Course:
ELEC ENG 3110 Electric Power Systems
ELEC ENG 7074 Power Systems PG

(Semester 2, 2021)

Assignment 2:
Power System Frequency Control

(Due 23:00 Fri. 29 October 2021
Electronic Submission)

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Investigation of power system frequency control using simplified models.

The objective of this assignment is to investigate some aspects of power system frequency control using simplified models. The investigation is intended to provide conceptual insights only. The models are not necessarily optimized to yield the best frequency control performance. The Mathworks Simulink program, which is a companion of Matlab, will be employed to build and simulate dynamic models of the systems. Thus, the assignment will also provide an opportunity for you to become familiar with a very widely used tool for simulating dynamic systems.

The deliverable outcome is to be an engineering report that clearly and concisely details the conduct and findings of your investigation and clear and pointed discussion of the technical and engineering significance of your findings. The report should address each of the matters and questions listed in the scope of work in Section 3. Credit will be given for innovative studies and analysis that either reveal other aspects of system performance or which improve the performance of the system.

It is recommended that you follow the guidelines for writing technical engineering reports produced by Monash University and which are available at the following web-site:
https://www.monash.edu/rlo/assignment-samples/engineering/eng-writing-technical-reports

With reference to the above guidelines your report is expected to convey information to other engineers about key aspects of the performance of the system and it is intended for selective reading. The latter point means that you should organize your report into sections with informative headings.

It is strongly recommend that you approach this assignment in the same way as you would as a professional engineer conducting the project for an employer or client.

Introductory analysis is presented in Section 1 to assist in the systematic formulation of the frequency control model.

1 Introductory Analysis

The objective is to explore the performance of the system frequency control system as the mix of generation sources is varied. We are interested in assessing performance for different proportions of synchronous and asynchronous generation and how the performance of the frequency control system performs as different proportions of generation capacity are equipped with primary frequency control. The overall structure of the system model is shown in Figure 1. In this model the equivalent generator model represents the effective inertial response of the system taking into consideration that a proportion of the generation is asynchronous. A proportion of both the synchronous and asynchronous generation sources are not equipped with frequency controls and therefore do not contribute to the control of system frequency. A proportion of synchronous sources are equipped with governors which control the speed of their generators and a proportion of asynchronous sources are also equipped with frequency controllers that are used to regulate their power output so as to control system frequency.

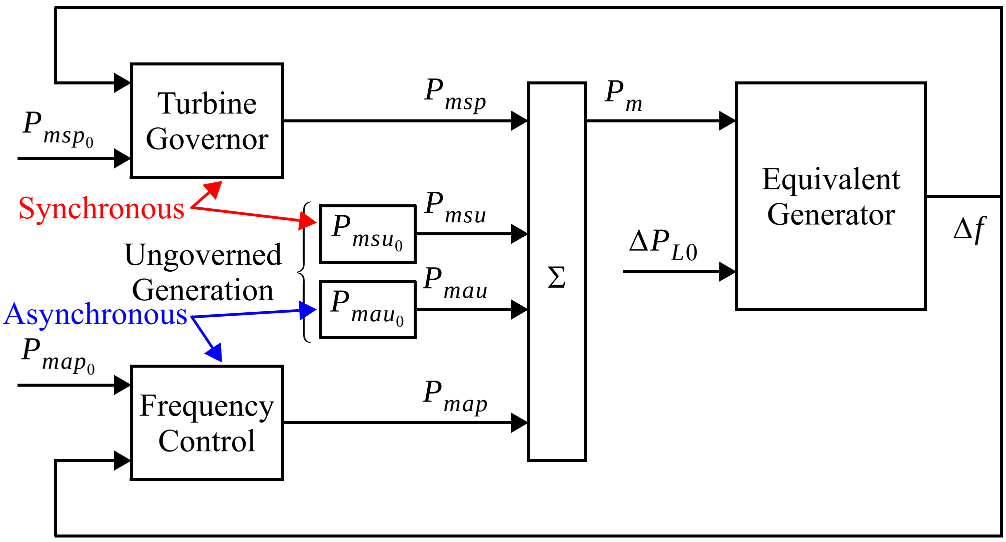

Figure 1: Simplified model of system frequency control containing synchronous and asynchronous sources. (Note that blocks with no input signal represent a fixed or constant input to the model with the value shown in the block.)

1.1 Per-unit scaling and specification of generation capacities

We will use the *total online generation capacity* (S_b in MW) as the base value of power. Thus, a power system load, P_l, of 0.8 per-unit means that the system is consuming 80% of the rated on-line generation capacity. (Note: We will see below that it is not necessary to specify the actual value of S_b).

To facilitate this exploration the total online generation capacity is divided into a number of components.

$$S_b = S_{sb} + S_{ab} \tag{1}$$

where S_{sb} and S_{ab} are respectively the online synchronous and online non-synchronous (or asynchronous) generation capacity.

$$S_{sb} = \alpha_{sb} S_b \text{ and } S_{ab} = (1 - \alpha_{sb}) S_b \tag{2}$$

where α_{sb} is the specified proportion of the total online generation capacity which is synchronous.

The online synchronous generation capacity is then partitioned into the following components:

$$S_{sb} = S_{spb} + S_{sub} \text{ where} \tag{3}$$

$$S_{spb} = \alpha_{spb} S_{sb} = \alpha_{spb} \alpha_{sb} S_b \text{ and } S_{sub} = (1 - \alpha_{spb}) S_{sb} = (1 - \alpha_{spb}) \alpha_{sb} S_b \tag{4}$$

are respectively the proportion of online synchronous generation capacity with primary governing control and the balance of online synchronous generation capacity is ungoverned.

The online asynchronous generation capacity is similarly partitioned into a fraction with primary governing control, S_{apb}, and the balance of asynchronous generation which is ungoverned, S_{aub}, where:

$$S_{ab} = S_{apb} + S_{aub} \text{ and} \tag{5}$$

$$\begin{aligned} S_{apb} &= \alpha_{apb} S_{ab} = \alpha_{apb}(1-\alpha_{sb})S_b \\ S_{aub} &= (1-\alpha_{apb})S_{ab} = (1-\alpha_{apb})(1-\alpha_{sb})S_b \end{aligned} \tag{6}$$

Thus, to define the online capacities of the different types of generation represented in our model the parameters α_{sb}, α_{spb} and α_{apb} must be specified.

For example, if $\alpha_{sb} = 0.8$ then 80% of all online generation capacity is synchronous and the balance $1-\alpha_{sb} = 0.2$ (i.e. 20%) is asynchronous. If $\alpha_{spb} = 0.4$ then 40% of the online synchronous generation capacity is under primary frequency control and the balance of such generation (i.e. 60%) is not under frequency control. In this example it means that $\alpha_{sb} \times \alpha_{spb} = 0.8 \times 0.4 = 0.32$ or just 32% of all online capacity is under primary frequency control.

1.2 Specification of the initial generation output

In this model we specify the initial power output from each of the generation sources. On the basis of this specification the initial system load is determined, on the assumption that the system is lossless.

The initial power output from the online synchronous generation with primary speed control is specified as a fraction β_{sp} of the specified online capacity S_{spb} of this type of generation. The initial power output is expressed in per-unit of S_b.

$$P_{msp_0} = \beta_{sp}\left(\frac{S_{spb}}{S_b}\right) = \beta_{sp}\left(\frac{\alpha_{spb}S_{sb}}{S_b}\right) = \beta_{sp}(\alpha_{spb}\alpha_{sb}) \text{ in pu of } S_b \tag{7}$$

The initial output from the other types of generation are similarly specified as follows:

$$\begin{aligned} P_{msu_0} &= \beta_{su}(1-\alpha_{spb})\alpha_{sb} \\ P_{map_0} &= \beta_{ap}\alpha_{apb}(1-\alpha_{sb}) \qquad \text{pu on } S_b. \\ P_{mau_0} &= \beta_{au}(1-\alpha_{apb})(1-\alpha_{sb}) \end{aligned} \tag{8}$$

The initial power output from the synchronous generation sources is:

$$P_{ms_0} = P_{msp_0} + P_{msu_0} \tag{9}$$

and the initial power output from the asynchronous generation sources is:

$$P_{ma_0} = P_{map_0} + P_{mau_0} \tag{10}$$

and finally, the initial output from all generation sources is,

$$P_{m_0} = P_{ms_0} + P_{ma_0}. \tag{11}$$

Thus, to define the initial steady-state operating point of the system it is necessary to specify β_{sp}, β_{su}, β_{ap} and β_{au}.

It is important to distinguish between online capacity of the various generation categories and the actual (initial) power output from each of these generation categories. Thus, if, for example, $\beta_{sp} = 0.5$ then it means that initially the power output of the online synchronous generation capacity that is under primary frequency control is 50%. If, furthermore, $\alpha_b = 0.8$ and $\alpha_{spb} = 0.4$ it follows that the initial power output from all online synchronous generation capacity that is under primary frequency control is:
$P_{msp_0} = \beta_{sp}(\alpha_{spb}\alpha_b) = 0.5 \times (0.8 \times 0.4) = 0.16$ pu of S_b.

1.3 Equivalent generator rotor dynamics

The transfer-function block diagram of the equivalent generator of the system is shown in Figure 2.

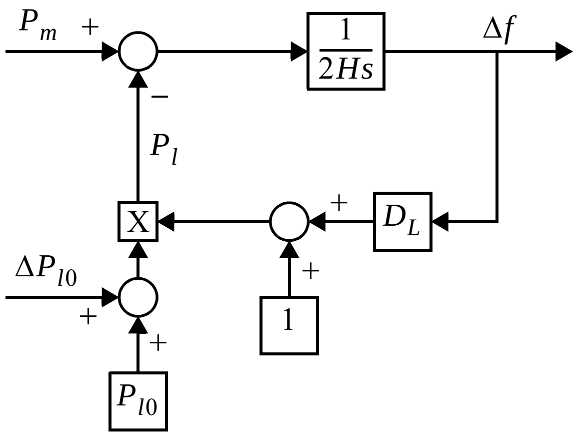

Figure 2: Equivalent generator rotor dynamics for system load / frequency analysis.

1.3.1 Specification of the inertia constant

The inertia constant of online synchronous generation limits the rate of change of frequency. In the model we specify the inertia constant, H_s, in per-unit of the on-line synchronous generation capacity. Typically, $H_s = 3.5$ pu on S_{sb}.

For use in the model this inertia constant must be converted to per-unit on S_b. Thus,

$$H = H_s\left(\frac{S_{sb}}{S_b}\right) = \alpha_{sb}H_s \tag{12}$$

1.3.2 Frequency dependent load

The system load is linearly dependent on the system-frequency perturbation as follows

$$P_l(f) = P_{l_0}(1 + D\Delta f) \tag{13}$$

where $f = (1 + \Delta f)$ pu is the system frequency in per-unit of the system nominal synchronous frequency, $f_0 = 50$ Hz, Δf is the per-unit perturbation of the system frequency and P_{l_0} is the initial steady-state value of the load. Note that under initial steady-state conditions the system is operating at synchronous frequency, i.e. $\Delta f_0 = 0$ pu.

1.3.3 Composite rotor equation of motion for the analysis of system-frequency controls

The acceleration equation of the system is, as detailed in the lectures,

$$2H\frac{d\Delta f}{dt} = P_m - P_l \text{ in pu of } S_b \tag{14}$$

where P_m and P_l are respectively the generation and load, Δf is the per-unit system-frequency perturbation and H is as defined in (12). The block diagram of this equation, including the frequency dependence of the load, is shown in Figure 2.

1.4 Synchronous generator turbine-governor model

The block diagram of the synchronous generator turbine governor system employed in the assignment is shown in Figure 3. This block diagram shows the conversion from per-unit quantities on the system MVA base, S_b, at the input and output from the model to per-unit quantities on the turbine rated capacity, S_{spb}, within the turbine-governor model. The block diagrams of the governor and turbine models are shown respectively in Figures 4 and 5. The turbine model is representative of a steam turbine which is presently the most commonly deployed turbine in Australia.

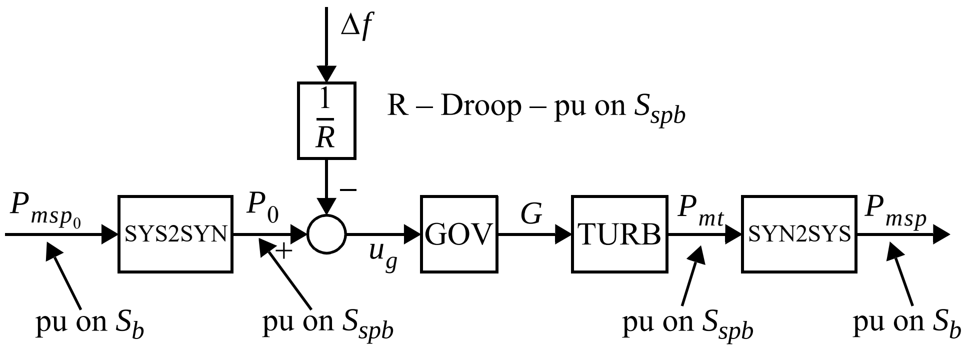

Figure 3: Synchronous generator turbine-governor model including base conversions at the turbine / governor model interfaces. (Note: Pref = Pmsp0 is the turbine load reference and is represented as an external input. In Simulink such an external input can be represented as a constant block).

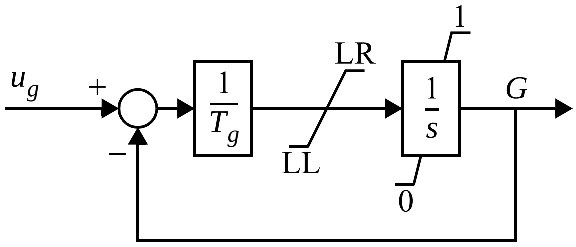

Figure 4: Governor model (i.e. the block GOV in Figure 3).

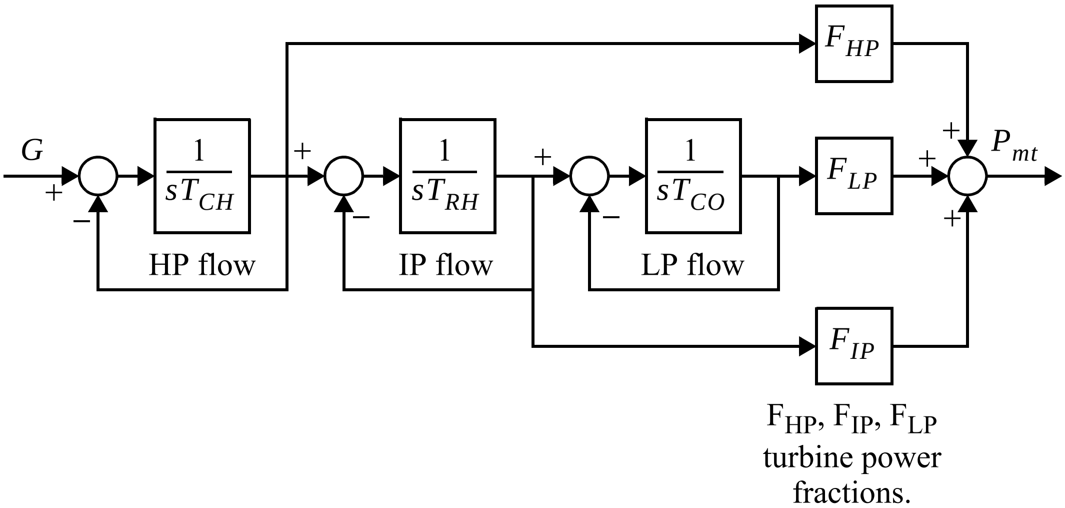

Figure 5: Turbine model (i.e. the block TURB in Figure 3).

1.5 Simulink Model

A Simulink model and associated Matlab driver software of the system in Figure 1 is provided as an input to the assignment as listed in Table 1. The provided model does not include the asynchronous-generation frequency control system. A key task in this assignment is to implement and assess the performance of an asynchronous control system.

Table 1: Simulink and Matlab files

File	Description
FrequencyControlSystem.slx	Simulink implementation of the frequency control system in Figure 1 except that the asynchronous-generation frequency control system is omitted.
FrequencyControlSystem_SimDriver.m	This Matlab m-file contains a Matlab function that can be used and adapted to drive the Simulink model programmatically.
FCS_01.m	This Matlab script demonstrates how to set up the frequency control system model and to run a simulation using the above driver.

2 Getting started with Simulink

The University makes Matlab and Simulink licences available to students as described at https://www.adelaide.edu.au/technology/your-services/software/software-for-students#matlab

Mathworks, the company that provides Matlab and Simulink, provide a number of getting started resources. The following may be useful:

- A listing of getting started resources is available at https://au.mathworks.com/help/simulink/getting-started-with-simulink.html
- A text based overview and introduction to the Simulink program is available at: https://www.mathworks.com/help/pdf_doc/simulink/sl_gs.pdf

The assignment includes a Simulink model and associated Matlab driver software which can be used as a good basis for developing skills in using Matlab and Simulink. To run the simulation specified in the FCS_01.m script.

3 Scope of work

3.1 Base case parameters

The system parameters for the base case model are listed in Table 2. In subsequent sections parameters are specified as variations of this set of base case parameters. In this base case all online generation is synchronous (i.e. there is no asynchronous generation). All online synchronous generation capacity is governing and is loaded to 80% of its capacity.

Table 2: Base case model parameters

Parameter	Value	Parameter	Value	Parameter	Value
Capacity fractions					
α_{sb}	1.0	α_{spb}	1.0	α_{apb}	0.0
Load fractions					
β_{sp}	0.8	β_{ap}	0.8		
β_{su}	0.8	β_{au}	0.8		
Equivalent generator parameters					
H_s	3.5	D	1.0		
Turbine / governor model parameters					
R	0.05	T_g (s)	0.3	LR (pu/s)	0.1
LL (pu/s)	-1.0	T_{CH} (s)	0.3	T_{RH} (s)	7.0
T_{CO} (s)	0.5	F_{HP}	0.3	F_{IP}	0.3
F_{LP}	0.4				

3.2 Ungoverned frequency response

Suppose the system is not equipped with any frequency control system. The change in frequency is then limited only by the frequency sensitivity of the loads.

Setup the model with its base case parameters in Table 2 and then set $\alpha_{spb} = 0$ so that there will be no frequency control. Calculate the response of the system to a step increase in the load of $\Delta P_{L0} = 0.02$ pu.

Plot and discuss the response of the system frequency. Conduct mathematical analysis to verify that the initial rate of change of frequency and the final frequency obtained from the model response is correct.

3.3 Synchronous only system with governors.

The objective in this section is to use the Simulink model provided to analyse the frequency control performance of the base case system and verify that its performance accords with theoretical expectations.

Using the base case model perform a simulation in which a step increase in the load of $\Delta P_L = 0.02$ pu is applied.

Based on your knowledge of the steady-state behaviour of governors with a steady-state droop characteristic what do you expect the final frequency deviation Δf_f to be after the application of the step-change in load. Ensure that you also include the frequency dependence of the system load. How does your expectation compare with the final steady-state frequency from your Simulink study?

What is the initial rate-of-change-of-frequency (RoCoF) from your Simulink study? How does this compare with what you expect from a mathematical analysis of the model? (Note that the initial RoCoF due to a step-change in load is not influenced by the governor and turbine. Why?)

From the instant that the step is applied how long does it take for the system-frequency to settle to within 5% of its final value. This time is referred to as the 5% settling time of the response. If the final frequency deviation from nominal frequency is Δf_f then the 5% settling time is determined by the time taken for the frequency deviation to first fall within, and then remain within, the frequency band $\Delta f = (1 \pm 0.05)\Delta f_f$.

What is the maximum deviation in frequency Δf_{max} and at what time $t_{f_{max}}$ does it occur after the step is applied? (Note, Δf_{max} may be positive or negative).

Plot the responses of the turbine power output (P_{mt}), the frequency deviation (Δf) and the governor valve position (G).

3.4 Investigate factors that influence system frequency response – Governing by synchronous generators only.

Analysis in this section is based on the simplified model of the primary frequency control system of a power system in which frequency control is only performed with governors fitted to synchronous generators. The factors that influence the system-frequency response are investigated. Use, as a minimum, the following measures to assess the system-frequency response.

1. The final value of the frequency deviation, Δf_f.
2. The initial RoCoF.
3. The 5% settling-time of the system-frequency response.
4. The maximum frequency deviation (Δf_{max}) and the time ($t_{f_{max}}$), following the step, at which it occurs.

In this investigation the emphasis is on comparing these measures as certain parameters are varied.

The above performance measures are meaningful only if the system is stable. It is conceivable that the system will be unstable for some combinations of model parameters. If so you should clearly indicate in your report if a scenario is unstable and suggest reasons why.

At a minimum investigate the influence of the following factors on the system-frequency response to step-changes in the system load.

1. Starting with the base case, investigate the effect of varying the synchronous machine inertia constant, H_s, within the range from 1.0 to 6.0 pu.s on S_{sb}. Report your findings with emphasis on those performance factors most influenced by the variation in inertia. Explain the reasons for and engineering significance of your findings.
2. Starting with the base case, investigate the effect of varying the governor droop, R, within the range from 1.0 to 8.0 % on S_{spb}. Report your findings with emphasis on those performance factors most influenced by the variation in droop. Explain the reasons for and engineering significance of your findings.
3. Starting with the base case investigate the effect of reducing the proportion of online synchronous generation capacity from 100% (base case) in steps of 25% to 25%. Report on how this variation in capacity affects the system inertia constant H and the droop R when the latter parameters are expressed in per-unit on the system MVA base S_b. Adjust other capacity and loading fractions to keep the total system load equal to the base case value of 0.8 pu on S_b. Report your findings with emphasis on those performance factors most influenced by the variation in online synchronous generation capacity. Relate your findings in this section to your findings concerning the variation in inertia and the variation in droop. Explain the reasons for and engineering significance of your findings.

Carefully consider how you present the results of your studies. It is important that you use tables and figures that succinctly summarize the key findings of your studies. Importantly, overlaying responses from multiple studies helps to visualize the sensitivity of the system responses to parameter variations. Similarly, summarizing in a single table the variation in performance metrics due to variation in system parameters aids interpretation.

You are encouraged to similarly investigate the effect on the system-frequency response of varying other model parameters such as the following.

1. The size and direction of the step change in load.
2. The proportion of synchronous generation that is under primary frequency control.
3. The proportion of load supplied from synchronous sources.

3.5 Modelling of asynchronous frequency control.

In this section you will extend the Simulink model to include a model of an asynchronous source (SRC) that is equipped with a frequency controller (FC) as shown in Figure 6. The asynchronous source is assumed to have a much faster response than the steam turbines assumed to supply the synchronous generators. The asynchronous source could be, for example, an electrochemical battery or a solar PV source (in which "sun is spilled" to allow spare capacity for frequency control purposes.)

Extend the Simulink model of the frequency control system to include the model shown in Figure 6. The base case parameters of the frequency control system following the inclusion of asynchronous frequency control are listed in Table 3.

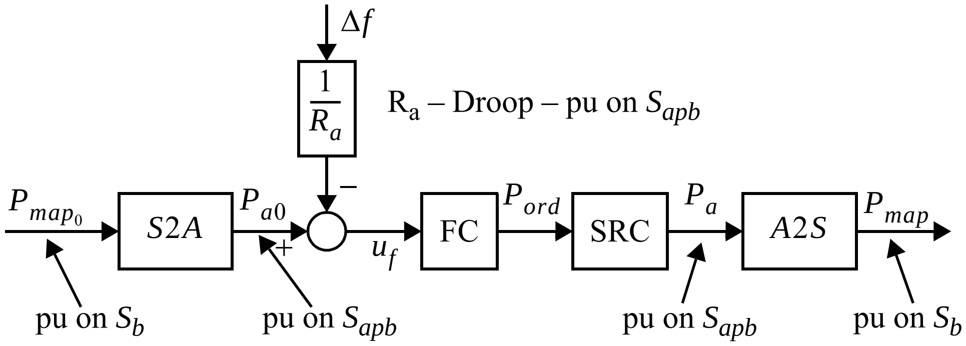

Figure 6: Asynchronous generator frequency-control model including base conversions at the frequency-control model interfaces. (Note: (i) S2A is the conversion factor to convert power from a power base of S_b to a base of S_{apb}; (ii) (ii) A2S is the inverse conversion factor; and (iii) Pref = Pmap0 is the load reference of the asynchronous source and is represented as an external input. In Simulink such an external input can be represented as a constant block).

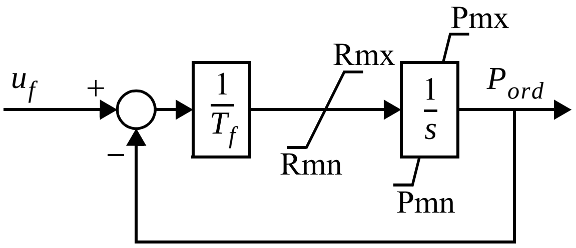

Figure 7: Frequency controller model (i.e. the block FC in Figure 6).

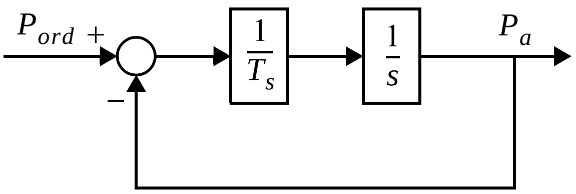

Figure 8: Asynchronous source model (i.e. the block SRC in Figure 6).

Table 3: Base case model parameters with asynchronous-generation frequency control included.

Parameter	Value	Parameter	Value	Parameter	Value
Capacity fractions					
α_{sb}	0.5	α_{spb}	1.0	α_{apb}	0.5
Load fractions					
β_{sp}	0.8	β_{ap}	0.8		
β_{su}	0.8	β_{au}	0.8		
Equivalent generator parameters					
H_s	3.5	D	1.0		
Turbine / governor model parameters					
R	0.05	T_g (s)	0.3	LR (pu/s)	0.1
LL (pu/s)	-1.0	T_{CH} (s)	0.3	T_{RH} (s)	7.0
T_{CO} (s)	0.5	F_{HP}	0.3	F_{IP}	0.3
F_{LP}	0.4				
Asynchronous source / frequency controller model parameters					
R_a	0.05	T_f (s)	0.1	R_{mx} (pu/s)	0.1
R_{mn} (pu/s)	-0.1	P_{mx} (pu)	1.0	P_{mn} (pu)	0.0
T_s (s)	0.08				

3.6 Investigate system frequency response of system with a mixture of synchronous and asynchronous frequency controls.

The objective is to investigate the system frequency response of the system with a mixture of synchronous and asynchronous frequency controls. The performance of the frequency response is to be assessed using the measures that were employed in Section 3.4. You should design a set of simulation tests that you expect to reveal interesting aspects of the frequency control performance of the system. To assist you the following table lists an initial set of tests which you should extend to consider additional factors. Discuss the results of each test with reference to theoretical considerations and compare the responses obtained with different combinations of parameters.

Table 4: Initial tests for investigating frequency control performance.
(The Parameters column lists those parameters that are changed from Table 3)

Test	Parameters	Purpose
C01	$\alpha_{sb} = 1, \alpha_{apb} = 0$	Base case with no asynchronous generation. Should yield same performance as in Section 3.3
C02		Base case with mixture of synchronous and asynchronous frequency control. Compare frequency responses from C01 and C02 and relate differences in behaviour to theory.
C03	$\alpha_{spb} = 0.5$	Reduce fraction of synchronous generation with governors enabled from 1.0 to 0.5. Compare with C01 and C02.
C04	$T_f = 1.0$ s	Assess effect of increasing frequency controller time constant from 0.1 to 1.0 s.

4 Factors considered in assessment

This assignment is structured as an engineering investigation and the assignment report will be assessed in that context.

It is strongly recommend that you approach this assignment in the same way as you would as a professional engineer conducting the project for an employer or client.

Thus assessment will consider:

(a) Completion of the scope of work.

(b) Report organization, brevity and clarity.

(c) Clarity and sophistication in explaining the engineering significance of the findings.

(d) Accurate, relevant and clear application of power system analysis principles to the scope of work.

(e) Accuracy and correctness of results.

(f) Skill in application of the Matlab and Simulink programs.