Integrated control and structural analysis of DFIG wind turbines using a monolithic approach

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Abstract:

Design of wind turbines requires the coupled analysis among the mechanical, control and aerodynamic subsystems. Different from previous research, which either uses a complicated mechanical model with a simple control system model, or vice versa, this paper studies the coupling of subsystems' dynamics using a high-fidelity aeroelastic model of wind turbine and a detailed analytical model of control generating systems. A monolithic time integration approach is applied so that better numerical accuracy and stability are achieved. Control strategies on power optimization are discussed taking into account the influence of structural flexibility. Simulation examples are given on both stable and turbulent wind situation.

Keywords: DFIG wind turbine, power optimization control, structural coupling, monolithic approach

1 Introduction

High-fidelity and integrated multi-disciplinary models of wind turbine systems are important for the correct evaluation of the extreme loads and the fatigue life, and thus might reduce the failure rate in the design stage. There is no doubt that accurate structural modelling and aeroelastic dynamics analysis is essential in the field of wind turbine design. However, the aeroelastic model should also be applicable for detailed control system design, which will be necessary as the design goes deeper. Indeed, linear simplified control models, e.g., a simple generator model, are not sufficient to account for the necessary coupling effects among the components. Ref. [1] shows that the coupling between generator and turbine dynamics can result in an unstable vibration mode, which occurs only if a dynamic generator model is considered. Thus, the dynamics of the generator should be taken into account in the aeroelastic computations of the wind turbines.

For the coupled analysis of the aerodynamic, structural and control generating systems, many works either use a very simple mechanical model with a detailed electrical model, or vice versa [2,3]. Hence, the interactions cannot be accurately represented. Usually, for an electrically-targeted software tool, a lumped-mechanical model is used in the control analysis for representing the structural flexibility. Indeed, complicated structural model is not necessary from the control point of view. However, the structure flexibility is a complex phenomenon due to the non-uniform distribution of the mass, the stiffness and the coupling of the components etc., which can hardly be represented by a simple mathematical model for the dynamic interaction analysis [4]. On the other hand, simplified control models are mostly used for a variety of wind-turbine specific codes, which are comparatively accurate from the structural point of view. The consequence is that the dynamics coupling, which might be important as afore-mentioned, cannot be accurately predicted.

The current prevailing methods for the wind-turbine structural analysis codes to include control functions are either through external DLLs or by the co-simulation approach with a third party software tool such as Simulink. By these means, models that can accurately represent the aerodynamic, mechanical and electrical systems of wind turbines are developed on different simulation tools. Ref. [5] uses DIgSILENT and HAWC2, and Ref. [3] uses Simulink and FAST as platforms for electrical and mechanical systems respectively. It could be efficient from the computational point of view for that different micro time steps are applied to different subsystems. However, on the other hand, since different solvers are used for different platforms respectively and data are exchanged only at particular communication times [6], unconditional global stability cannot be assured with the consequence that rather small time steps are required, leading to large computational costs. Moreover, the dynamic interaction analysis among subsystems is limited if an open simulation scheme is performed, e.g., the generator speed is not identically reflected on the two platforms [3].

This paper aims at the control-generator-structure coupled analysis in wind turbines using a monolithic modeling and simulation approach. Variable-speed doubly-fed induction generator (DFIG) wind turbines are studied. Power optimization control strategies considering structural effects are discussed for the below-rated wind speed situation. The integrated system models are developed on Samcef for Wind Turbines (S4WT) through a nonlinear finite element method (FEM) formalism, which is adapted to account for large structural rotations and transformations and is extended to represent mechatronic dynamics in a strongly-coupled way [7,8].

2 Description of monolithic approach

Wind turbine system is a typical mechatronic system comprising of structure, control, aerodynamics etc. Dynamics of the mechatronic system can be represented by the coupling of the second-order structural dynamics, kinematic constraints and the first-order control dynamics, which are integrated as follows:

$$\left.\begin{aligned} \mathbf{M}\ddot{\mathbf{q}} + \boldsymbol{\phi}_{\mathbf{q}}^{T}(k\boldsymbol{\lambda} + p\boldsymbol{\phi}) - \mathbf{g}(\mathbf{q},\dot{\mathbf{q}},t) - \mathbf{L}^{a}\mathbf{y} &= \mathbf{0} \\ k\boldsymbol{\phi}(\mathbf{q}) &= \mathbf{0} \\ \dot{\mathbf{x}} - \mathbf{f}(\mathbf{q},\dot{\mathbf{q}},\ddot{\mathbf{q}},\boldsymbol{\lambda},\mathbf{x},\mathbf{y},t) &= \mathbf{0} \\ \mathbf{y} - \mathbf{h}(\mathbf{q},\dot{\mathbf{q}},\ddot{\mathbf{q}},\boldsymbol{\lambda},\mathbf{x},\mathbf{y},t) &= \mathbf{0} \end{aligned}\right\} \quad (1)$$

where $\mathbf{M}$ represents the mass matrix; $\mathbf{q}$, $\dot{\mathbf{q}}$, $\ddot{\mathbf{q}}$, respectively the vectors of position, velocity and acceleration; $\boldsymbol{\phi}$, the constraints; $\boldsymbol{\lambda}$, the Lagrangian multipliers; k, the scaling factor; p, the penalty factor; $\mathbf{x}$, the control state variables; $\mathbf{y}$, the vector of the output of the control system; $\mathbf{L}^{a}\mathbf{y}$, the action of the controller on the structural dynamic equilibrium.

For the monolithic simulation approach, the mechanical structure is modelled using finite element description, while the control system and generator models are described using the block diagram language. The coupled mechanical and state equations are obtained by numerical assembly and the simulation is based on an extended generalized-*α* time integration method. Thus, the index-3 differential-algebraic equations (DAEs) are computed in a strongly coupled way [8].

The extended time integration method uses a scheme similar to the traditional generalized-*α* method, which is well known for the structural dynamics, by introducing additional integration formula for the states:

$$(1-\alpha_m)\mathbf{a}_{n+1} + \alpha_m \mathbf{a}_n = (1-\alpha_f)\ddot{\mathbf{q}}_{n+1} + \alpha_f \ddot{\mathbf{q}}_n,$$
$$\mathbf{a}_0 = \ddot{\mathbf{q}}_0 \quad (2)$$
$$(1-\delta_m)\mathbf{w}_{n+1} + \delta_m \mathbf{w}_n = (1-\delta_f)\dot{\mathbf{x}}_{n+1} + \delta_f \dot{\mathbf{x}}_n,$$
$$\mathbf{w}_0 = \dot{\mathbf{x}}_0 \quad (3)$$

where **a** and **w** are auxiliary variables. Eqn.(2) stands for the structural part and Eqn.(3) stands for the control part. The extended generalized-*α* scheme is then obtained using **a** in the Newmark integration formula and **w** in the state integration formula:

$$\left.\begin{aligned} \mathbf{q}_{n+1} &= \mathbf{q}_n + h\dot{\mathbf{q}}_n + h^2(0.5-\beta)\mathbf{a}_n + h^2\beta\mathbf{a}_{n+1} \\ \dot{\mathbf{q}}_{n+1} &= \dot{\mathbf{q}}_n + h(1-\gamma)\mathbf{a}_n + h\gamma\mathbf{a}_{n+1} \end{aligned}\right\} \quad (4)$$

$$\mathbf{x}_{n+1} = \mathbf{x}_n + h(1-\theta)\mathbf{w}_n + h\theta\mathbf{w}_{n+1} \quad (5)$$

Here, α_m , α_f , δ_f , δ_m , β , γ , and θ are the algorithm parameters.

Note that second-order accuracy and unconditional stability are important for a time integration scheme in structural dynamics as the system can be very stiff with a broad range of system eigenfrequencies. With an optimal selection of the parameters, second-order accuracy and unconditional stability in linear regime can be ensured for both the structure and the control system dynamics [8]. A brief discussion of the choice of the algorithmic parameters is given as below. The condition of second-order accuracy yields:

$$\gamma = 0.5 + \alpha_f - \alpha_m \quad (6)$$

$$\theta = 0.5 + \delta_f - \delta_m \quad (7)$$

For stiff problems, high frequency solution should rather be damped out by the numerical damping, which is represented by the spectral radius of the algorithm at infinity ρ_∞ with $\rho_\infty \in [0,1]$: $\rho_\infty = 1$ stands for an undamped case, whereas $\rho_\infty = 0$ represents asymptotic annihilation of the high-frequency response. Optimal parameters can then be derived from a frequency domain analysis. For the second-order mechanical systems, the optimal algorithmic parameters are defined as:

$$\alpha_m = \frac{2\rho_\infty - 1}{\rho_\infty + 1}, \ \alpha_f = \frac{\rho_\infty}{\rho_\infty + 1} \tag{8}$$

$$\beta = 0.25(\gamma + 0.5)^2 \tag{9}$$

The parameters for the first-order control systems are defined as:

$$\delta_m = \frac{1}{2}\left(\frac{3\rho_\infty - 1}{\rho_\infty + 1}\right), \ \delta_f = \frac{\rho_\infty}{\rho_\infty + 1} \tag{10}$$

Detailed analysis on the convergence rate can be found in [8].

3 Integrated control of DFIG wind turbines for power optimization

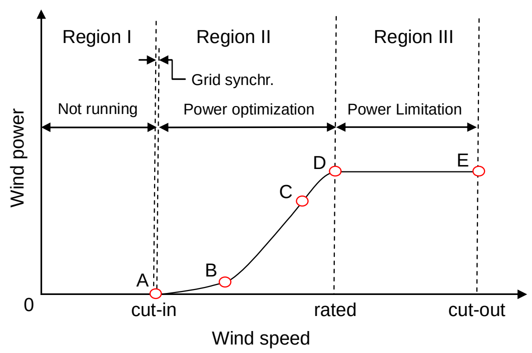

Figure 1: Operating regions vs. control strategies

Up scaling of wind turbine size leads to increasing structural flexibility, and adds to the difficulty of the analysis of the coupling effects. The control of wind turbine systems depends on a predefined operating profile. A DFIG wind turbine system operates within a range of wind speed. The operating regions are classified into three divisions according to the variation of wind speed. That is, below the cut-in wind speed, above the rated wind speed while still below the cut-out wind speed, and the region in-between the cut-in speed and the rated wind speed, as shown in Fig. 1. Controllers are designed accordingly.

Baseline wind turbine controllers should be designed for soft grid synchronization and power regulation via optimal state-feedback loops. Power regulation is realized via either a generator torque controller or a pitch controller, or the combination of these two controllers in the transitional region from region II to III [9]. Generator torque controller is to maximize power output under rated wind speed, while pitch controller is for power output limitation above the rated wind speed. Activation of controllers depends on the wind speed estimation. While maintaining the main control objectives, coupling effects of structural flexibility are also taken into account for load reduction such as alleviation of the blade loads or adjustment of the torsional damping on the drive train.

Here in this paper, the DFIG model is a 5th order mathematical model based on grid-voltage-oriented reference frame in order to derive the vector control strategies [10-11]. Control of reactive and active power is decoupled through the regulation of *d* and *q*-axis rotor current respectively. The control strategies discussed here are focused on the active power optimization in region II, see Fig. 1. Power optimization control is actually to track the maximum power coefficient with an optimal pitch angle held constant below rated wind speed. That is, The wind turbine is controlled to track a predefined power-speed profile via the generator torque controller. Here in this study, a cascaded control loop is implemented. The controllers comprise of a current controller (PI), a torque controller (P) and a speed controller (IP), as can be seen in Fig. 2. The coefficients of PI or IP controllers are derived by internal model control (IMC) and pole placement methods respectively. A detailed discussion on the design of the controllers can be found in the authors' previous work [15]. Moreover, in order to overcome the windup phenomena of the integral parts of the controllers, an anti-windup scheme is implemented.

As the electrical dynamics is much faster than the structural dynamics, the speed controller in the cascaded loop is assumed to be dominantly influential in the structural response. Large variations of the generator torque will increase the mechanical fatigue of the drive train, and could damage the drive train systems. In order to improve the damping of the low-speed torsional oscillation of the shaft system, the speed controller should be designed with a bandwidth smaller than the antiresonance frequency [12] of the drive train system, and it can thus reduce the gains at the oscillating frequencies [13].

Given that wind speed can be very stochastic in reality and the inertia of WTs is high compared to the wind speed variation, a low-pass filter is necessary for extracting a smooth corresponding rotor speed reference command. The bandwidth of the filter should be smaller than or comparable to that of the speed controller so that a stable speed tracking can be achieved [13]. Figure 2 shows the control block of DFIG WTs for power optimization. Description and the modular implementation of the models based on a block diagram description are detailed in [14,15].

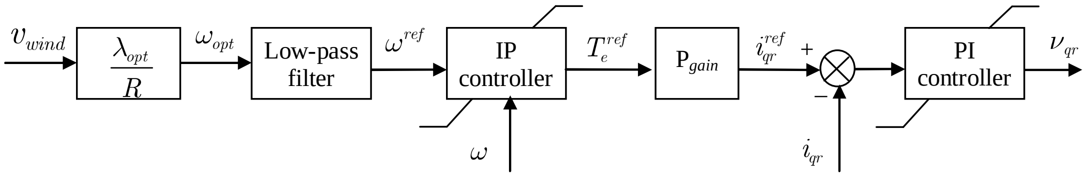

Figure 2: Control block for power optimization

4 Simulation and Validation

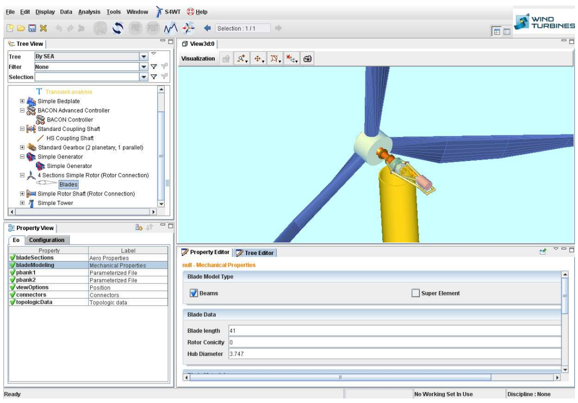

Figure 3: S4WT user interface

A 2MW DFIG prototype model is used for simulation and analysis. Figure 3 shows the user interface of the tool. The structural components include the tower, the blades, the shafts, the bed-plate, the gearbox and the planet carriers etc. They can be modelled either by super-element, which are based on a linear modal description of elastic effects in a body attached frame, or by fully nonlinear finite elements. In this example, shafts, blades and tower are modelled by nonlinear beam elements with 6 degrees of freedom per node, and thus they can properly represent the phenomena of shear, bending and torsion. For the sake of computational efficiency, the gearbox model is represented by a rotational speed ratio as well as by the mass and inertia properties of the gears and the housing. The mechanical properties of the generator are represented by the inertia and mass, while the electrical properties and the controllers are described using the state-space representation. The aerodynamic loads are modelled according to the blade element momentum (BEM) theory. Specific correction terms are included to account for the effects of tip and hub losses, tower shadow, wind shear, turbulent wake state, dynamic inflow and dynamic stall [17]. The aero-elastic coupling is computed at the 1/4 chord length position of a set of discretized, equally-spaced blade sections using the aerodynamic blade section elements. Load cases including wind conditions as defined by the IEC norm are also available in the user interface. Some selected parameters of the turbine system are as: 41m of blade length, 75m of tower height and 106 of the gearbox ratio. The optimal tip-speed-ratio λ_{opt}=0.68.

The first example studies the wind turbine control system under a rather stable wind situation. The simulation situation is as follows. The initial wind speed is set to 8m/s and the initial turbine rotor speed is to be 1.1rad/s (accordingly 0.74p.u.). When the generator rotating speed reaches 0.8p.u., the stator is connected to the grid with a soft synchronization control system [16]. After 8s, the wind speed step changes to 10m/s. For 8m/s of the wind speed, the maximum wind power is to be extracted with 0.9p.u. of the rotating speed, while 1.125p.u. is that for a wind speed of 10 m/s.

The controllers are first implemented without anti-windup schemes. The purpose is to validate the controller and to analyze the effects of the controllers on structure response. Considering that the electrical dynamics is a lot faster than the structural dynamics, the speed controller in the cascaded loop is assumed to have an essential role in the structural response. While maintaining the other coefficients, the settling time coefficient for the speed controller is changed in order to study its influence on the structural response. Selected simulation results such as the loads on the rotor blades are chosen for comparison. Fig. 4 shows the rotor speed response with different settling time coefficients; Fig. 5 shows the bending moment on the blade root. As one can see from the figures, faster speed controller leads to extra load on the mechanical systems. The bandwidth of the speed controller thus should be carefully chosen to be sufficiently small. However once the settling time gets slow enough, load reduction on the blade roots becomes limited. It can thus be concluded from this coupled analysis that there exists an optimal settling time coefficient leading to the best compromise between the speed response and the load reduction.

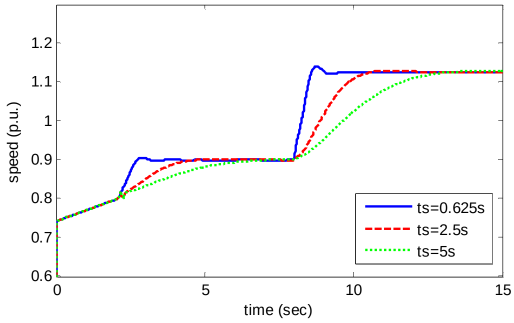

Figure 4: Speed response

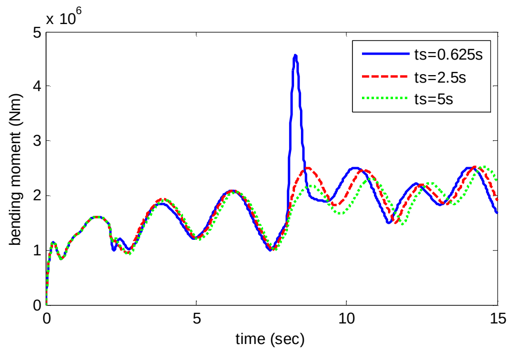

Figure 5: Bending moment on the blade root

In reality, the time constant of wind gust varies from a couple of seconds to dozens of seconds, and the reference rotor speed changes accordingly. The following example tends to validate the controller under turbulent wind situation. The wind model is generated by the Kaimal spectra, with a mean value of 8m/s. As the variation of the wind speed is very fast in comparison with the inertia of the WTs, a low-pass filter is applied to provide a smooth reference rotor speed. Anti-windup schemes are also implemented in order to avoid integral windup phenomenon. The settling time of the speed controller is set to be 5s, corresponding to 0.33Hz of the bandwidth, while the bandwidth of the filter is set to 0.25Hz. Figure 6 shows the variation of the wind speed and the electrical power extraction. Figure 7 shows the speed tracking response of the DFIG wind turbine.

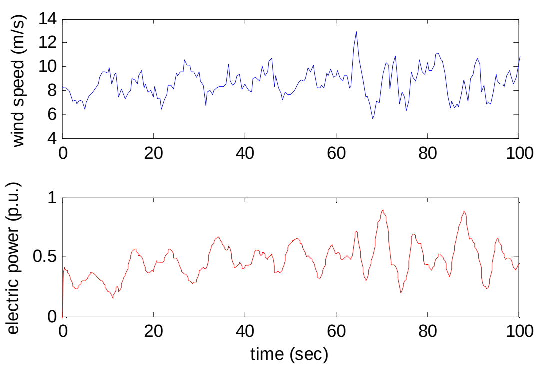

Figure 6: Wind speed and electrical power output

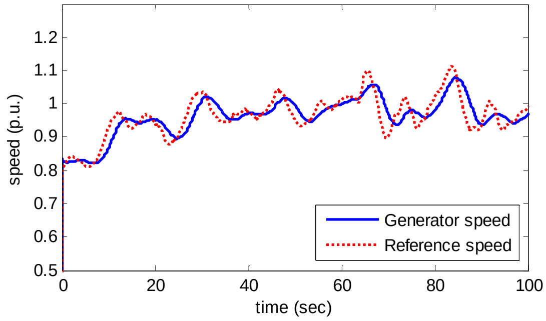

Figure 7: Speed tracking

5 Conclusion

This paper studies the generator-control-structure interactions in DFIG wind turbines using a monolithic finite element approach. New block diagram functionalities for the description of control systems are developed, and are integrated in the high-fidelity wind turbine design tool, and thus extend this tool to well represent both the aeroelastic and control systems dynamics. The approach is proven to be second-order accurate and unconditionally stable in the linear regime, and therefore has better numerical behaviour.

Controller models are presented and show good control effects for power regulation. Structural flexibility is also taken into account in speed control loops for load reduction. Comprehensive wind turbine system models are presented to analyze the coupling effects. It aims at the optimization in the design of wind turbines. In the future work, more advanced controllers are supposed to be designed for alleviation of extreme loads from a more comprehensive point of view, and their coefficients will be automatically adjusted using optimization techniques.

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