Double fed induction machine: a EUROSTAG model

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Introduction

Variable speed induction machines and particularly Double Fed Induction Machines (DFIM) are more and more used for wind energy conversion. This allows for operating the turbine at variable speed enhancing the conversion efficiency. The concurrent option is presently based on full AC-DC-AC conversion with a gearless mechanical implementation. The size of the power electronic package is reduced to 30 – 50% when considering DFIM. That's why this option is often selected.

EUROSTAG® package proposes a standard library of rotating machine models like synchronous machines; induction machines etc..

The duble fed induction machine model hereunder presented, not yet present in the standard library, has been **developed using the macro-language of EUROSTAG**. This model includes a global modeling of the DC link, the voltage/reactive compensation control using the rotor IGBT's bridge (machine "excitation"). The network side bridge works at cos φ=1.

Information concerning EUROSTAG, software for the simulation of power system dynamic for transient to long term stability, is available on www.eurostag.be

Assumptions

- The wind-turbine inertia is represented as a **lumped-mass**. The shaft-torsion effects are not taken into account.
- A collection of WTG's (wind farm) can be modelled as an **aggregated model** represented by one equivalent unit.
- The model takes into account the rotor flux dynamic but **neglects the stator dΨ/dt terms**, as usually when considering electromechanical simulation.
- The **magnetic saturation** of the induction machine is taken into account. This permits to model realistically the reactive power limits when working in abnormal voltage conditions.

Coherently with the detailed induction motor model used in EUROSTAG, the **stray load losses** can be taken into account, even if they have less importance as compared to motor starting conditions.

- The wind can be set by the user, but usually for most of the system studies, the **wind speed** can be held constant, at its most critical value (corresponding to maximum output). It is reasonable to assume that the wind speed remains uniform for the 5 to 30 s following a disturbance.
- The model has been developed for performing power system studies; hence the protective scheme and the resynchronization process have been modeled in detail.

References

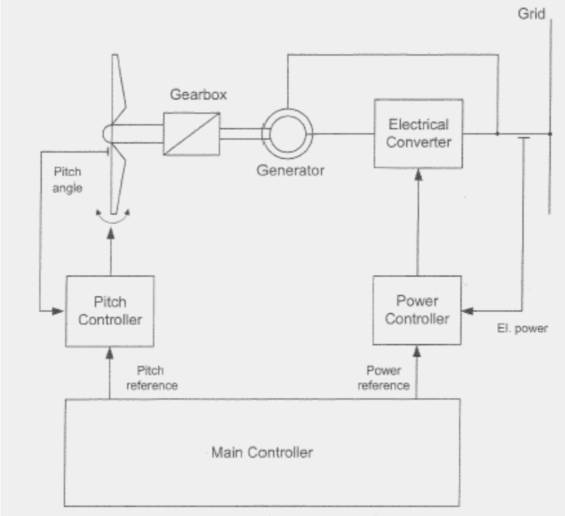
[1] J.G.Slootweg, H.Polinder, W.L.Kling; "Dynamic modeling of a wind turbine with double fed induction generator" Proceedings. 2001 IEEE Power Engineering Society Summer Meeting (Vancouver, 15-19 July 2001), IEEE Power Engineering Society, S.l., 2001, p. 1-6. ISBN: 0-7803-7031-7, cat. c.

General Scheme

The following figure represents the global control scheme.

The model of the DFIM is composed of the following different parts:

- Model of the double fed machine and its converters (continuous equivalent model are considered, taking account of the "phasor" modeling used in transient stability studies);
- Model of reactive power control;
- Aerodynamic model of the wind blades;
- Model of the wind turbine control.



Double fed machine and its converters

The asynchronous motor is modeled with classic Park's equations. The rotor voltage is controlled by the converter in order to obtain the desired electrical torque and reactive power.

The mutual reactance is variable in order to take the magnetic saturation of the machine into account. As indicated, the transformation e.m.f's are neglected in the considered equations.

When the machine is disconnected from the grid, the stator current is forced to zero 100 ms after the disconnection pulse. This corresponds to the expected tripping time of the stator circuit breaker. The modeling requires that the simulation process remains "active" while the machine is disconnected from the system, as the preparation of the resynchronization process must be simulated. The speed controller resets the machine speed by action on the pitch.

The rotor converter of the DC link magnetizes the machine so to have the actual grid voltage at the machine terminal.

If required by the operating conditions, the converter is first switched off (IGBT rated current criterion). If necessary a crowbar protection is operated. It protects the rotor converter from too high voltages and decouples the DC bus from the rotor. In such cases, the rotor voltages are set to zero (short circuited rotor) and the machines behaves as a traditional asynchronous machine.

The behaviour of the DC link is critical during fault conditions. Some additional means should be made available if the voltage stability of the DC link must be guaranteed, like for example a suitably controlled discharge resistor (few machines are presently equipped with such circuit).

Reactive power control

Nowadays, most variable speed WTG's with DFIM are operated at constant power factor or at constant reactive power production. Terminal voltage control is a feature that is not available on most commercial turbines yet.

The reactive power setpoint in this model, which is introduced in the rotor control, is resulting from a direct user setpoint or from a power factor setpoint.

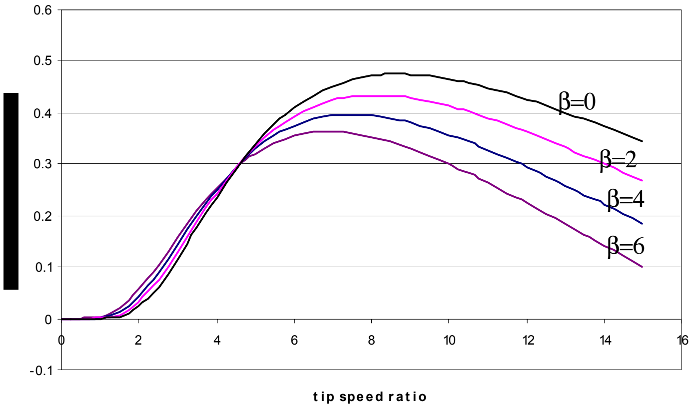
The power factor is kept constant as long as the terminal voltage remains in an acceptable zone. Once the voltage exceeds the zone, the power factor is adapted accordingly.

Aerodynamic model

The mechanical power extracted from the wind is expressed by the following well known formula:

$$P_{wind} = \frac{1}{2} \cdot C_p(\lambda,\beta) \cdot \rho_{air} \cdot A_{rotor} \cdot v^3 ,$$

with ρ the air density [kg/m^3], C_p the performance coefficient, λ the tip speed ratio $\omega_{rotor} \cdot R_{blades}/v_{wind}$, the ratio between blade tip speed and wind speed upstream the rotor, β the pitch angle of the rotor blades [degrees], and A_{rotor} the area covered by the rotor [m^2]. The performance coefficient C_p is determined by aerodynamic laws and thus may change from one WT type to another. A good approximation for the C_p curves in function of the tip speed ratio λ and the pitch angle β for a recent 2 MW wind turbine is given in next figure [1]:



Wind turbine control

The control functions are divided into 3 blocks called Main Controller, Pitch Controller and Power Controller.

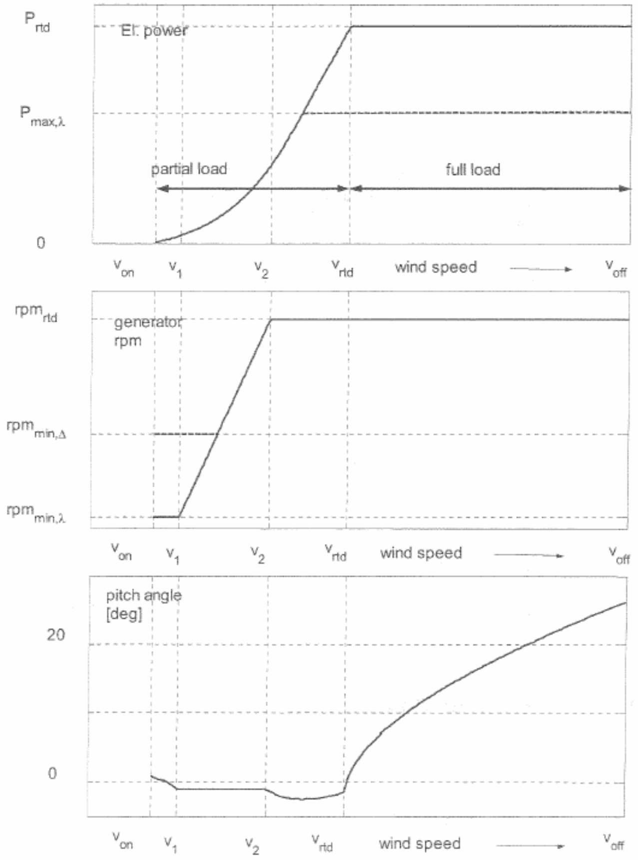
Main controller

The main controller manages the overall control functions, whereas pitch and power controllers are subordinate units. The objective is to determine the optimal values of the WT speed and of the pitch angle for a given wind speed in order to maximize the electrical power produced.

There are two main operating modes:

- When the wind speed is below a certain threshold (called the rated wind speed), the turbine is not able to produce the rated power. In this case, the partial Load Controller is activated. It controls the turbine speed maximizing the produced power by continuously adapting the electrical power;
- When the wind speed is above the rated value, the full load controller is activated. It controls the pitch angle limiting the produced power to the rated value.

Next figure illustrates the different operating area's in function of the wind speed.



Partial load control

The partial load area can be divided into three portions:

- Operation at low speed (V_{on} < wind speed $\leq V_1$). The reference speed is kept to the minimum speed corresponding to the maximum permissible slip.
- Operation at the efficiency optimum (V_1 < wind speed $\leq V_2$). The reference speed is controlled in order to maximize the aerodynamic efficiency of the turbine.
- Operation at nominal rotor speed (V_2 < Wind speed $\leq V_{rtd}$). In such case, the tip speed ratio is lower than the optimal value.

Speed control: its main objective is to keep the speed at its setpoint value to keep the tip speed ratio λ at its optimal value. The set points are given by the characteristic: Cp_{opt} $(\lambda_{opt},\beta_{opt})$. The optimal speed reference is given directly by the input wind speed.

The pitch angle in partial load mode is assumed to be kept constant and equal to zero. In reality, the pitch angle is slightly adapted (in the last portion) in order increase the power coefficient C_p at a given tip speed.

Full Load Controller

The full load controller is automatically activated as soon as the power output rises above the power demand.

The main objective of the full load controller is to limit the mechanical torque of the turbine and to keep the generator speed constant at its nominal value. The speed is controlled directly by the pitch controller, as the electrical power output is set to it's the nominal generator power.

The pitch controller can be modelled as a first order dynamic.

Special operation conditions

In case of system short-circuit; mechanical shocks corresponding to the fault onset and to the fault clearance can damage the machine. That's why wind turbine manufacturers promoted the transient disconnection of the machine, in case of to low voltage or to high stator current. Moreover, the rotor converter has its own protections.

When short circuits occur, high currents are flowing in stator and rotor windings. When rotor currents are exceeding the rated value of the valves, the control electronics blocks rotor side converter, putting the bridge out of service. But the energy from the rotor is still flowing through the fly wheel diodes[1] and continues to load the dc capacitor.

The transient working with short circuited rotor via fly wheel diodes or via the crowbar protection, cannot last for a long time and will generally leads to a disconnection[2]. After such a disconnection (generator and/or converters protection), the wind turbine will resynchronise autonomously within a delay of 30 s[3].

The EUROSTAG® model contains all these features. They can be adapted for modelling adequately a specific wind turbine.

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[1] The rating of these diodes is significantly higher than the rating of the main valves made of IGBT's.

[2] New models of wind turbines can presently remain connected to the network in case of faults cleared in base time ("ride-through capability").

[3] The Danish grid operator imposes that the wind turbine is able to resynchronise itself, within a 5 seconds time span and at least for two successive faults within a 30 seconds window.

Operation with limited power production

Primary reserve

The possibility is given to the user to limit the active power which is produced by the wind turbine, e.g. to provide a certain primary reserve. In such conditions, the switch to full load mode is forced keeping the power constant and equal to the fixed value. The power limitation is done varying the pitch position. As the wind speed is no more sufficient to produce the user setpoint, the wind turbine is automatically brought back to the partial load mode.

Priority to reactive power

The user can select the option to give priority to reactive power production. The regulator will, if necessary, decrease active power production to provide enough margin for the reactive power in order not to exceed the maximum MVA. (cfr. simulation 3).

Simulations

Model base values: V_{base} = 690 kV, P_{base} = 2 MW, $\omega_{base} = 2\pi f_{base}$, f_{base} = 50 Hz

2 MW induction wind turbine parameters

Stator resistance Rs: 0.0069314 pu

Rotor resistance Rr: 0.00906 pu

Stator reactance Xs: 0.08083 pu

Rotor reactance Xr: 0.09934 pu

Magnetizing reactance Xm: 3.29 pu

Lumped inertia constant H: 3.52 s

Control model parameters

Cut-in speed = 3 m/s, cut-off wind speed = 25 m/s, rated wind speed v_{rated} = 12.2 m/s

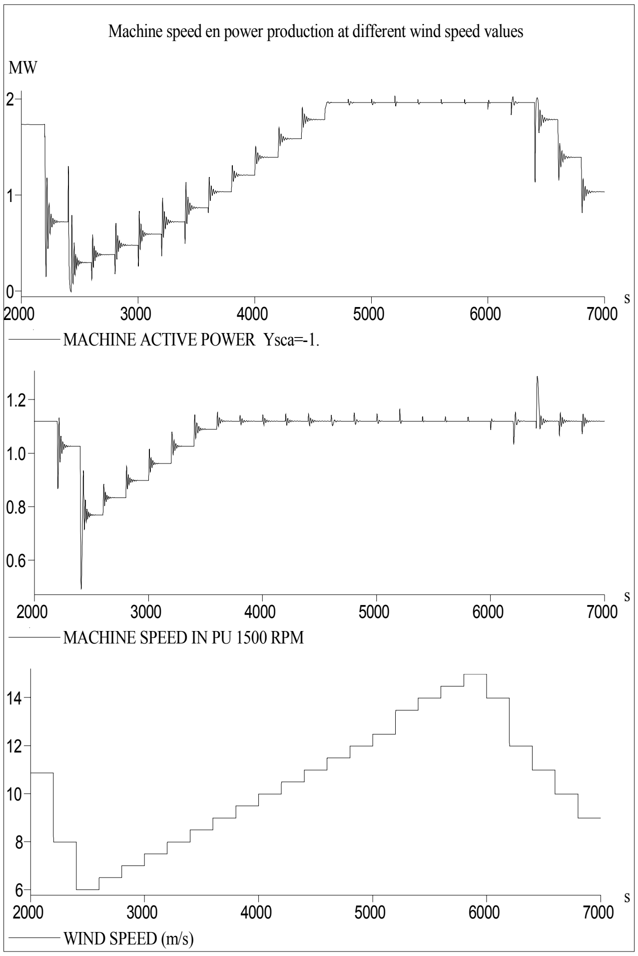
Full load regulation parameters:
Kfl = 0.035 Tfl = 2 s

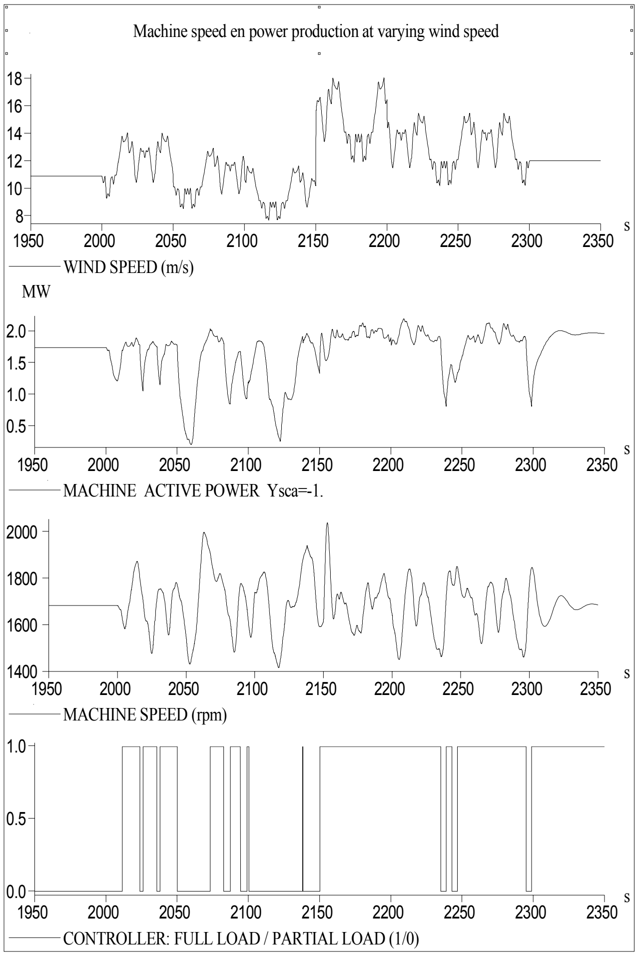
Partial load regulation parameters:
Kpl = 7 Tpl = 5.5 s

Blade pitch time constant: Tpitch = 0.18 s

Simulation 1 : discrete and continuous wind speed variations

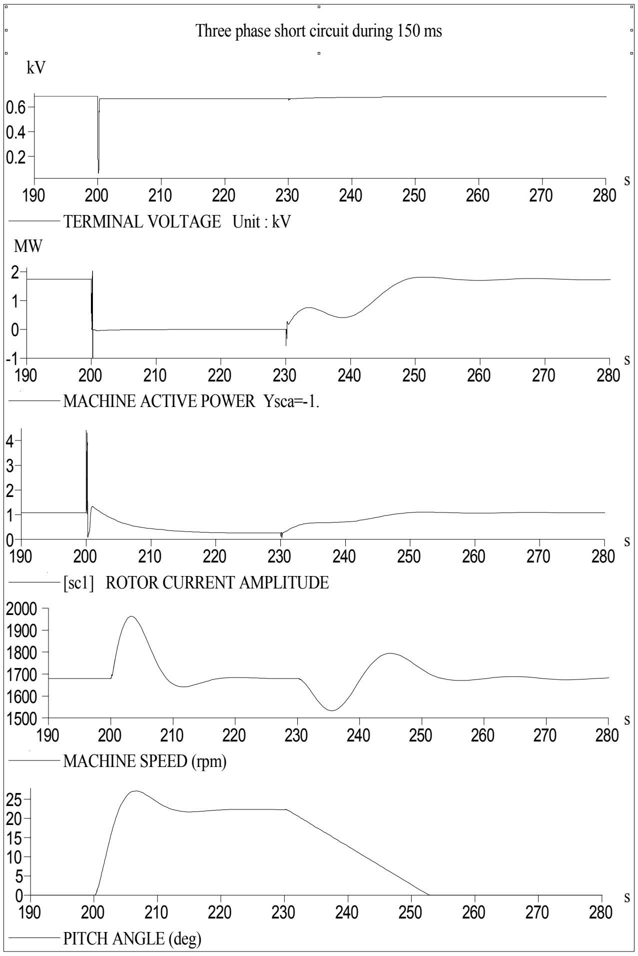
These simulations show the rotor speed and the active power output following wind speed variations. Note the transitions from full load to partial load control.





Simulation 2 : three phase short circuit

A three phase short circuit is simulated on a 150 kV transmission line close to wind mill. The fault is eliminated by opening the transmission line. The machine is disconnected from the grid and reconnects automatically after 30 s. During the islanded operation the main controller switches to full load control. The rotor is short circuited with a crow-bar protection. This means that the machine is behaving as a traditional asynchronous generator with short circuited rotor windings.



Simulation 3 : reactive power and cosφ control

In the left figure: at t= 300 s, the reactive power setpoint is set to 1 Mvar. The reactive power evolves very slowly to the steady state value.

At t=500 s, the wind speed is increased to 13 m/s. The active power is increased to its maximum value and therefore the reactive power is instantaneously reduced, while its setpoint is still at 1 Mvar.

At t= 700 s, the wind speed is reduced to 10 m/s. The active power decreases and this makes it possible for the reactive power to increase again to its set value.

At t=900 s, priority is given to produce reactive power. The wind speed is again increased to 13 m/s, but the active power does not reach its maximum value. On the contrary, the reactive power remains at 1 Mvar.

In the right figure, the setpoint of the cos φ control is varied.

At t= 300 s: set value of cos φ = 0.8 capacitive

At t= 500 s: set value of cos φ = 0.9 capacitive

At t= 700 s: set value of cos φ = 1

At t= 900 s: set value of cos φ = 0.9 inductive

The active and reactive power output is shown in the right figure.