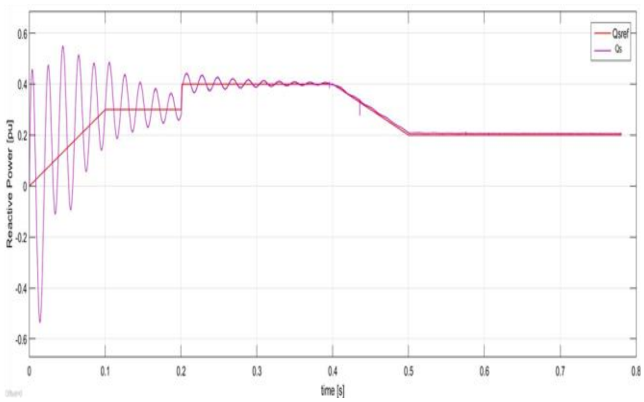

Figure 8. Output Reactive Power.

As we can see in figures 7 and 8, there is not a significant difference between Ps and Pref, or between Qs and Qref after a certain period has passed and the controller stabilizes the output. From that point on, it is clear that there will be slight fluctuations in the output and that we would have an almost constant average error value.

V. CONCLUSION

Through the design and implementation of the controller we were able to design a suitable controller without needing to evaluate system dynamics of an order higher than one, which shows the power of this control technique in reducing very complex systems into a more manageable form. Another strength of this type of controller is the possibility of showing system’s overall stability by applying a standard Lyapunov theory. Nonetheless, the tracking errors are not negligible and it may be necessary to consider other possible control variables excluded in this analysis, like the control of the rotor currents, which may contribute to a better response of the system. Finally, from simulation outputs, we can say that backstepping usefulness can be applied successfully to control doubly-fed induction generators used in wind energy conversion systems.

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