Case Study 11: **LQG Control of WECS with Flexible Drive Train Using the 2LFSP structure**

This case study contains an application implementing the optimal control structure designed according to the frequency separation principle on a flexible drive-train based WECS. This control structure contains two loops, one dealing with the low-frequency (LF) evolutions of system variables (LFL), and the other one processing the high-frequency (HF) components of the system variables (HFL). The optimization target requires restraining the operating point position around a certain domain including ORC, but the minimization of the total fatigue loads exerted on the drive train (electromagnetic and wind torque) variation is also envisaged. This trade-off is expressed by a linear quadratic performance index; the two contradictory requirements are weighted using the coefficient α. The application can be split into two parts. The main (first) part uses the mdl-file named `flexible_2LPSF_ctrl.mdl`, implementing the control, and three m-files `lin_param_comp.m`, `LQR_comp.m` and `estimator_comp.m`, serving for determining the linearized system parameters, the LQG controller components and the state estimator parameters, respectively. The second part implements the filtering and prediction method for obtaining the LF wind speed component (see Section 6.3.3 of the textbook) and uses the `LFwind_prediction.m` file and associated data (in file `vwind.mat`). All these are briefly described below.

Scope:

I: Generation of the LQG control and state estimator parameters and assessment by numerical simulation of the two-loop optimal control structure applied on the flexible-drive-train-based WECS.

II: To obtain the LF component of the wind velocity by using a reduced-order low-pass filter and an ARMA-based predictor. This ensures a smaller time lag of the LF wind component than the one issued by simple low-pass filtering.

Application analysis: The file `data_flexible_2LFSP.m` contains the system data. The mdl-file is organized as follows. The plant is placed at the right, the controller blocks are below the plant. One of them contains the control structure and the other one performs the splitting of the frequency ranges. The wind generator, situated upper-central, uses a pre-computed non-stationary wind velocity sequence (from file `vinti.mat`). In the upper-left corner one can see, from up to down: the system data loading button, the linearized system parameter computation (around a steady-state operating point corresponding to the ORC for a certain LF wind speed value), the LQG control components computation, the scopes and some computation/display blocks. The electromagnetic system within the plant is simplified, its dynamic behaviour being approximated to that of a first-order element having t_g as time constant. The block named `LF-HF splitter / adder` contains the wind velocity, rotational speed and electromagnetic torque identification of their low- and high- frequency components; the start-up sequence also is handled here. The LF sequence used for driving the LFL is issued from a low-pass filtering and ARMA prediction procedure (see Section 6.3.3 of the textbook). The block named `2LFSP control` contains the LFL and HFL control structures, based on PI and LQ controllers, respectively. The HFL scheme contains the HF model state estimator, also.

Running the application:

Target I – analysis of the 2LFSP control structure (uses the mdl-file)

A: **Computation** of the linearized model parameters and LQ controller

Step 1: Load system parameters (WECS data).

Step 2: Compute the linearized (HF) system parameters around a certain steady-state wind velocity (double-click on the appropriate block runs the script-file `lin_param_comp.m`). The HF model parameters can be viewed in the command window and will be automatically employed in the HFL. Compute the state estimator parameters (vector `L`) for the obtained HF model by double-click on the associated block (the file is `estimator_comp.m`).

Step 3: Compute the LQ controller parameters for a certain weighting parameter (double-click on the appropriate block runs the script-file `LQR_comp.m`). The controller parameters (vector `K`) can be viewed in the command window and will be automatically employed in the HFL.

B: 2LFSP **assessment**

Step 1: Run part **A** of the application. Consider a value of the average wind velocity, `wind_st` (say 7.5 m/s), and a value of the weighting coefficient, α (the variable `weight` – say 10).

Step 2: Select from the menu “Simulation → Parameters” a convenient time horizon and proceed with the simulation (say 1800 s).

Step 3: Dynamical system behaviour can be overviewed by opening the scopes (upper-left corner of the application file). Operating point position and/or its deviation around the ORC can be seen directly on the XY scope or can be plotted using the LSS mechanical power and rotational speed data (vectors `pwrl` and `omgl`) saved in the workspace from the associated scopes. Check the control performance by opening the tip speed (`lam`) (or else the power coefficient – `cp`) scopes and the scope visualizing the total HF efforts that induce fatigue loads on the drive train (the sum of mechanical torques, `sum_Trq`). These are the two terms of the quadratic performance criterion and should be antagonistic. This means that if the tip speed variance is small, the total HF effort variations around its average value is large (this takes place for large α). The HF variations of the control input, `HF_emT`, of total HF efforts, `sum_Trq`, and of the tip speed ratio, `HF_lam`, can be visualized and assessed separately (*e.g.*, by computing their histograms or their FFTs).

Step 4: Restart from *Step* 1. Run only *Step* 2 and *Step* 3 of part **A** using a new value of the weighting coefficient, α.

Step 5: Compare the standard deviation of the HF tip speed ratio and of the HF component of the mechanical effort for different values of α; the operating point dispersion around ORC should also be analyzed.

Step 6: Change the value of the steady-state wind speed, `wind_st` (restart from *Step* 1), and compare the control law efficiency for the same wind velocity sequence and for the same weighting coefficient, `weight`.

Remarks: During its start-up the system works at zero electromagnetic torque; after few moments, the reference automatically switches to the one issued from the 2LFSP control algorithm. The start-up signal is activated when the rotational speed exceeds a certain value and has been filtered to ensure smoother control changes (only during the system start-up). The start-up strategy can be changed by the user, if desired.

The operating point dispersion around ORC – visualized on the XY scope – makes the simulation to run slow; therefore, it may be better to plot the operating point evolution by using the program sequence:

```
figure; hold on;                  % actual power & speed versus optimal ones
plot(omgl(:,2),pwrl(:,2),'g'); plot(omg_opt(:,2),Popt(:,2),'k')
```

The performance of the control structure is related on various factors, listed bellow.

The state estimator related to the HF model (see `estimator_comp.m` file) must be fast. One must ensure that the states reconstruction is sufficiently good in dynamic conditions (for turbulent winds) – see scopes associated to `state1` – `state4` in the block labelled `Supplementary Computations & Displays`. The estimator dynamics can be adjusted by imposing the poles position. Please note that not all the combinations are possible, since parameters `L` can result as complex numbers.

The drive train must be sufficiently flexible, which requires careful choice of the stiffness and damping, *i.e.*, parameters `Ks` and `Bs` (if they are not known). The wind sequence chosen for tests must excite the flexible coupling such that the LSS and HSS instantaneous rotational speeds to result not equal. See, for example, scopes labelled `total speeds` or `HF speeds` in block `Supplementary Computations & Displays`. This is why in the wind speed generator structure additional turbulence has been used. In order to obtain a more relevant effect, reiterate the simulation with other values of `Ks` and `Bs`, for example $K_S = 50$ Nm/rad and $B_S = 0.1$ kgm^2/s. Use the "no turbulence" position of the switch in the wind generator to obtain the variable evolutions presented in the textbook.

When changing the weighting coefficient only the re-computation of the LQ controller, `K`, is necessary. The structure in the mdl-file has been tested for $\alpha \in [0.2;\ 500]$.

Changing the steady-state value of the wind speed (`wind_st`) requires the re-computation of the state estimator, `L`.

Target II – the LF wind velocity component synthesis for driving the LFL (uses the file `LFwind_prediction.m`)

Step 1: Read the comments in the file `LFwind_prediction.m`. The file to be processed, `vwind.mat.m`, contains a three-row matrix, `v`, having: the time in the first row, the total wind velocity on the second row and the LF wind velocity component obtained by low-pass filtering in the third row. The file is split in 3 parts: initialization, prediction iteration and presentation of results.

Step 2: Run the file and wait about 20 seconds.

Step 3: The results are shown on 5 figures. Compare the lag of the predicted LF wind velocity evolution with the one characterizing the LF wind speed obtained by low-pass filtering.

Remarks: The obtained LF wind velocity component can be used within the file `flexible_2LPSF_ctrl.mdl`, provided that the initial total wind sequence is applied to the concerned WECS.