Wind Turbine Controller Design Based on Quantitative Feedback Theory

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Abstract: *To enable wind turbines to produce power under great variety of wind conditions a sophisticated control system is needed. Wind turbine system is highly nonlinear and its dynamic changes rapidly with the change of wind speed. Many classic control methods fail to properly address the problem of the uncertainty of wind turbine dynamics. In this paper an approach to controller design based on Quantitative feedback theory is presented that demonstrates good ability to cope with system uncertainties. Quantitative feedback theory is applied for synthesis of wind turbine rotor speed controller.*

Keywords: QFT, template, QFT boundaries, wind turbine, Bladed, pitch controller

1. Introduction

Modern wind turbines in megawatt scale have to operate in wide range of operating conditions determined primarily by wind speed. To make it possible for wind turbine to produce power in such a variety of operating conditions a sophisticated control system is needed that will account for changes in operating conditions and accompanying changes in wind turbine dynamics. Wind power, or the power of air that moves at speed v_w over the area swept by turbine rotor with radius R is given by:

$$P_W = \frac{1}{2}\rho_{air} R^2 \pi v_w^3 \quad (1)$$

where ρ_{air} is density of air. From expression (1) it is clear that wind energy increases rapidly with increase in wind speed. This results in two different operation regions of wind turbine, each of them placing specific demands upon control system. During weak winds power contained in the wind is lower than the rated power output of wind turbine generator. Therefore, the main task of the control system in this region is to maximize wind turbine power output by maximizing wind energy capture. It can be shown that for each value of wind speed energy conversion efficiency reaches its maximum for only one particular value of rotor speed. Since modern wind turbines are connected to grid using AC-DC-AC frequency converters, generator frequency is decoupled from grid frequency what enables variable speed operation. Therefore it becomes possible to vary the rotor speed and to maintain optimal energy conversion during varying wind speeds. On the other hand, during strong winds power of the wind is greater than the rated power output of wind turbine generator. Therefore, the wind energy conversion has to be constrained in this region to assure generator operation without overloading. Very efficient method for constraining wind energy conversion is pitching the rotor blades around their longitudinal axis what deteriorates their aerodynamic efficiency. In this way only a part of wind energy is used for driving the generator. The principle scheme of the control system that enables wind turbine operation in two described operating regions is shown in the Fig. 1 [4]. As wind turbine power is directly proportional to its rotational speed, power control is usually done by controlling turbine speed.

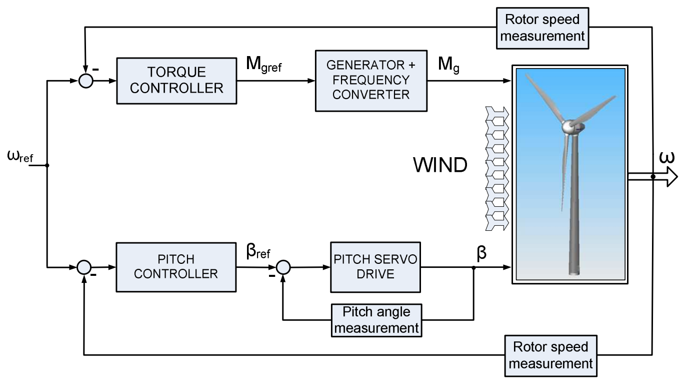

Figure 1: Principle scheme of wind turbine control system [4]

As it can be seen in this figure turbine speed can be influenced and thus controlled by two means – by generator electromagnetic torque M_g which opposes rotor driving torque M_t and by pitch angle β which alters the wind energy conversion. For this reason turbine speed control system consists of two control loops: torque control loop and pitch control loop. Those control loops operate simultaneously but depending on operation region one of them is dominant. In the below rated operation region the torque control loop is used to control turbine speed to values that will result in maximal wind power capture. This control loop is not in the scope of this paper. The pitch control loop is used for setting the adequate pitch angle that will keep turbine speed at its reference value under all operating conditions determined by various winds. Below rated wind speed this loop sets pitch angle to value that assures maximal wind power capture which is usually around 0°. In this paper we assume that all blades have the same pitch angle what is known as "collective pitch". Controller in this loop, although used to control turbine speed, is commonly termed *pitch controller*. It is usually implemented in a form of PI controller. Blade positioning is mostly done using electrical servo drives that rotate blades by means of gearboxes and slewing rings. Position control of servo drives is usually achieved using frequency converters. The described control structure is a core of control system of almost all modern multimegawatt wind turbines and it can assure rather satisfactory turbine behavior under various operating conditions. However, due to its simple structure it is not always capable to cope with wind turbine dynamics.

2. Problems of classic wind turbine control systems

The main problem for most of classical control methods is handling of nonlinear dynamic systems. Wind turbine system is highly nonlinear due to very nature of aerodynamic conversion that takes place on all rotor blades. Even if higher order phenomena (such as: aeroelasticity of the blades, wake effects, yaw errors, stall effect, tower shadow, wind shear etc) are neglected, design of wind turbine controller remains tough challenge for most of classical methods. The classic approach to this problem is design of the controller in several operating points (determined by wind speed) and use of gain scheduling [2]. Such an approach is not capable to explicitly account for uncertainty of process dynamic behavior that arises from changes in working conditions that are wind speed dependant. Furthermore, when a controller is parameterized, there are usually no guarantees of stability and quality of disturbance rejection when operating point changes. For that reason it is necessary to perform extensive time simulations to a posteriori determine if initial specifications for stability and disturbance rejections are satisfied in all cases. For that reason in this paper Quantitative Feedback Theory (abbr. QFT) [1] is applied that rises up to this challenge as it can a priori process uncertainty, quantify it and use it in combination with closed loop specifications. It can also a priori guarantee fulfillment of closed loop specification.

3. Quantitative feedback theory

In the beginning of 1960s Horowitz introduced a new frequency domain based control method called “Quantitative Feedback Theory” which presented a generalization of Bode's frequency domain work. During Horowitz's involvement in the development of control system for battle aircrafts [2], QFT method was completed and received a form in which it is used today. Successful utilization of QFT in aircraft control has proved the power of the method and enabled its application in helicopter control systems. Considering how much of wind turbine aerodynamic modelling stems directly from helicopter aerodynamic theory, it is reasonable to expect that QFT should handle in a satisfying manner control of wind turbine rotor speed. The main characteristic of QFT is the ability to explicitly take into account uncertainty of a process that is to be controlled, and use this knowledge to develop a controller capable of meeting certain specifications (i.e. for efficient disturbance rejection, noise reduction, etc.). Due to high transparency of the method it is possible to surveill almost every aspect of the problem in scope and thus make needed trade-offs between quality of disturbance rejection, stability margins, controller complexity and bandwidth utilization. This feature is especially appealing as it enables engineers to synthesize very efficient low-bandwith linear controllers of low order. Utilization of low-bandwith controllers decreases system’s sensitivity to noise and unmodelled dynamics. The basis of all QFT methods (all variants of MIMO QFT, dicrete QFT, QFT for non-minimum phased systems) is comprised in MISO QFT. The control structure of MISO QFT is shown in Fig.2. [1]

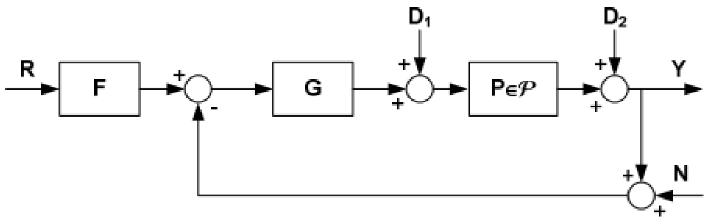

Figure 2 : MISO QFT control structure [1]

The elements of the structure shown in Fig.2. are described below:

𝓟 – a set of transfer functions $P_i(j\omega)$ (where $P_i(j\omega) \in \mathcal{P}$) describing the area of process parametric uncertainty.

G – QFT controller whose purpose is to make this feedback system robust, to reject disturbances and reduce sensitivity to noise .

F – prefilter that enables quality tracking of reference signal R.

Signals in Fig.2. are: measurement noise (**N**), disturbance on process P input (**D1**), disturbance on process P output (**D2**), reference signal (**R**).

The process of obtaining an adequate QFT controller G(s) and prefilter F(s) can be described through following steps given in Tab.1.:

Table 1 : QFT controller design steps

1	Determine the set of transfer functions $\mathcal{P}$={ $P_i(j\omega)$ } that describe the whole range of process dynamic behavior.
2	Choose a nominal process $P_O(j\omega)$ from the given set $\mathcal{P}$ (any one will do).
3	Choose discrete frequency set $\Omega=\{\omega_1, \omega_2,\ldots, \omega_M\}$ from frequency range relevant for control. Controller synthesis is performed on this set of frequencies.
4	For every frequency from Ω generate set of values called templates. Template $\Pi(j\omega_k)$ is a set of values whose elements are values of $P_i \in \mathcal{P}$ calculated at certain frequency $\omega_k \in \Omega$.
5	Determine a set of specification for closed loop system (i.e. allowable upper and lower boundary for tracking of **R**, upper boundary for disturbance rejection) and translate them to frequency domain.
6	Using Nichols chart, given specifications and templates find frequency boundaries $\mathcal{B}_i$ on Nichols chart. For every specification there is a set of boundaries $\mathcal{B}_i$ generated on Nichols chart. This set is calculated only for frequencies from Ω. For example, $\mathcal{B}_i(j\omega_k)$ would present a boundary for i-th specification evaluated on ω_k. Crucial detail is that all of these boundaries are calculated in dependence of before mentioned nominal process $P_O(j\omega)$. Namely it is important to realize that in QFT the controller design does not imply simultaneous calculations for numerous cases (for every $P_i \in \mathcal{P}$). Instead the simultaneous design problem is transformed into a single nominal design problem built around $P_O(j\omega)$.
7	Draw the nominal open loop characteristics $L_O(j\omega) = P_O(j\omega)\, G(j\omega)$ on the same Nichols chart and commence with classical loop shaping procedures in order to satisfy calculated boundaries.
8	Draw the whole set of closed loop transfer functions on Bode diagram and find suitable **F** to satisfy servo specifications (if such exist) for tracking of **R** signal.
9	Perform frequency and time validation of control design.

Step 6) is crucial for QFT method and it will be explained in more details. For example assume a stability margin specification given as:

$$\left|\frac{L(j\omega)}{1+L(j\omega)}\right| \leq M_m \qquad (2)$$

This relation is represented as a red closed curve around critical point (-180°, 0 dB) on Nichols chart in Fig.3.

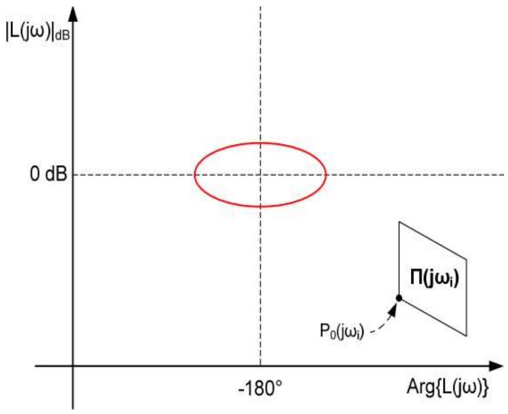

Figure 3 : Closed curve around critical point and the template Π(jωi) [1]

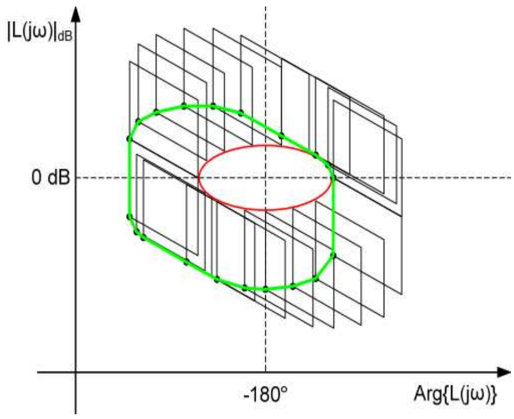

Figure 4 : Template moved around the curve forming a stability boundary ℬs(jωi) [1]

$\Pi(j\omega_i)$ represents the process template (set of values of $\mathcal{P}$ on frequency ω_i) and $P_O(j\omega_i)$ represents the nominal process. The template needs to remain outside the region enclosed by the red curve. Firstly move the template maximally close to the red curve (none of the points belonging to the template should enter the enclosed region) and mark the position of the nominal process for every position of the template. Connect these markings of the nominal process (green line in Fig.4.). This green line actually represents the stability boundary $\mathcal{B}s(j\omega_i)$ on frequency ω_i. If during step 7) of the QFT controller design process the value of open loop transfer function $L_O(j\omega_i)$ remains outside the $\mathcal{B}s(j\omega_i)$, then there is a guarantee that none of all possible closed loop systems values on ω_i will be within forbidden enclosed area. Similar logic applies to other types of specifications as well. The described design process may seem time consuming if done manually but there are several QFT software tools (i.e. MIMOQCAD, QSyn, SISO-QFTIT [5] – used in this paper) that handle boundary generations by solving systems of inequalities. However, this area of QFT is still in the development phase.

4. Application of QFT to wind turbine rotor speed control - simulation results

The design process described in the section 3 was used to design wind turbine pitch controller. The specifications for the design were:

- Overshoot of rotor speed due to unit step wind speed change must be below 1 rpm in the whole wind speed range from 12 m/s to 25 m/s and settling time (+/- 0.2 rpm around nominal rotor speed) must be below 5 s. These values are summed up in a disturbance **D2** rejection characteristic (3) that was calculated by trial and error until a satisfactory time response has been reached:

$$G_{D2}(s) = \frac{2.2s^2 + 1.76s}{0.8s^3 + 2.3s^2 + 2.1s + 0.65} \quad (3)$$

- Stability margin defined as described in Fig.3. is given (4):

$$\left|\frac{L(j\omega)}{1 + L(j\omega)}\right| \leq 1.46 \quad (4)$$

  This stability margin translates into *amplitude margin* larger than 3.3 dB and *phase margin* larger than 40°.

Designed controller was tested using professional wind turbine simulation tool GH Bladed ([6], [7]). GH Bladed relies on a complex aerodynamic and structural wind turbine model what makes its results very reliable and in accordance with behavior of real wind turbines (as recognized by Germanischer Llyod and other major certification institutions). Simulations were performed using specially developed interface between GH Bladed and Matlab Simulink which enabled use of Bladed's very detailed model of the wind turbine at one side and the flexibility of controller design and implementation in Matlab at the other (see Fig.5). As it can be seen from Fig. 5. measured data set is collected from GH Bladed (wind speed, pitch angle, rotor speed). New reference signals (pitch and torque reference values) are calculated within Simulink environment and passed back to GH Bladed. Designed continuous QFT controller was discretized using ZOH method with sample time T_s=0.02 s. Stepwise wind speed changes covering wind speed range between 12 m/s and 25 m/s was used to test the QFT control algorithm (see Fig.6). Such wind speed changes are not natural but offer very clear view of the system dynamic behavior. The red line represents the set allowable upper bound for the rotor speed overshoot under given wind conditions.

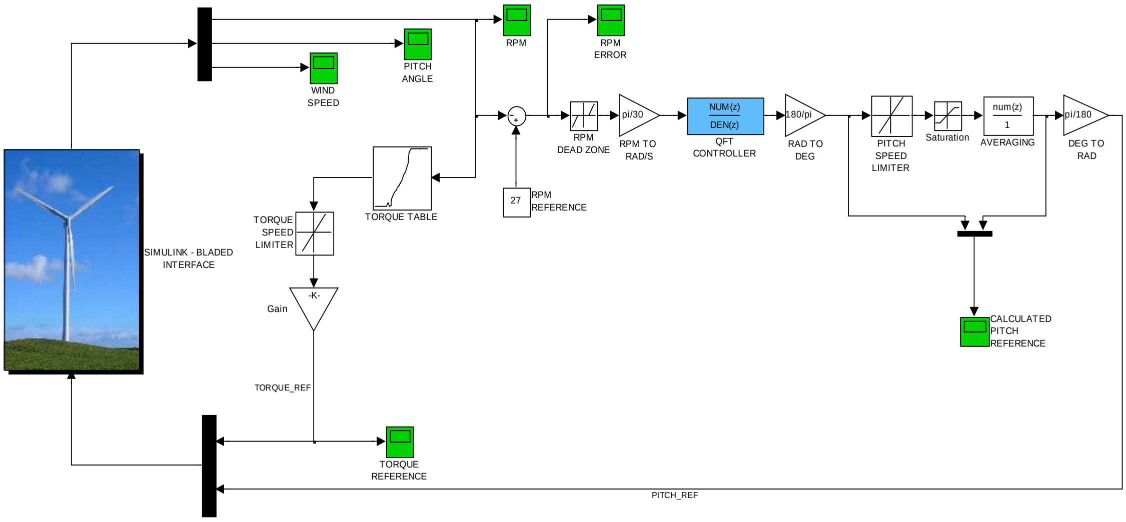

Figure 5 : Simulation schematics that utilizes a developed interface between Simulink and GH Bladed

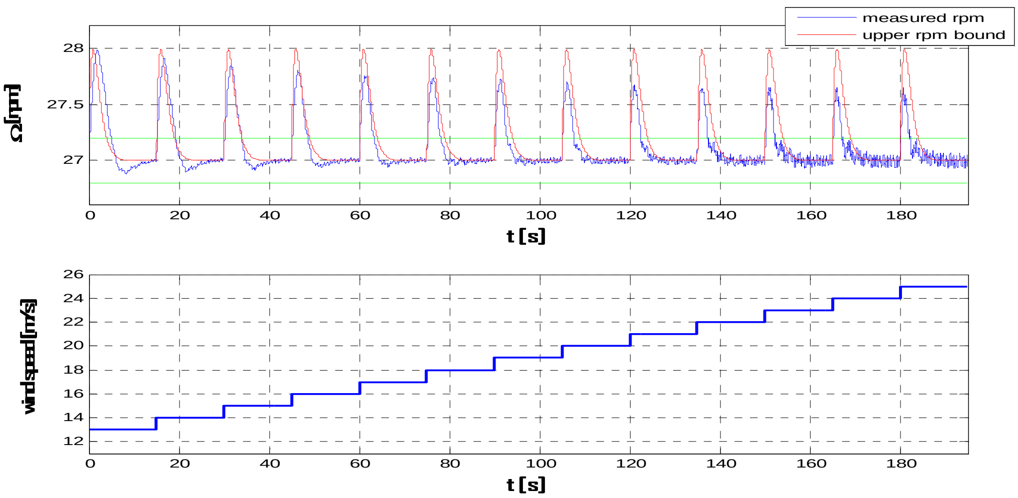

Figure 6 : Comparison of rotor speed response and specified upper bound for rotor speed response

In Fig. 7. 2nd order QFT controller was compared to PI and PI gain-scheduled controller. PI controller was configured to obtain a satisfying response in high wind regimes, while PI gain-scheduled controller should give equally satisfying results in all above rated wind speed regimes. As it can be seen from Fig.7. QFT demonstrated that it is capable of producing a simple 2nd order linear controller superior to PI and even gain-scheduled PI controller. Another great comparative advantage is that during the design process guarantee of stability and disturbance rejection **D2** was obtained.

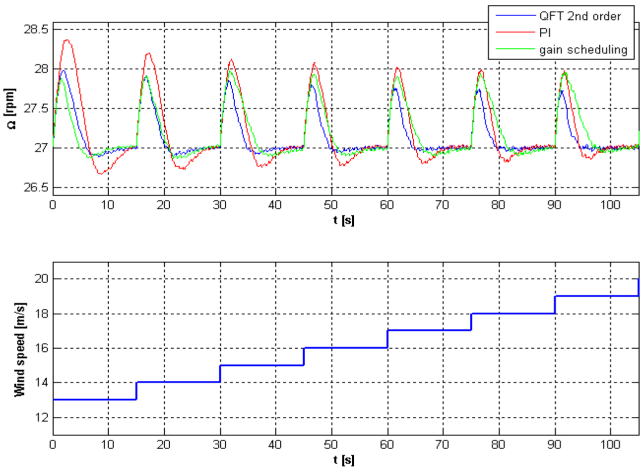

Figure 7 : Comparison of QFT, PI and PI gain-scheduled controller for wind speed range between 12 m/s and 19m/s

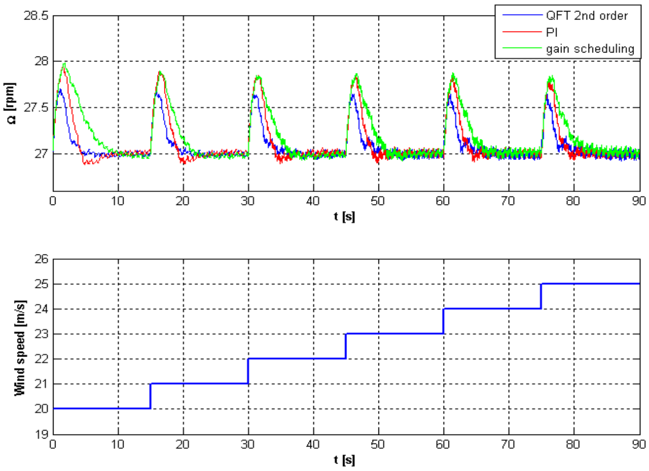

Figure 8 : Comparison of QFT, PI and PI gain-scheduled controller for wind speed range between 19 m/s and 25 m/s

5. Conclusion

In this paper application of QFT to wind turbine control problem is described. QFT proved to be a very adequate method for synthesis of rotor speed controller that is capable of tackling existing variations in wind turbine dynamics. Compared to state of the art solutions for wind turbine control, QFT controller gives the rare ability to a priori address the process uncertainty (due to change in operation point and neglected higher order wind turbine dynamics) and a priori guarantee fulfillment of specified closed loop behavior. Great results in utilization of QFT in wind turbine control system could have been expected since it has been very successfully integrated in helicopter and airplane control systems. Unlike many robust controllers that are of high order, in this case due to transparency of the QFT and its ability to explicitly address the uncertainty of wind turbine dynamics, a very efficient controller of second order was synthesized that requires no other aids (feedforward action, gain scheduling, etc.) to achieve specified closed loop behavior.

Acknowledgment:

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