QFT Report

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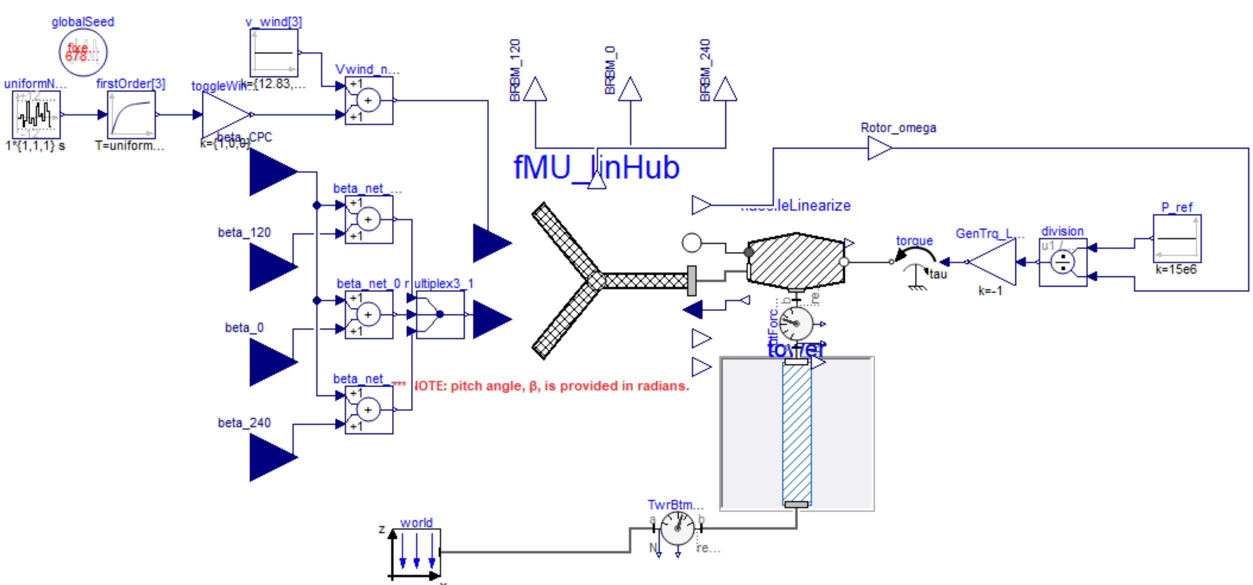
This report serves to describe the procedure taken in attempting to design a set of robust controllers for the FOWT MIMO system using the QFT framework. Three different approaches were taken; (1) Independent SISO controller design, (2) Method 1, and (3) Method 2, all of which are discussed in detail in Dr. Mario Garcia-Sanz book "Robust Control Engineering: Practical QFT Solutions (2017)".

Model Setup and Plant Generation

Before we can begin designing the controller us the QFT framework, we first need to generate a model of the plant along with the uncertainties associated with it. For this purpose, the FOCAL turbine model from within the CRAFTS platform was used. A specific model used for the QFT design was derived from the original, basic FOCAL turbine that was tested and verified thoroughly throughout campaigns 1 and 2 of phase I of the ARPA-e project.

This model was modified to accommodate for the desired I/O combination to be used in the QFT plant generation. For the inputs, 4 channels were selected: CPC and IPC 1-3. For the outputs, 4 channels were selected: RotSpd and BRBM 1-3. For the sake of simplicity, the generator torque (defined as $P_{ref}/RotSpd$) along with wind source were embedded within the model that is to be linearized. A screenshot of the model used can be found below.



The linearized model wind source was allowed to fluctuate between $12.83\ m/s$ and $14.11\ m/s$, maintaining the turbine operation strictly in regime 3. Similarly, the rotor speed (RotSpd) was initially set at $8.13\,rpm$ to ascertain that the turbine is operating in regime 3 at startup of the simulation.

To linearize the model, a Python script was developed that utilizes PyFMI as its base driver, a module developed by Modelon and published under "*Andersson, C, Åkesson, J & Führer, C 2016, PyFMI: A Python Package for Simulation of Coupled Dynamic Models with the Functional Mock-up Interface. Technical Report in Mathematical Sciences, nr. 2, vol. 2016, vol. LUTFNA-5008-2016, Centre for Mathematical Sciences, Lund University*".

The use of PyFMI allowed for the creation of a script that automates varying model parameters and the linearization of the generated FMU corresponding to the FOCAL model. For the plant uncertainty, the azimuth angle (Ψ) was chosen as the parameter to be varied, starting from $0°$ through $360°$, stepping in $30°$ increments such that $\Psi \in [0, 30, 60, \ldots, 330, 360)$, yielding 12 distinct plants.

<u>Independent 4x4 MIMO Model (Chapter 8, Example 8.1, Page 186 – 192)</u>

In this approach, we deal with the MIMO system as a set of 4x4 independent SISO systems. This facilitates the design of the controller by sacrificing performance and allowing interactions across all channels due to coupling. A practical approach to finding I/O pairing is by using the RGA matrix defined as $\Lambda = P_0 \otimes (P_0^{-1})^T$, where P_0 is the $n \times n$ nominal plant at steady-state $(\omega = 0)$ which is chosen to be the plant at $\Psi = 0°$ and the operator $\otimes$ denotes element-wise multiplication (also known as Hadamard or Schur product). Ideally, the I/O pairing corresponds to the elements of the RGA matrix closest to one.

```
%   Example:
%                                          _   u1      u2      u3   _
%                                         |  0.3180  0.0195  0.6630  | y1
%       Λ_0 = P(s=0) .* (P(s=0)^-1)^T =  |  0.6820  0.0091  0.3090  | y2
%                                         |_    0    0.9710  0.0287 _| y3
%
%   According to RGA matrix, pairing is:
%       ( u1, y2 ) --- ( u2, y3 ) --- ( u3, y1 )
%
```

However, for the sake of simplicity and due to symmetry the I/O channels IPC 1-3 were assigned to BRBM 1-3 and CPC to RotSpd, respectively. This pairing allowed for the successful generation of 2 controllers, the first corresponding to CPC – RotSpd channel and the second corresponding to IPC 1 – BRBM 1 channel. Due to symmetry, one would believe that the transfer functions (TF) relating IPC 1-3 – BRBM 1-3 are similar, however, for some peculiar reason the TFs relating IPC 2-3 – BRBM 2-3 are similar to one other but different from IPC 1 – BRBM 1. As can be seen in the TFs listed below, all TFs share the same poles with one complex pole pair in the right half plane (RHP). One distinction is that IPC 1 – BRBM 1 has no zeros in the RHP while IPC 2-3 – BRBM 2-3 both have a zero in the RHP.

$$\frac{BRBM\ 1}{IPC\ 1} = \frac{-1.46 \times 10^8\ (s + 1.94 \times 10^4)\ (s + 6.69)\ (s\text{^}2\ +\ 0.002164s\ +\ 0.783 \times 10^{-4})}{(s\text{^}2\ -\ 0.007471s\ +\ 1.50 \times 10^{-5})\ (s\text{^}2\ +\ 692.2s\ +\ 1.59 \times 10^5)}$$

$$\frac{BRBM\ 2}{IPC\ 2} = \frac{-1.19 \times 10^8\ (s + 2.37 \times 10^4)\ (s + 6.99)\ (s - 0.007687)\ (s + 20.08 \times 10^{-4})}{(s\text{^}2\ -\ 0.007471s\ +\ 1.50 \times 10^{-5})\ (s\text{^}2\ +\ 692.2s\ +\ 1.59 \times 10^5)}$$

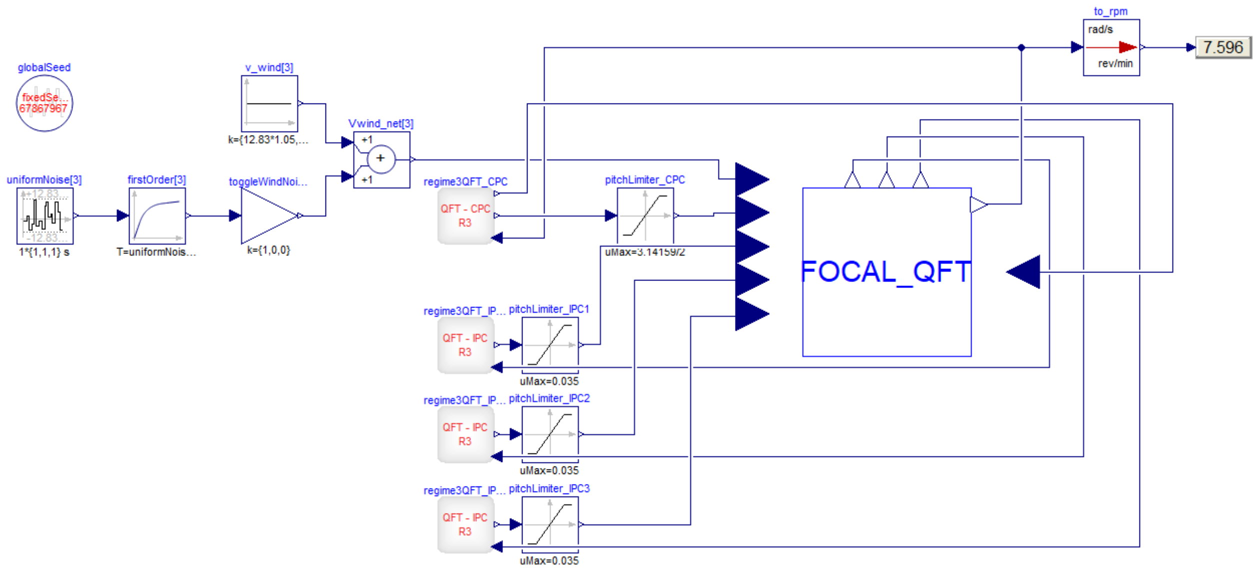
$$\frac{BRBM\ 3}{IPC\ 3} = \frac{-1.10 \times 10^8\ (s + 2.56 \times 10^4)\ (s + 7.619)\ (s - 0.01076)\ (s + 9.17 \times 10^{-4})}{(s\text{^}2\ -\ 0.007471s\ +\ 1.50 \times 10^{-5})\ (s\text{^}2\ +\ 692.2s\ +\ 1.59 \times 10^5)}$$

Nonetheless, due to the existence of theoretical symmetry, the controller designed for IPC 1 – BRBM 1 was also used for IPC 2-3 – BRBM 2-3. The controllers that were designed have the form of

$$g_{11}(s) = \frac{-1.2075\ (s + 45.24)\ (s + 0.115)}{(s + 4.783)\ (s + 0.7157)\ (s + 0.06003)}$$

$$g_{22,33,44}(s) = \frac{5.14 \times 10^{-11}\ (s - 7.755)}{(s + 0.2776)\ (s + 0.001436)}$$

where the controller $g_{11}(s)$ corresponds to the CPC – RotSpd channel, and the controller $g_{22,33,44}(s)$ corresponds to the IPC 1-3 – BRBM 1-3 channels. Furthermore, the controller $g_{11}(s)$ was saturated at $\beta_{CPC} \in [0,\ \pi/2]\ rad/s$ while the controllers $g_{22,33,44}(s)$ were limited to operate in the range of $\beta_{IPC} \in [-0.035,\ 0.035]\ rad/s$. An illustration of the simulated model can be found in the image below.



Note that for simulation purposes, the wind source was moved outside of the model. Running the Independent 4x4 SISO model (CPC+IPC) resulted in a 33% reduction of the BRBMs FFT signal when compared to the model with only CPC active.

<u>Method 1 4x4 MIMO Model (Chapter 8, Example 8.1, Page 240 – 248)</u>

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<u>Method 2 4x4 MIMO Model (Chapter 8, Example 8.1, Page 248 – 259)</u>

W.I.P

NOTE: Will add specifications used in the continuation of this report.