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# Doubly-fed wind turbine generator control: A bond graph approach

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ABSTRACT

In this contribution, a bond graph doubly-fed wind turbine generator control is proposed. The control law is derived from the inverse model of the doubly-fed induction generator, which allows a different structure for the torque control to be obtained. The bond graph methodology and the concept of bicausality are applied to derive the control law. The robustness of the proposed control is verified and the simulation of the complete model is conducted for constant and variable wind speed operation conditions, respectively.

## 1. Introduction

The possibility of controlling active and reactive power, the capability of reducing stresses of the mechanical structure and acoustic noise are some of the advantages of using a doubly-fed induction generator (DFIG) in a wind turbine [1]. Also, losses in the power electronics converter are reduced, as compared to a direct-driver synchronous generator. This is due to the fact that the converter placed between the grid and the induction machine rotor handles only a fraction of the turbine rate power [2,3].

Control of a doubly-fed induction generator has been addressed in several works, e.g. [4–7]. In [4] a sliding mode control is used, and in [5] the power control of a doubly-fed induction machine via output feedback is presented. The behavior of such machines in large wind farms, along with the general active and reactive power control has been addressed in [6]. A novel simplified model of the DFIG appropriate for bulk power system studies is presented in [7]. In this paper, a different structure for the DFIG control, based on the bond graph methodology [8–10] is proposed.

The wind turbine is a complex system in which different technical areas are involved (mechanics, aeronautics, electrical, among others). In order to analyze the system in the same reference frame, the bond-graph methodology can represent the whole structure. This methodology presents some proprieties that can be directly applied to the model reported in [11].

A bond graph consists of subsystems linked together by half arrows, representing power bonds [9]. They exchange instantaneous power at places called ports. The variables are forced to be identical when two ports are connected; the power variables are assumed to be functions of time. The different power variables are classified into an universal scheme, and are called either effort $e(t)$ or flow $f(t)$. Their product $P(t) = e(t)\cdot f(t)$ is the instantaneous power flowing between the ports.

The main advantages of the bond graph tool for modeling purposes is summarized through few keywords, which makes this approach quite specific and justifies its use in the paper [12]. These are the following:

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**Nomenclature**

| | |
|---|---|
| DFIG | doubly-fed Induction generator |
| MSC | machine side converter |
| NSC | network side converter |
| PLL | phase lock-loop |
| $P$ | active power |
| $Q$ | reactive power |
| PI | proportional integral controller |
| $M_{d/q}$ | I-field magnetic coupling (axis $d/q$) |
| $L_s$ | stator self-inductance |
| $L_m$ | mutual inductance |
| $L_r$ | rotor self-inductance |
| $J_m$ | moment of inertia |
| $R_s$ | stator resistance |
| $R_r$ | rotor resistance |
| $p$ | number of pair of poles |
| $\omega_s$ | network angular frequency |
| $T_{nom}$ | nominal torque |
| $\phi_{s/r,d/q}$ | fluxes of stator/rotor in axis d/q |
| $i_{s/r,d/q}$ | currents of stator/rotor in axis d/q |
| $v_{rd/q}$ | voltages of rotor in axis d/q |
| $v_{d/q}$ | voltages of stator in axis d/q |
| $\widehat{R}_r$ | estimated of $\mathrm{R_r}$ |
| $\widehat{L}_r$ | Estimated of $\mathrm{L_r}$ |
| $k_{1,2}$ | controllers |
| $n$ | gearbox ratio |
| $J_{hole}$ | inertia |
| $C_p$ | power coefficient |

- It provides the analyst with a unified graphical language to represent power exchanges with a physical insight, energy dissipation and storage phenomena in dynamic systems of any physical domain.
- It allows the visualization of causality properties before writing equations, according to selected modeling hypotheses.
- Some software exists with a bond graph graphical editor, thus exempting the analyst from writing global equations.

In this contribution, the bond graph is used to model the DFIG; with the concept of bicausality [13] being applied to obtain the control law.

The outline of the paper is as follows: the wind turbine model is first detailed. The induction machine model is recalled, and then simplified in Section 3; the proposed control is described in Section 4. The models of wind turbine and converter, respectively, are presented in Section 5, and the whole system simulated in Section 6. The global conclusions of the conducted investigation are drawn in Section 7.

## 2. System description

From the generator point of view, a wind turbine has different configurations. Also, the wind turbine can operate with either under fixed-speed or variable-speed mode. This operation depends directly on the generator connection. It means that for fixed-speed wind turbines, the generator is directly connected to the power network, since the speed is closely tied to the grid frequency. Besides, for a variable-speed wind turbine, the generator is controlled through power electronics converters, which make possible to control the rotor speed.

Each configuration has its own advantages and is used under different operation conditions. Four basic configurations are often described in the literature:

1. Fixed-speed wind turbine with an induction generator.
2. Variable-speed wind turbine with a cage-bar induction generator or synchronous generator.
3. Variable-speed wind turbine with multiple-pole synchronous generator.
4. Variable-speed wind turbine with doubly-fed induction generator.

For a fixed-speed wind turbine, the rotor speed is in principle determined by a gearbox and the number of generator pole-pairs number. In this configuration, the connection to the power network is directly made, as shown in Fig. 1. A two-windings generator having different ratings and pole-pairs is normally used in this configuration.