Analysis of Wind Turbine Driven DFIG Using Plecs Software Package

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Abstract
A cost and energy efficient method of wind power generation is to connect the output of the turbine to a doubly-fed induction generator (DFIG), allowing operation at a range of variable speeds. DFIG wind turbine is a complex design involving multiple physical domains strongly interacting with each other. The electrical system, for instance, is influenced by the converter's cooling system and mechanical components, including the rotor blades, shaft and gearbox. This means that during component selection and design of control schemes, the influence of domains on one another must be considered in order to achieve an optimized overall system performance such that the design is dynamic, efficient and cost-effective. Modelling such complex systems while including switching power electronic converters requires a powerful and robust simulation tool. PLECS is a simulation platform developed for power electronic engineers that allows for very efficient and robust modelling. This paper presents a detailed study on DFIG wind turbine system that is designed using PLECS, where components from its different physical domain libraries, including electrical, magnetic, thermal and mechanical, as well as signal processing and control systems, are coupled together and the results are displayed.

Keywords
DFIG, Plecs, Cooling System, Multiple Physical Domains.

I. Introduction

Wind turbines use a Doubly-Fed Induction Generator (DFIG) consisting of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter. The stator winding is connected directly to the 50 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter as shown in Fig 1. The DFIG technology allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine speed, while minimizing mechanical stresses on the turbine during gusts of wind. The optimum turbine speed producing maximum mechanical energy for a given wind speed is proportional to the wind speed. Another advantage of the DFIG technology is the ability for power electronic converters to generate or absorb reactive power, thus eliminating the need for installing capacitor banks as in the case of squirrel-cage induction generator.

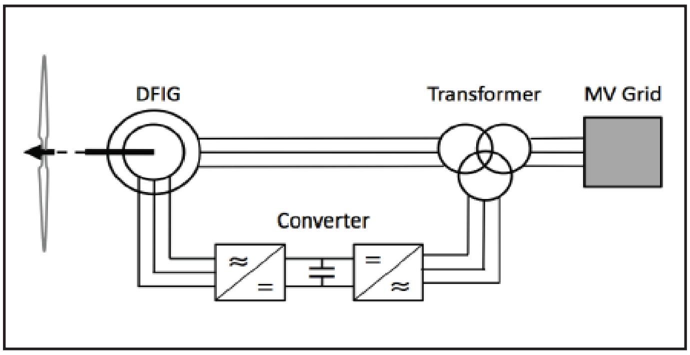

Fig. 1: System Overview of the Wind Turbine With DFIG

II. System overview

A. Power in the Wind

Wind turbines are capable of converting only a portion of the available wind power into mechanical power due to mechanical design considerations of the system. This mechanical power is expressed as

$$Pmech = \frac{1}{2}\rho A C_p v^3 \quad (1)$$

Where, ρ is the air density, A is the area swept by the turbine blades, Cp is the performance coefficient of the turbine, and v is the wind velocity. For steadystate calculations of the mechanical power, the typical Cp(λ,β) curve can be used, as shown in Fig. 2.

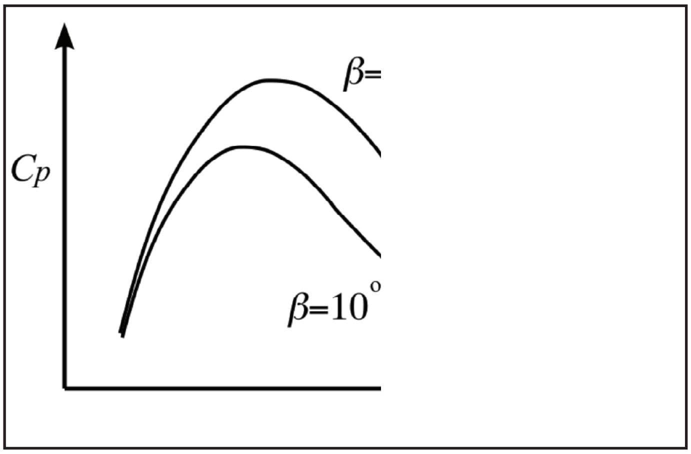

Fig. 2: Typical Performance Coefficient Vs. Tip Speed Ratio Curve

In the curve, β represents the blade pitch angle and λ is the tip speed ratio, given by:

$$\lambda = \frac{\Omega R}{v} \quad (2)$$

where Ω is the mechanical rotational speed of the turbine and R is the turbine radius. It can be observed that a certain turbine rotational speed must be maintained in order to achieve the maximum mechanical power input under a given wind speed and blades pitch angle. In normal operation the pitch angle remains constant, while in special cases such as under strong winds, the pitch control is activated to shed the excess wind power and protect the wind turbine from damage.

B. Electromagnetic System

The electrical part of the DFIG wind turbine consists of a wound-rotor type induction machine. The machine's stator terminals are directly connected to the medium-voltage grid via a three-winding transformer, while the rotor is excited by one end of the power electronic converter, consisting of two AC-DC converters in a back-to-back configuration with a common DC-link bus. The grid-side of the converter feeds the rotor power into the grid via the transformer's tertiary winding. Under a limited variable-speed

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range (e.g. ±30%) the converter only needs to handle a percentage (20 − 30%) of the total power, which in steady state is given by:

$$P_r = \frac{s}{1-s} * P_{mech} \quad (3)$$

The power flow on the stator is given by:

$$P_s = \frac{P_{mech}}{1-s} \quad (4)$$

In both of the above equations, s is the slip of the machine, and is defined by:

$$s = \frac{w_1 - w}{w} \quad (5)$$

where w_1 is the stator electrical rotational frequency, which is synchronous with the grid, and w is the electrical rotational speed of the machine. The DFIG configuration is significantly more cost effective and less lossy as compared to a configuration using a permanent magnet generator (PMSM), which is the other common option and where the converter uses the full power range.

C. Cooling System

Power is dissipated during the wind turbine's operation, in part due to the conduction and switching losses of the semiconductor devices (IGBTs and diodes) in the converter. The power losses not only reduce the available electrical power that can be fed into the grid but also lead to high junction temperatures, which may destroy the semiconductor devices. Therefore, a proper cooling system should be used with the converter system such that as much heat-conduction will be transferred away from the semiconductors as is possible.

D. Mechanical system

The rotational components of the wind turbine couple the mechanical and electrical systems. The three blades transfer the wind torque to the hub shaft, which is connected to a gearbox. Using a specific gear ratio the gearbox boosts the rotational speed of the hub shaft onto the shaft of the induction machine's rotor. The coupling between the components shows elastic and damping effects due to the material characteristics, and friction occurs on the bearings, which also leads to power losses.

III. Modeling in PLECS

A 2 MW DFIG wind turbine model has been designed in PLECS and schematic diagram is as shown in fig. 3 The components of the system are from the libraries for the different physical domains, including electrical, magnetic, mechanical, as well as signal processing and control systems.

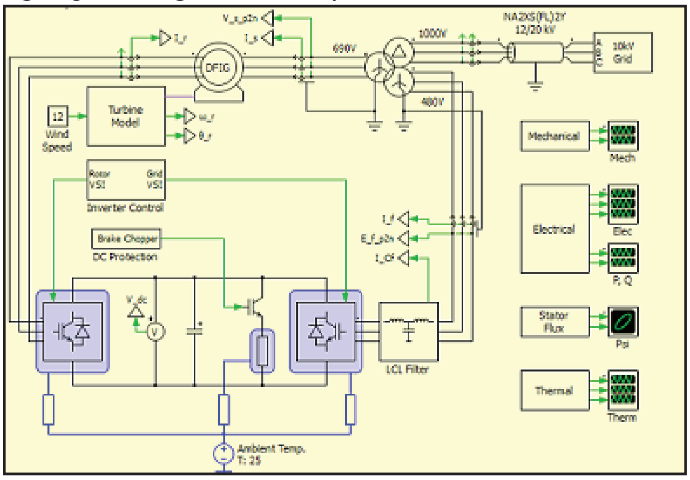


Fig. 3: Schematic of the DFIG Wind Turbine Model in PLECS

IV. Electrical Domain

The wound-rotor induction machine, power electronic converter and LCL filter, as well as the long distance transmission line and medium-voltage (MV) grid are all modeled in the electrical domain:

A. Induction Machine

The wound-rotor induction machine model shown in Fig.4 (the "Induction Machine (Slip Ring)" library component) is based on a stationary reference frame (Clarke transformation). A proper implementation of the Clarke transformation facilitates the connection of external inductances in series with the stator windings, which in this case are the leakage inductances of the transformer. External inductors cannot be connected to the rotor windings though, due to the fact that the electrical interfaces there are modeled as controlled current sources.

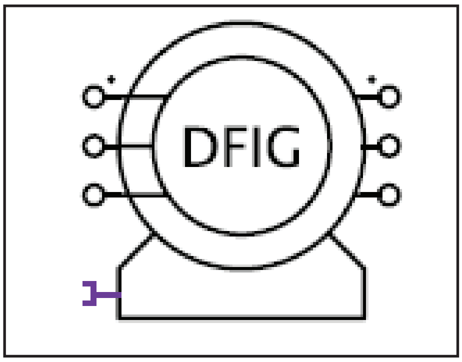


Fig. 4: PLECS Induction Machine Component

B. Power Converter

The back-to-back converter topology is selected for control of the rotor power, where two three-leg, two-level IGBT bridges are connected together via a DC-link capacitor. For protection reasons a chopper IGBT and break resistor is connected onto the DC-link to clamp the capacitor voltage to a safe level as shown in fig. 5. The rotor-side inverter is directly connected to the induction machine's rotor, while the grid-side inverter is connected through an LCL filter to the tertiary winding of the transformer.

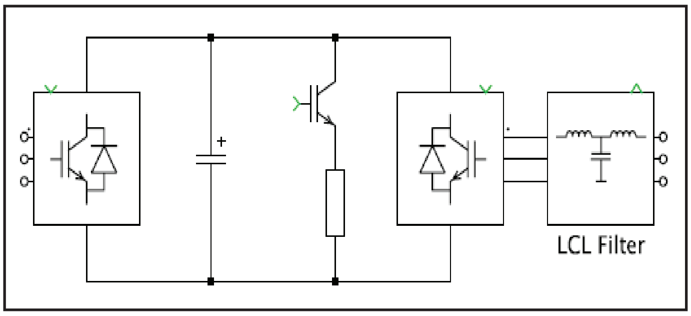


Fig. 5: Back-to-Back Converter Model

C. Filter

The LCL-type filter is used to smooth the current ripple caused by the PWM modulation of the grid-side inverter. According to the electric grid code for renewable energy generation, a certain THD standard needs to be fulfilled when selecting the inductance and capacitance values. In comparison to the inductor only filter, the LCL filter is able to suppress the harmonics with much smaller inductance values, and the reduced weight and volume therefore leads to a higher power density.

D. Transmission Line

Wind turbines are often placed far from the high voltage-to-medium voltage (HV/MV) substation. To model a cable of such a long distance, one can either connect multiple PI-sections (capacitor – inductor - capacitor) together in series, or imitate the traveling-wave behavior of the current and voltage.

E. MV Grid

The medium-voltage grid is simplified as a three-phase voltage source with a line to line voltage of 10 kVrms

V. Mechanical Domain

The variations of the aerodynamic torque on the blades and, consequently, electrical torque on the induction machine's rotor are propagated to the drivetrain of the wind turbine. The resulting fluctuations of the rotational speeds can lead to disturbances in the electrical domain, which depend substantially on the torsional characteristics of the drivetrain to dampen out the oscillations. This model uses a wind source to perturb the mechanical system in order to investigate the effects of such system resonances. The three blades transfer the wind torque to the hub shaft, which is connected to a gearbox. Using a specific gear ratio, the gearbox increases the rotational speed of the hub shaft onto the induction machine's rotor shaft Friction occurs on the bearings, leading to additional power losses. The mechanical portion of this model consists of a number of lumped inertias, which are elastically coupled with each other, as shown in Fig. 8.

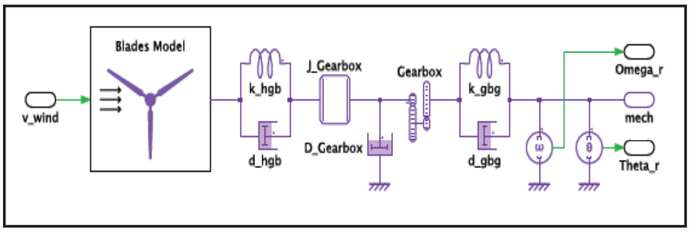


Fig. 6: Complete Drivetrain Modeled in the PLECS Mechanical Domain

VI. Results and Analysis

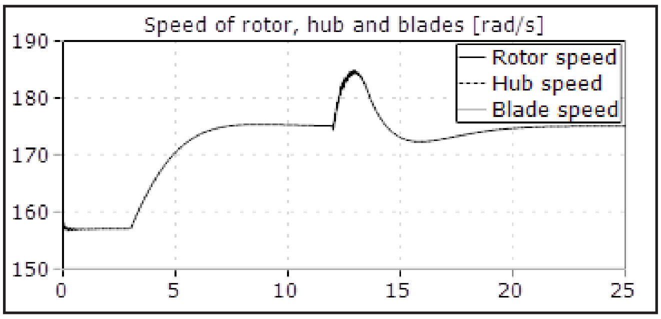


Fig. 7: Speed of Rotor, Hub and Blades [rad/s]

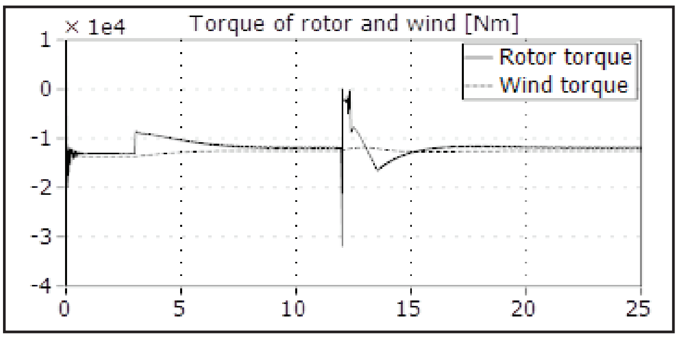


Fig. 8: Torque of Rotor And Wind [Nm]

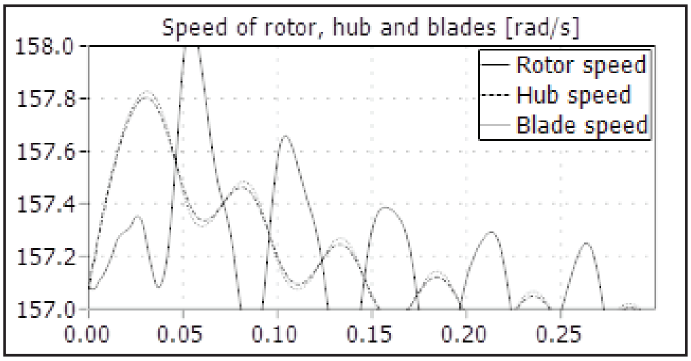


Fig. 9: Speed of Rotor, Hub and Blades [rad/s]

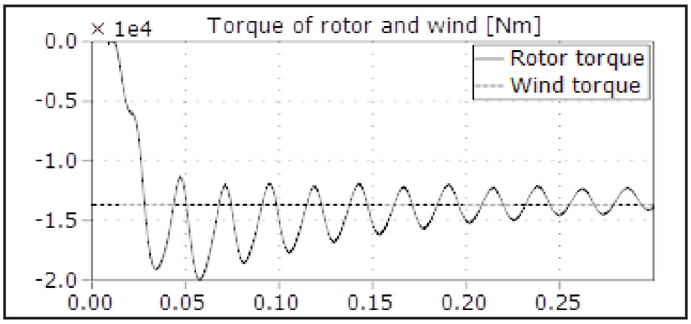


Fig. 10: Torque of Rotor, Hub and Blades [Nm]

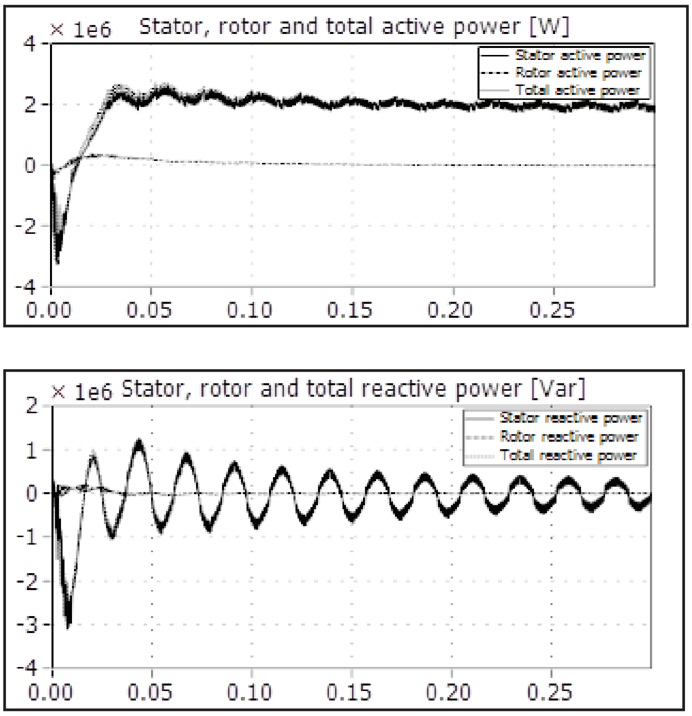
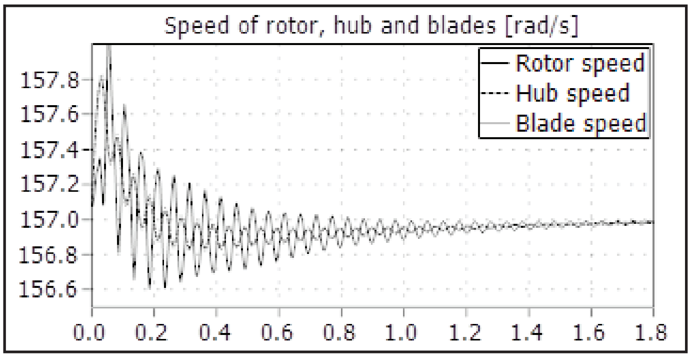


Fig. 11: Stator, Rotor and Total Active and Reactive Power



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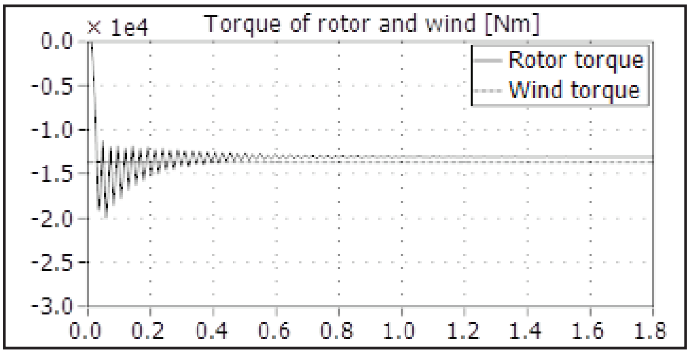
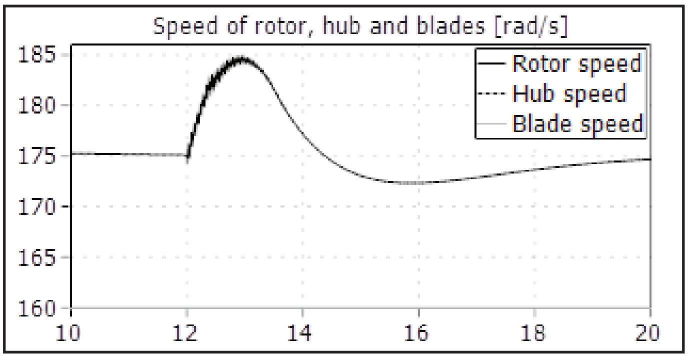


Fig. 12: Mechanical Oscillations at Startup of the Wind Turbine



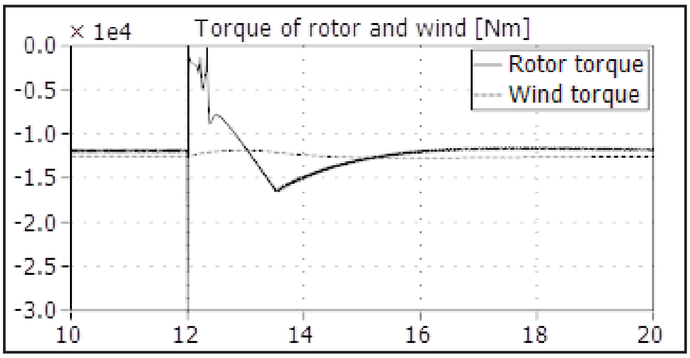


Fig. 13: Mechanical Transient During Grid Fault

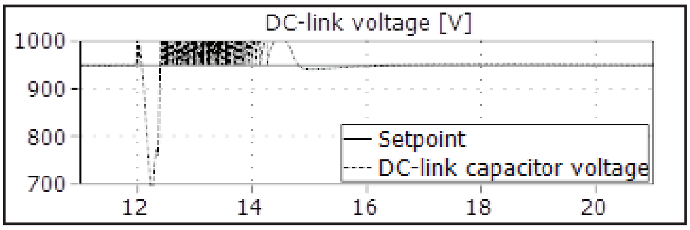


Fig. 14: DC Link Voltage [V]

VII. Analysis

Analysis of Fig 7: Initial State: At the simulation start the generator operates at 157rad/s ,which is synchronous to the grid frequency. Acceleration: At 3s the rotation speed of the turbine is accelerated to 175 rad/sec. Grid Fault: At 12sec a three phase short circuit fault occurs on the 10kv grid.

Analysis of Fig 10: At the start of 157rad/s the speed of blade and hub increases but as the rotor speed decreases their speed also decreases over a period of time. Rotor torque represented by thick line is positive at start but as the wind torque is negative correspondingly rotor torque also decrease and become negative.

Analysis of Fig 11: Rotor active power which is show in red color which is negative and stator active power shown in green is also negative therefore total active power which is sum of both active and reactive power is also negative in the beginning.

Analysis of Fig 12: At the start of the simulation, a damped oscillation can be observed due to the elastic and lossy coupling between the mechanical parts.

Analysis of Fig 13: During a worst case grid-side fault condition, known as “low voltage ride through” (LVRT). As the grid voltage falls to zero at 14 s, the stator flux deceases to an extremely small value, where the induction machine is no longer able to generate electrical torque. When this happens, the power absorbed by the blades from the wind will be completely stored in the form of kinetic energy, and the turbine will accelerate. After the voltage starts to recover due to the clearing of the fault after 0.15 s, the stator flux recovers gradually such that electrical torque can be produced again to counteract the driving torque from the wind. As a result the speed will be restored back to the reference value 175 rad/s.

Analysis of Fig 14: The AC voltage on the transformer terminal does not fall to zero as the grid is stiff due to the inductance of the transmission line in between. So the DC-link voltage is nearly uncontrolled in the first seconds after the fault. The DC-link capacitor is then charged or discharged purely by the machine-side inverter.

VIII. Conclusion

The modeling and simulation of wind turbine using DFIG has been proposed in this paper. With the help of PLECS, the transient effects from multiple physical domains can be evaluated in a single system model without requiring excessive simulation times, thereby providing an effective and accurate means for investigating and addressing issues related to inter-physical domain interactions.

Such fully integrated models provide power electronic designers with more insight into the system before hardware is built, leading to time and cost savings.

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