Faculty of Engineering, Computer and Mathematical Sciences

ELEC ENG 3110 Electric Power Systems

Assignment 2

Power System Frequency Control

By

Tianze Zhou   a1752810

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Summary

This is an assignment report that documents the frequency control analysis for a power system with mix of generation sources. Students are expected to conduct power system frequency control analysis with various operational procudures and methods to explore the frequency in affecting the stability of a power system and how to assess the preformance of a power system equipped with synchronous frequency control and asychronous frequency control. This practical based assignment empowers students of linking the basic frequency theory concepts to the frequency control simulation in Matlab Simulink.

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1. System Parameter

System parameters for base case tabulate on Table 1 that shows the value used for the base case model in Matlab programming script and Simulink simplified model.

Parameter	Value	Parameter	Value	Parameter	Value
Capacity Fraction					
a_{sb}	1.0	a_{spb}	1.0	a_{apb}	0.0
Load Fraction					
B_{sp}	0.8	B_{ap}	0.8		
B_{su}	0.8	B_{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				

Table 1: Parameter Table

List of Parameter Acronyms

a_{sb} : online synchronous generation capacity fraction

a_{spb}: online asynchronous generation capacity fraction

a_{apb}: online asynchronous generation capacity fraction

B_{sp}: Proportion of initial power output of the online synchronous generation capacity that is under frequency control

H_s: Inertia constant in per-unit of the online synchronous generation capacity

D: Load damping constant

R: Droop of synchronous machine turbine governor (pu)

2. Ungoverned Frequency Response

Ungoverned frequency response is to explore the change in frequency for the electric power system without equipping frequency control system. To achieve ungoverned frequency control, it is essential to reset the parameter value of a_{spb} to 0 so that there is no frequency control for the system.

In Matlab FCS_01.m File,

```
% Capacity fractions
base_problem.a_spb    =   0.0;
```

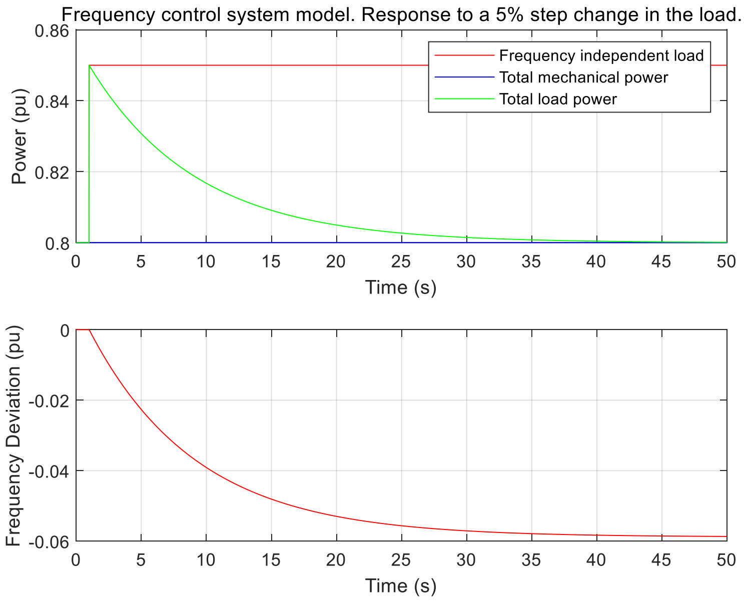

Figure 1: Ungoverned Frequency Control for the response of 5% change in the load

In the given Matlab demonstration, the step increase in the load was ΔP_{l0} = 0.05 pu, as shown in Figure 1. In this case, we are going to explore the situation of step increase with ΔP_{l0} = 0.02 pu. Thus, in Matlab FCS_01.m File, there needs to modify the parameter variable for *DPLStep* from 0.05 pu to 0.02 pu.

```
% Simulation parameters
base_problem.DPLStep = 0.02;
```

After adjusting the parameter value of `base_problem.DPLStep` in Matlab FCS_01.m File, the plot in figure 2 and figure 3 are shown the frequency control for the response of 2% change in the load in synchronous and asynchronous generations respectively. To calculate the response of the system to a step increase of ΔP_{l0} = 0.02 pu, the following equations and calculating steps are applied. Initial output from both asynchronous and synchronous generation sources can be calculated by

$$P_{m0} = P_{ms0} + P_{ma0}$$

$$= P_{msp0} + P_{msu0} + P_{map0} + P_{mau0}$$

$$= B_{sp}\left(\frac{S_{spb}}{S_b}\right) + B_{su}(1 - a_{spb}) * a_{sb} + B_{ap}a_{apb}(1 - a_{sb}) + B_{au}(1 - a_{apb})(1 - a_{sb})$$

$$= 0.8 * (1- 0) *1 = 0.8 \text{ pu}$$

From above calculation, P_{m0} has been identified as 0.8 pu as the initial power output from the generation. As ΔP_{l0} = 0.02 pu, then $P_l(f)$ is equal to initial power plus ΔP_{l0}. Frequency dependent condition is also applied to calculate the system response of the system towards a step increase in the load of ΔP_{l0} = 0.02 pu.

$$P_l(f) = P_{l0} * (1 + D * \Delta f) = 0.8001 \text{ pu}$$

$$= 0.82 * (1 + 1 * \Delta f) = 0.8001 \text{ pu}$$

$$\Delta f = (P_l(f) - P_{l0}) / (P_{l0} * D)$$

$$= \frac{0.8001 - 0.82}{0.82} = -0.02427 \text{ pu} \qquad (1)$$

$$f = (1-\Delta f) * 50 = (1- 0.02427) * 50 = 48.7865 \text{ Hz}$$

Therefore, Δf, the pre-unit deviation of the system frequency, is calculated as 0.025 pu. From the figure 2 below, the final frequency deviation is becoming steady and turning out to be a stable line, which has the frequency deviation of -0.02423pu as read from the labelled point on the plot of frequency deviation below.

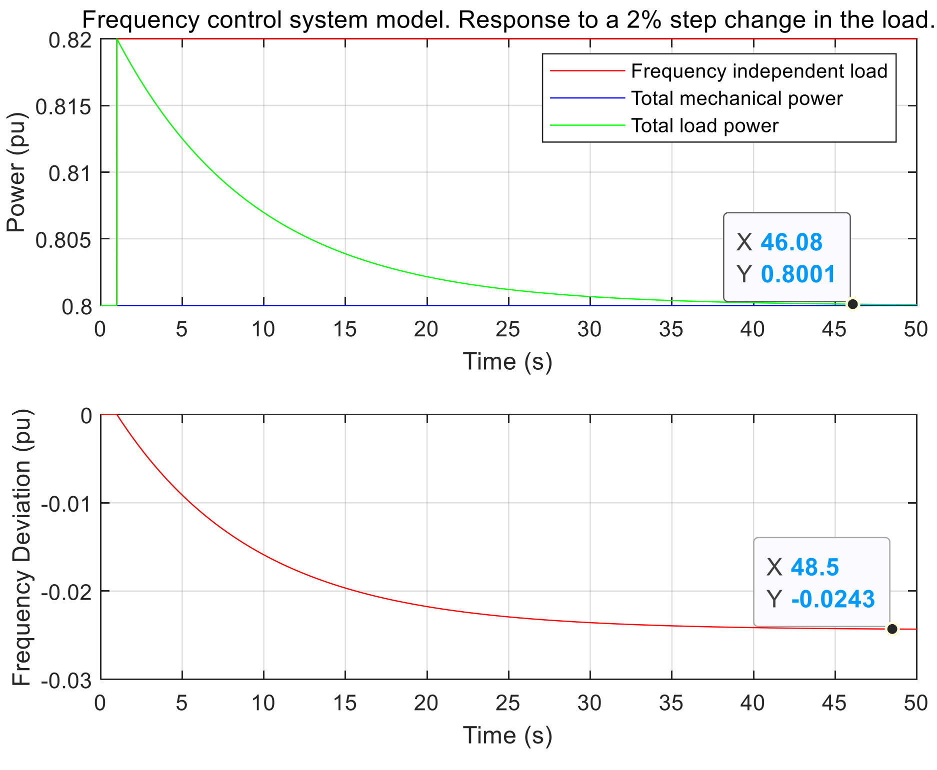

Figure 2: Ungoverned Frequency Control for the response of 2% change in the load in synchronous generation

From the Figure 2, the final frequency deviation of ungoverned frequency control obtained from the model response is -0. 0243 pu and equal to - 0.0243 * 50 = - 1.215 Hz. Thus, it can be verified the final frequency acquires from the system model response is correct as comparing with the final frequency results derived from mathematical analysis.

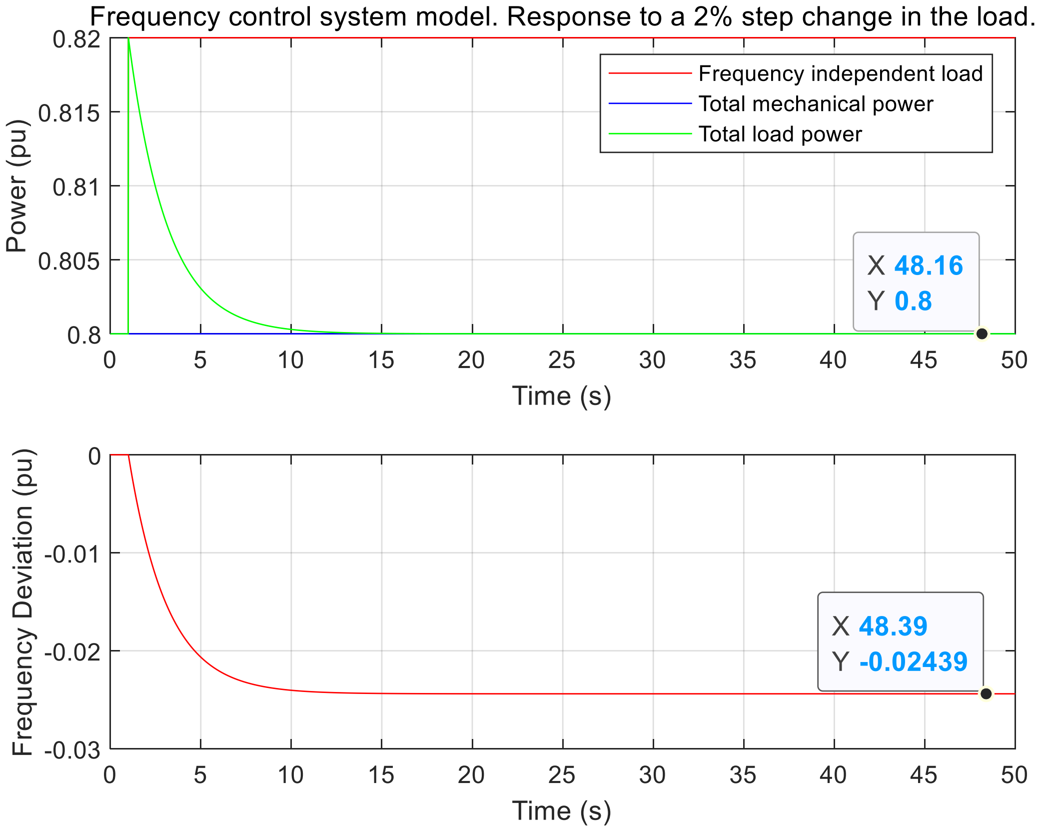

Figure 3: Ungoverned Frequency Control for the response of 2% change in the load in asynchronous generation

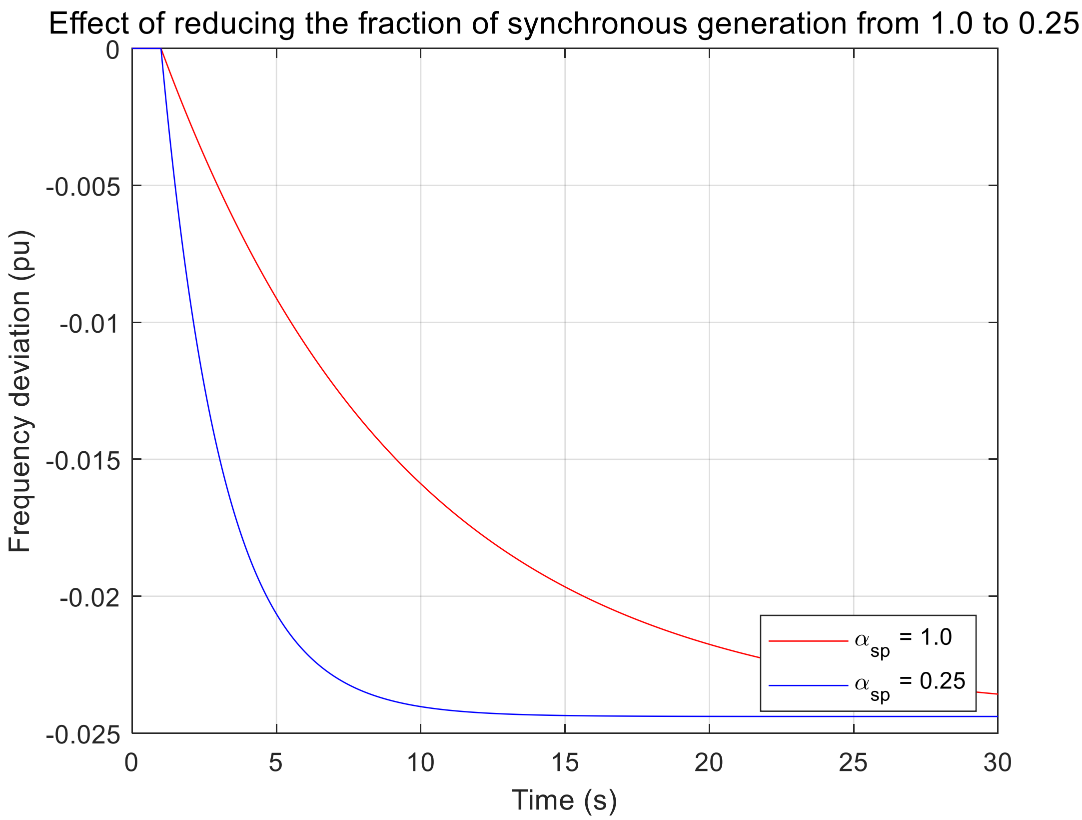

Figure 4: Effect of reducing the fraction of synchronous generation from 1.0 to 0.25

Initial rate of change of frequency can be calculated via the equation of

$$2 * \mathrm{Hs} * \frac{d\Delta f}{dt} = P_m - P_t$$

$$\frac{d\Delta f}{dt} = -\frac{P_m - P_t}{2*Hs}$$

$$= -\frac{P_m - P_t}{7}$$

$$= -\frac{0.82 - 0.82*(1-0.02439)}{7} = -2.857\ \mathrm{E}\ {-3}\ \mathrm{pu/s} \quad (2)$$

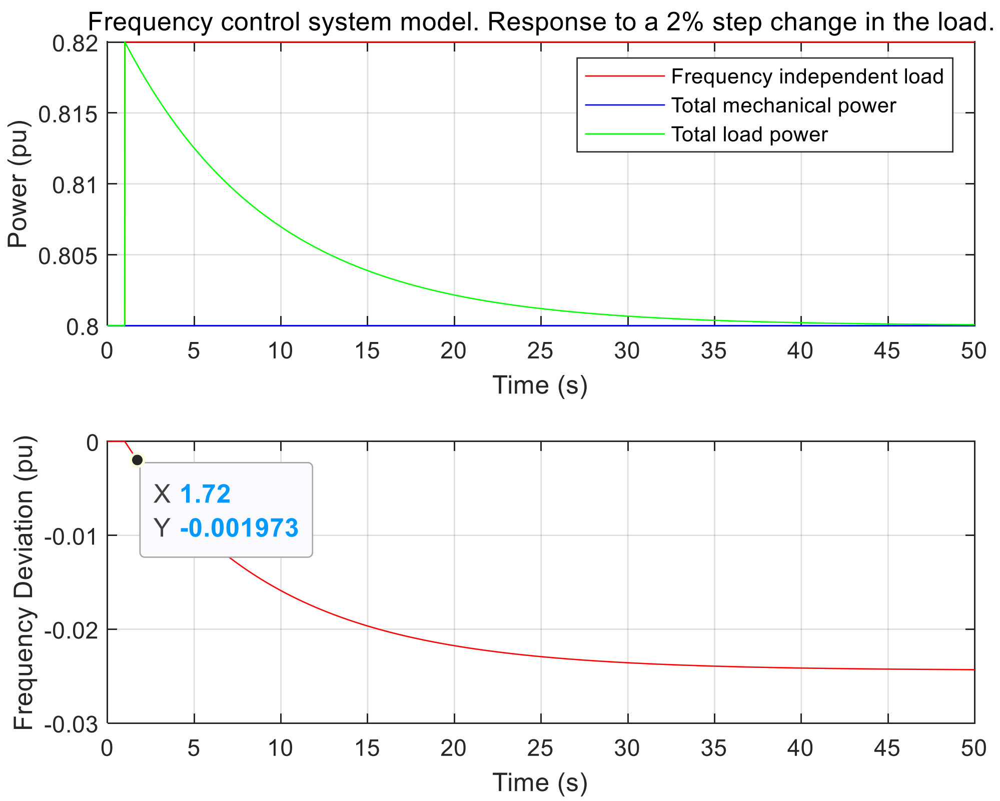

Figure 5: Initial RoCof Measurement

From the plot above (Figure 5), initial RoCof is identified as the initial drop of frequency deviation from 0. RoCof is the initial gradient of the frequency deviation curve drops from synchronous frequency.

$$\mathrm{RoCof} = \frac{0+0.001973}{1-1.72} = -2.74\ \mathrm{E}\text{-}3\ \mathrm{pu} \qquad (3)$$

Therefore, from equation (2) it can be verified that the initial rate of change of frequency obtained from system model response is correct as comparing with initial RoCof derived from the mathematical analysis.

3.Synchronous only system with governors

Synchronous only system with governor is the a power system which involves the primary control (governors) to enable generations' generated power gradually restore back to the initial power output. It is expected that the final frequency Δf_f of the governors with the steady state droop characterrisitc can have relatively small frequency deviation Δf_f and instantaneously become stable after a step increase in the load. As the frequency dependent load indicates that,

$$P_l(f) = P_{l0} * (1 + D * \Delta f) \quad (4)$$

If the governor frequency deviation is less so that the governor will be enabled to have smaller frequency deviation and will be characterised with smaller steady state droop characteristic. If the equation (4) has integrated with less Δf value, the final power output $P_l(f)$ will be approximately closer to P_{l0}. If Δf closes to 0, the term of D * Δf in the equation 4 can be neglected, so that

$$P_l(f) = P_{l0} * (1 + 0) = P_{l0}$$

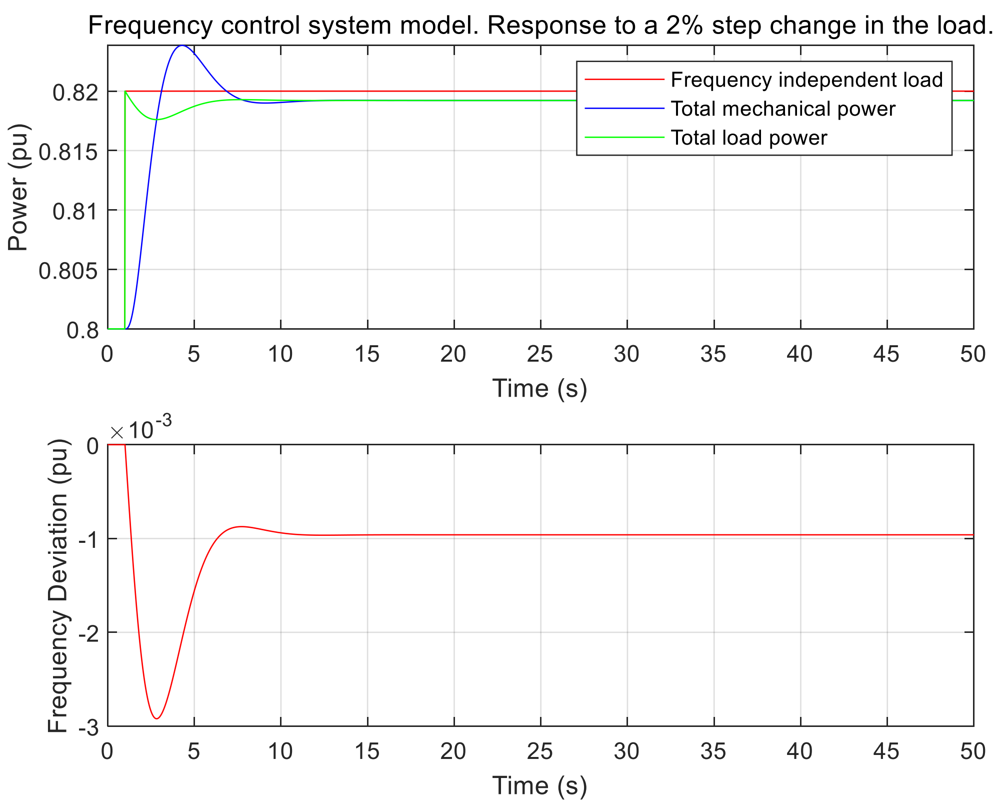

Figure 6: Frequency Control for the response of 2% change in the load in synchronous generation

Initial rate of change of frequency from the simulink study is

$$\text{Initial RoCof} = \frac{0+0.000608}{1-1.18} = -0.0028 \text{ pu}$$

Initial rate of change of frequency from the mathmatical analysis is calculated by the following computational process.

$$2 * \text{Hs} * \frac{d\Delta \text{f}}{dt} = P_m - P_t$$

$$\frac{d\Delta \text{f}}{dt} = - \frac{P_m - P_t}{2*Hs}$$

$$= - \frac{P_m - P_t}{7}$$

$$= - \frac{0.82 - 0.8}{7} = - 2.857 \text{ E } -3 \text{ pu} \qquad (2)$$

Therefore, it can be verified that the initial RoCof obtained from the simplified model is correct as comparing the result calculated from mathematical analysis. The initial RoCoF due to a power load chenge does not influenced by the governor and turbine since the intial Rocof is the instantaneous RoCoF after power system had an imbalance between power supply and its demand. Comparing the initial RoCof with the system without equipped frequency system control, initial Rate-of-change-of-frequency for frequency-controlled system and ungoverned are same so that the initial RoCof does not impact by governors and turbines.

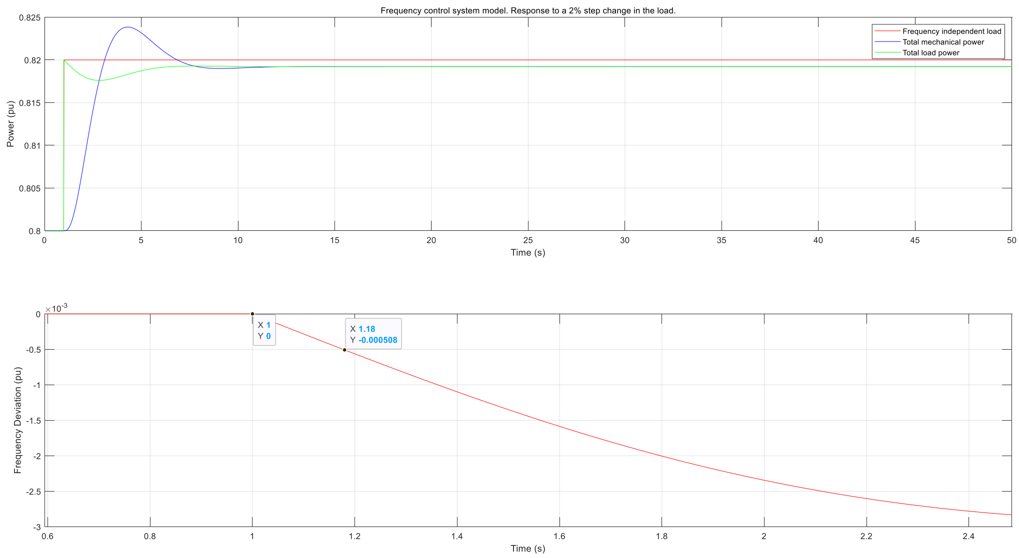

Figure 7: Initial RoCof Measurement

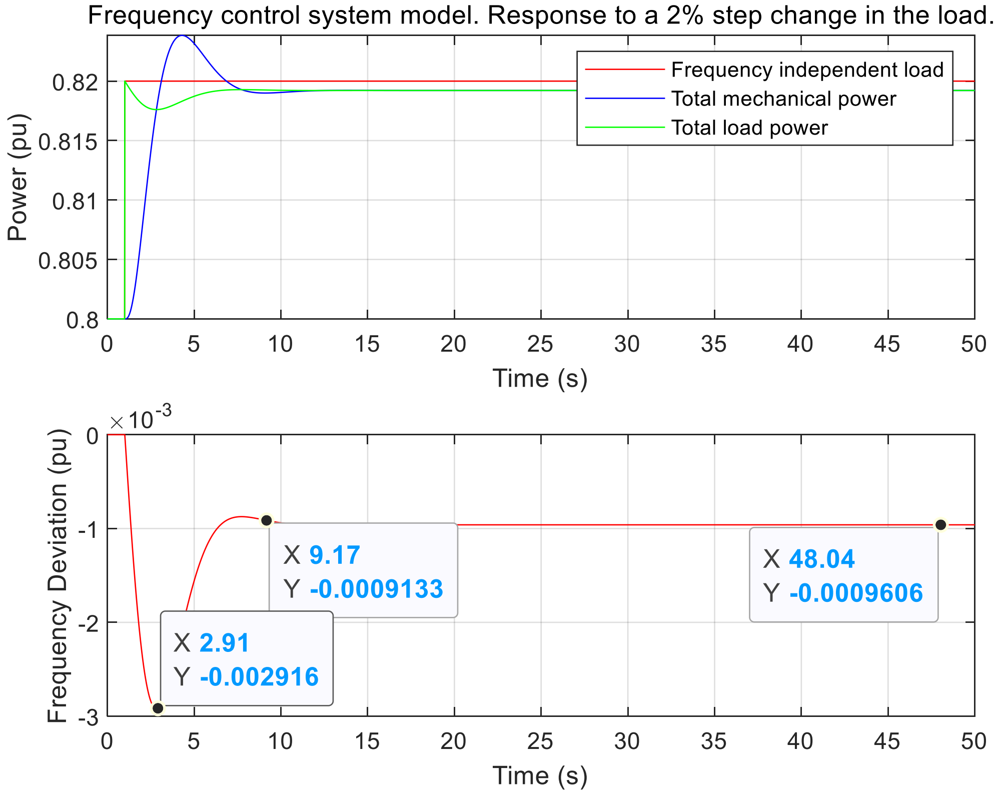

Figure 8: Frequency Control for the response of 2% change in the load in synchronous generation with labelling f_{max} and $t_{f_{max}}$

The maximum deviation in frequency Δf_{max} is -0.002918pu, which is marked and labeled on the figure below. $t_{f_{max}}$ is 2.77s which occurs after the step is applied. In terms of response settling time, once the frequency deviation is settling down to the range within (1 +(-) 0.05) *Δf_f abd remaining within the range, then the system will restore in 'settling' status. The final frequency deviation Δf_f is -0.0009606. Therefore, the lower bound of (1 + 0.05) *Δf_f is -0.001008 and upper bound is (1 - 0.05) *Δf_f which is -0.000912. From Figure 8, it can be identified that the system frequency took 9.17s to settle to within 5% of final frequency deviation. For plotting the Turbine power Output Pmt and Gvovernor Valve Position G, the modification on Matlab code has been shown below.

```
subplot(2,1,1);
plot(response.DF.Time,response.PMT.data,'g')
ylabel('Turbine Power Output (pu)')
xlabel('Time (s)')
ylim([0.8 0.825])
grid on
title("Turbine Power Output Pmt");

subplot(2,1,2);
plot(response.DF.Time,response.G.data ,'b')
xlabel('Time (s)')
ylabel('Governor position (pu)')
ylim([0.8 0.86])
grid on
title('Governor Valve Position G')
```

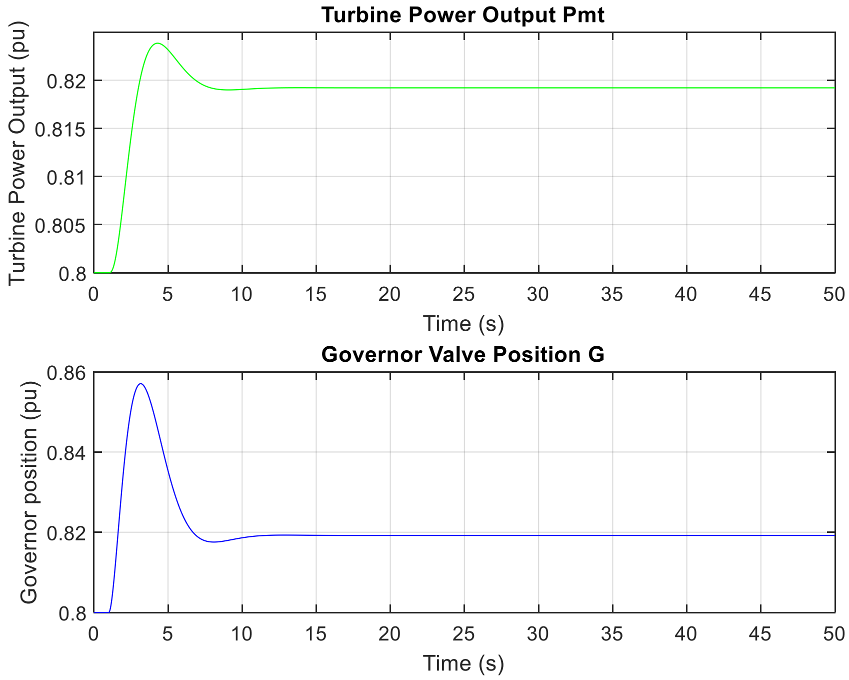

Figure 9: Plot for turbine power output Pmt and the governor valve position G

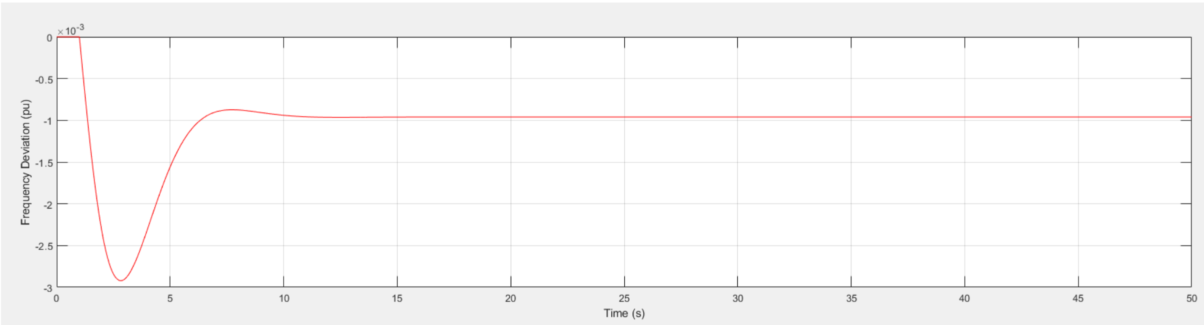

Figure 10: Plot for frequency deviation Δf

Comparing with figure 9(bottom) plot for governor and figure 10 plot for frequency deviation Δf

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

In this section, it is aimed to explore the frequency control of a power system that performed only by governors which equipped in synchronous generators. Factors that influence the system frequency control are investigated. Some measures to assess frequency control have taken into account include assessments as follows,

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_{max}, when it occurs after step is applied

Factors Investigation

Investigate the effect of varying the synchronous machine inertia constant, Hs, within the range from 1.0 to 6.0 pu.s on S_{sb}.

Hs = 1

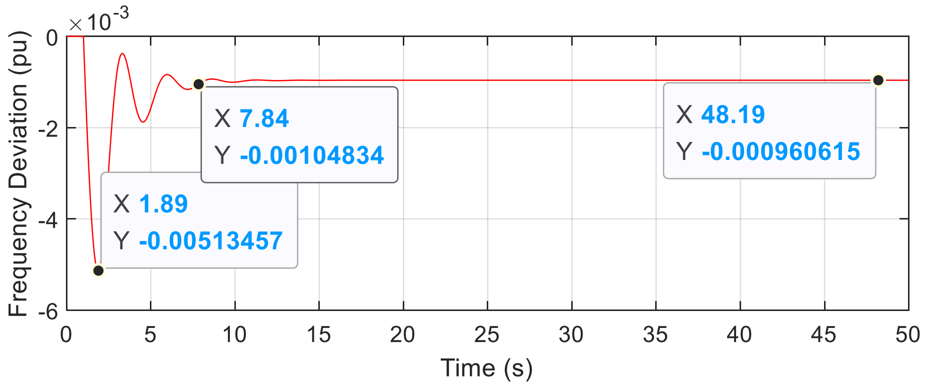

Figure 11: Synchronous generator only frequency control (H=1)

Hs=2

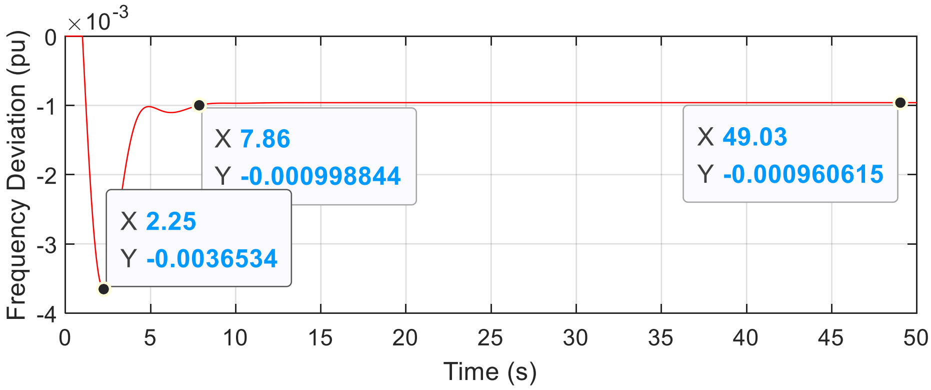

Figure 12: Synchronous generator only frequency control (H=2)

Hs=3

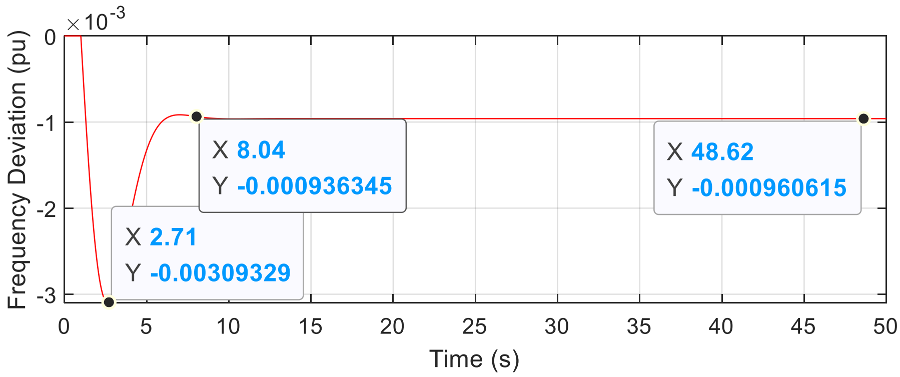

Figure 13: Synchronous generator only frequency control (H=3)

Hs = 3.5

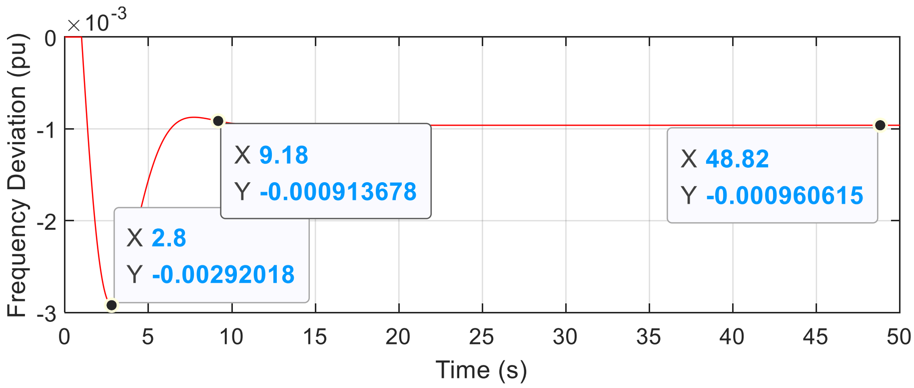

Figure 14: Synchronous generator only frequency control (H=3.5)

Hs=4

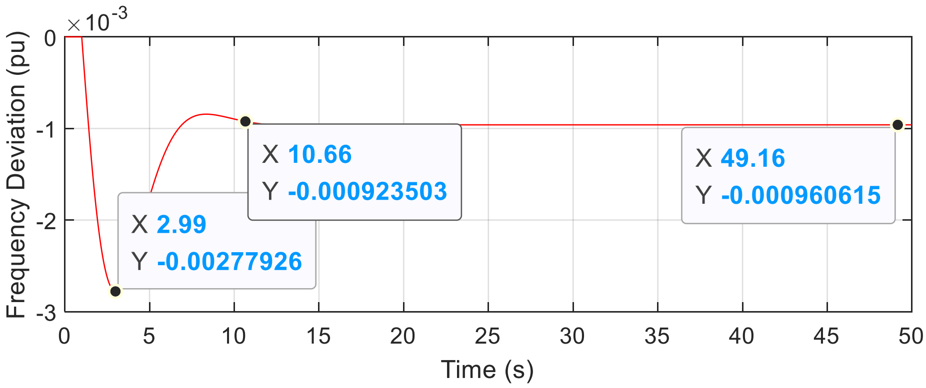

Figure 15: Synchronous generator only frequency control (H=4)

Hs=5

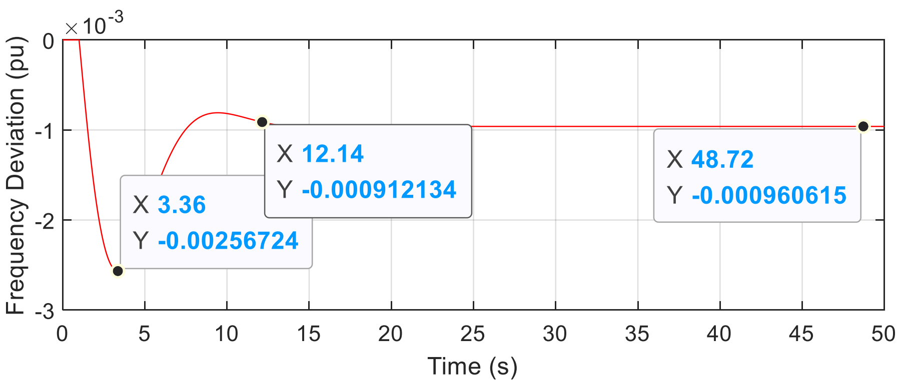

Figure 16: Synchronous generator only frequency control (H=5)

Hs=6

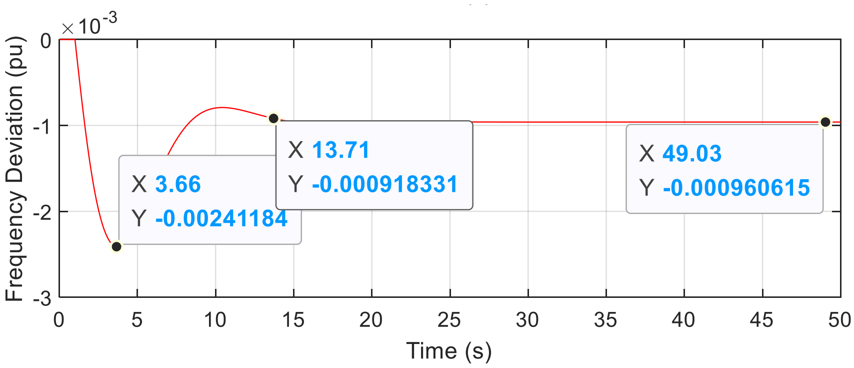

Figure 17: Synchronous generator only frequency control (H=6)

Hs [pu.s]	Δf_f [pu]	Initial RoCof [pu]	5% Settling time [s]	Δf_{max} [pu]	t_{max} [s]
1	-0.00096	-0.00979	7.84	-0.00513	1.86
2	-0.00096	-0.00492	7.86	-0.00365	2.25
3	-0.00096	-0.00336	8.04	-0.00309	2.71
3.5	-0.00096	-0.00282	9.18	-0.00292	2.8
4	-0.00096	-0.00238	10.66	-0.00278	2.99
5	-0.00096	-0.00197	12.14	-0.00257	3.36
6	-0.00096	-0.00164	13.71	-0.00241	3.66

Table 2: Synchronous generator only frequency control with vary Hs from 1.0 to 6.0

From the table 2 above, it can be observed the trending for 4 measurements regarding frequency response while synchronous machine inertia constant Hs raises from 1 to 6. Final steady frequency Δf_f does not impact by the increase of Hs which is constantly remained at -0.00096 pu. However, with the increase of Hs, initial RoCof and Δf_{max} were lower accordingly in inversely proportional with the Hs Settling time and the time when the maximum frequency deviation occurs are getting later when the Hs is increasing.

From the figure 11, it shows the synchronous generator only frequency control while Hs =1. There appear some descent oscillations in prior to entering the settling range.

Investigate the effect of varying the governor droop, R, within the range from 1.0 to 8.0 % on S_{spb}

R = 0.01

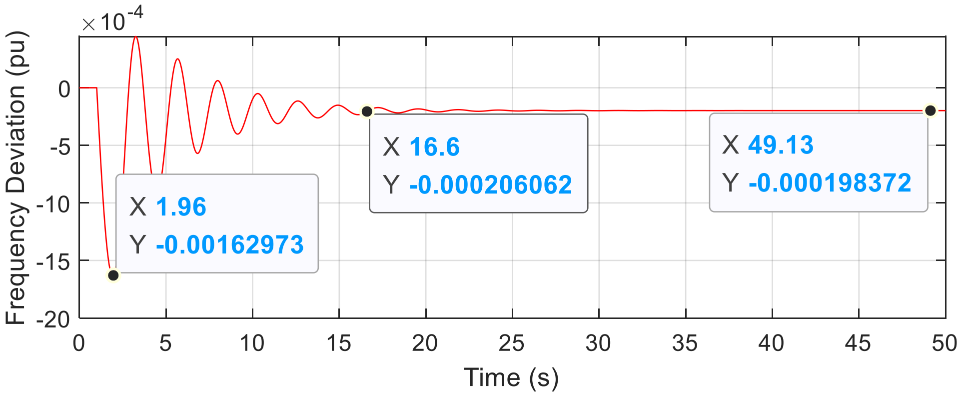

Figure 18: Synchronous generator only frequency control (R=0.01)

R = 0.02

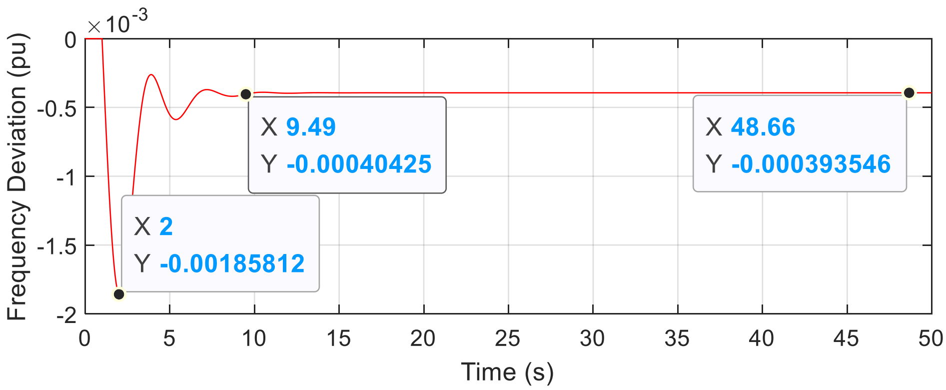

Figure 19: Synchronous generator only frequency control (R=0.02)

R = 0.04

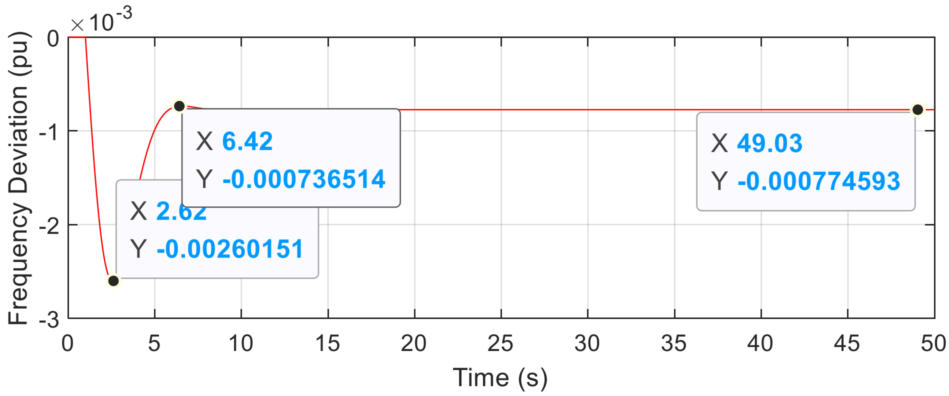

Figure 20: Synchronous generator only frequency control (R=0.04)

R =0.06

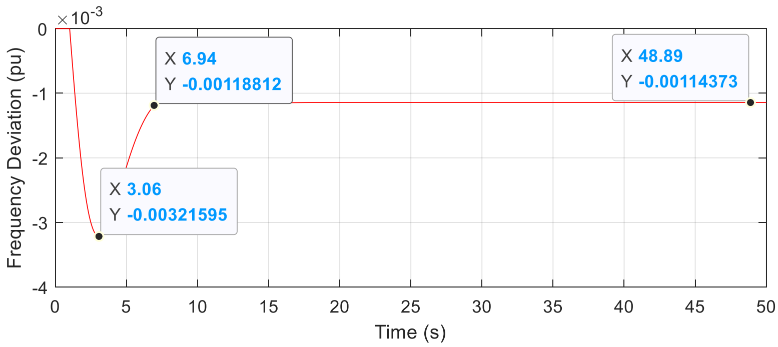

Figure 21: Synchronous generator only frequency control (R=0.06)

R = 0.08

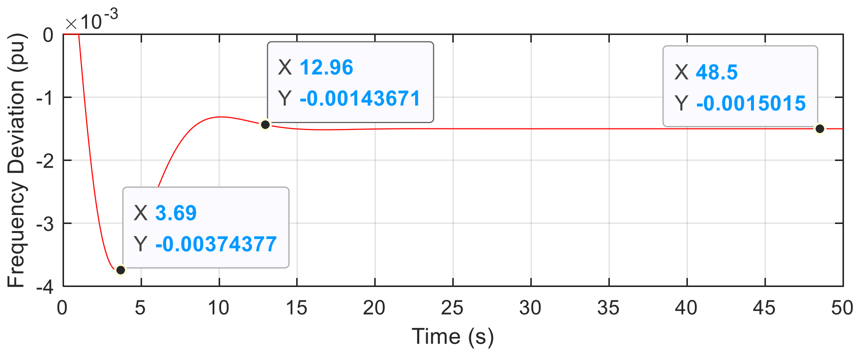

Figure 21: Synchronous generator only frequency control (R=0.08)

R	Δf_f [pu]	Initial RoCof [pu]	5% Settling time [s]	Δf_{max} [pu]	t_{max} [s]
0.01	-0.000198	-0.00282	16.6	-0.00163	1.96
0.02	-0.000393	-0.00284	9.49	-0.00186	2.00
0.04	-0.000775	-0.00285	6.42	-0.00260	2.62
0.06	-0.001143	-0.00282	6.94	-0.00322	3.06
0.08	-0.001501	-0.00289	12.96	-0.00374	3.69

Table 3: Synchronous generator only frequency control with vary R from 0.01 to 0.08

According to the table and figures above, with the varying droop constant R from 0.01 to 0.08 increasingly, it has affected Δf_f final steady frequency deviation tends to have larger deviation accordingly while Δf_{max} has the same trend to become larger. This is because droop R affects the speed of generator turning speed so that larger droop meant to provide the larger frequency deviation for the power system. When R = 0.01, the system does not in stable status and causes some oscillations since the little droop R of a synchronous generators unable to regulate the generation speed instantiously after a step increase in power load.

Investigate the effect of reducing the proportion of online synchronous generation capacity

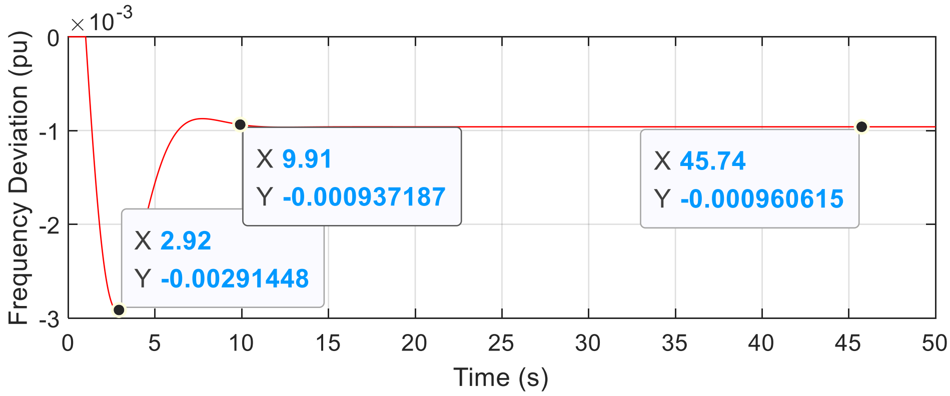

Figure 22: Synchronous generator only frequency control (a_sb = 1)

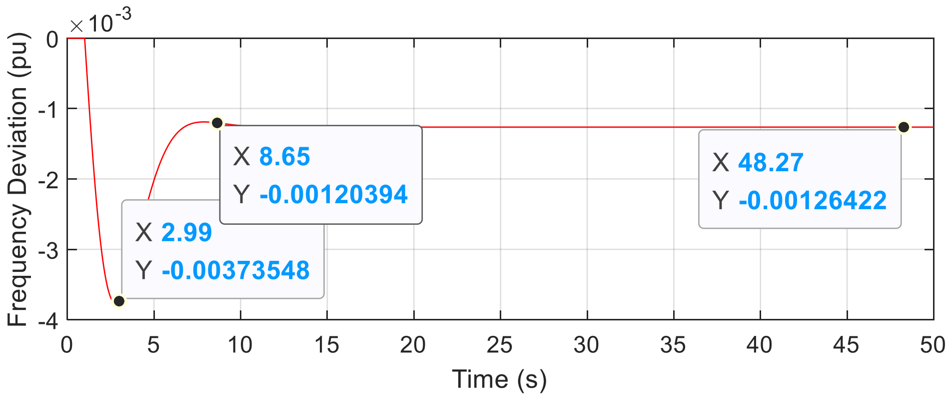

Figure 23: Synchronous generator only frequency control (a_sb = 0.75)

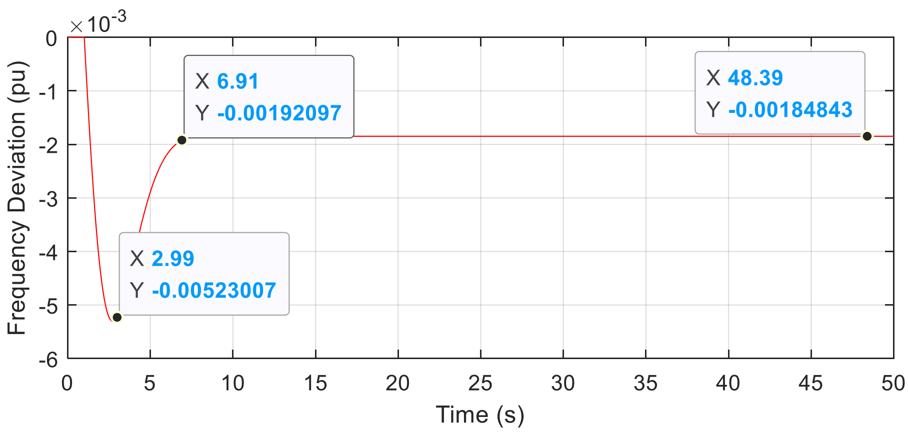

Figure 23: Synchronous generator only frequency control (a_sb = 0.5)

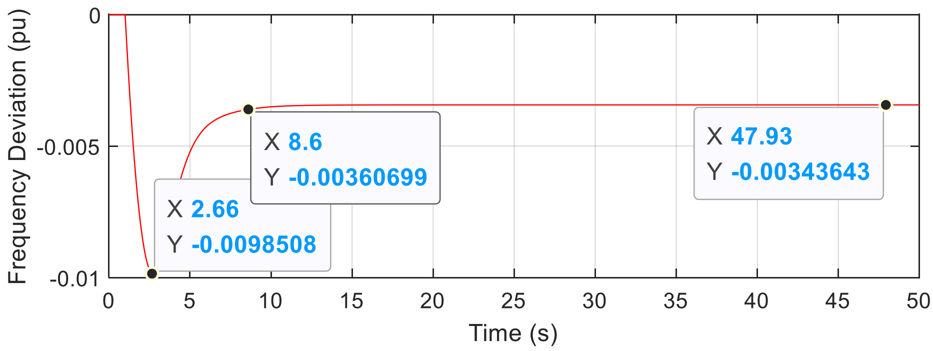

Figure 24: Synchronous generator only frequency control (a_sb = 0.25)

a_Sb	Δf_f [pu]	Initial RoCof [pu]	5% Settling time [s]	Δf_{max} [pu]	t_{max} [s]
1	-0.00096	-0.002632	9.91	-0.00291	2.92
0.75	-0.00126	-0.003709	8.86	-0.00374	2.97
0.5	-0.00184	-0.005562	6.91	-0.00531	2.74
0.25	-0.00343	-0.010612	8.60	-0.00985	2.66

Table 5: Synchronous generator only frequency control with vary Sb from 1 to 0.25

With the reduction of proportion of online synchronous generation capacity from 1 in steps of 25% to 25%, there has the significant effects on the final frequency deviation and maximum frequency deviation where both are increasingly along with the a_sb reduction. This is since the synchronous generation capacity is reduced so that the total amount of the power generation is decreased accordingly. Lower generated power causes from generators causes governor has less capability to maintain the frequency with the droop characteristic. Therefore, there has the larger frequency deviation while a_Sb is lowering.

5. Modelling of asynchronous frequency control

This section is to model an asynchronous source and equips with a frequency controller. This model is a mixed with synchronous source generator and synchronous source. Figure 25 below has demonstrated the highest level of simplified modelling of asynchronous frequency control in Matlab Simulink.

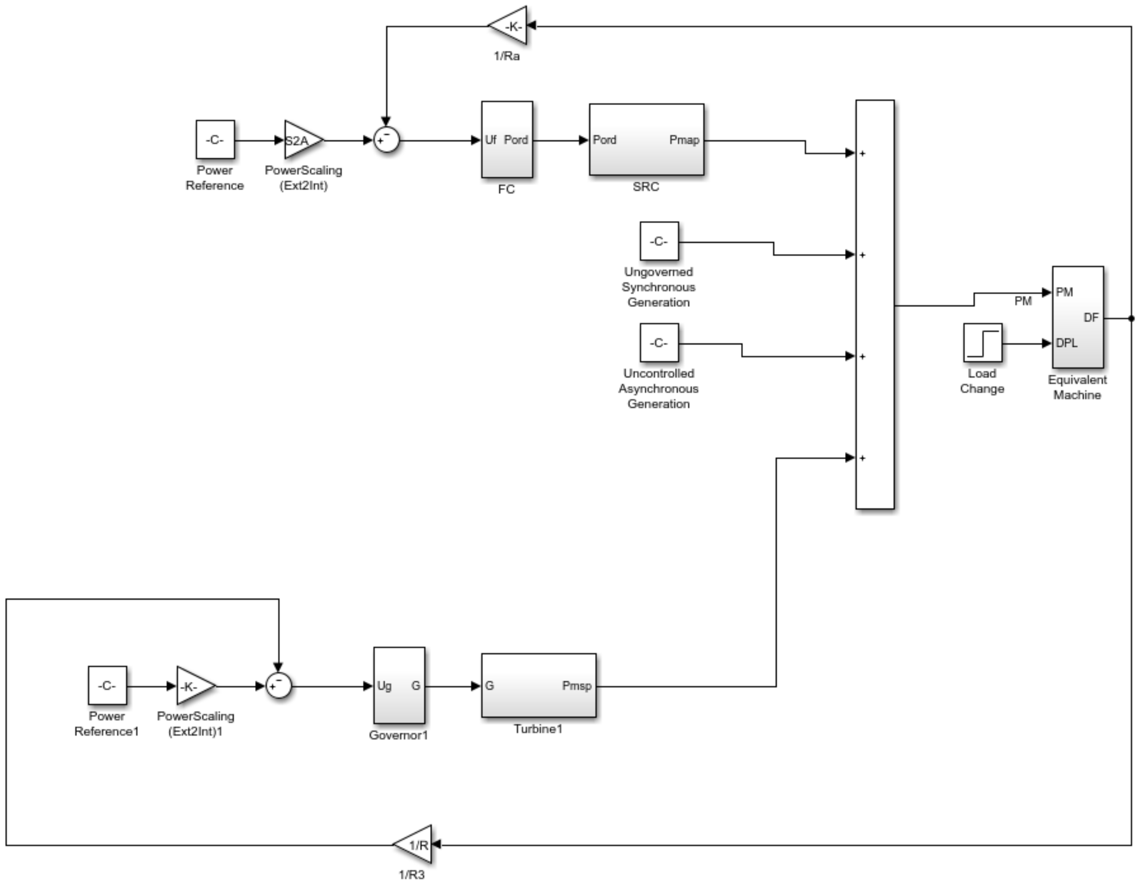

Figure 25: Highest level Hierarchy of asynchronous frequency control model

In the figure 25, upper part is the model for asynchronous generator and lower part is the modelling for synchronous generation source. The structure for both synchronous and asynchronous source modelling are similar, power reference connected a gain block and received Δf * 1/R, which is the product for Δp and taking the sum of parameters with P and - Δp to governor 1 block and then turbine block. For asynchronous source, initial input is power reference of Pmap0 and follows by signalising a gain block with the value of S2A, the conversion factor to convert power from a power base of Sb to a base of Sapb. Subsequently, a sum block is to sum the variables of power and Δp to frequency controller model and thereafter asynchronous source (SRC) block. The lower hierarchy for blocks of FC, SRC and blocks' setting parameters are shown in the following figures and tables.

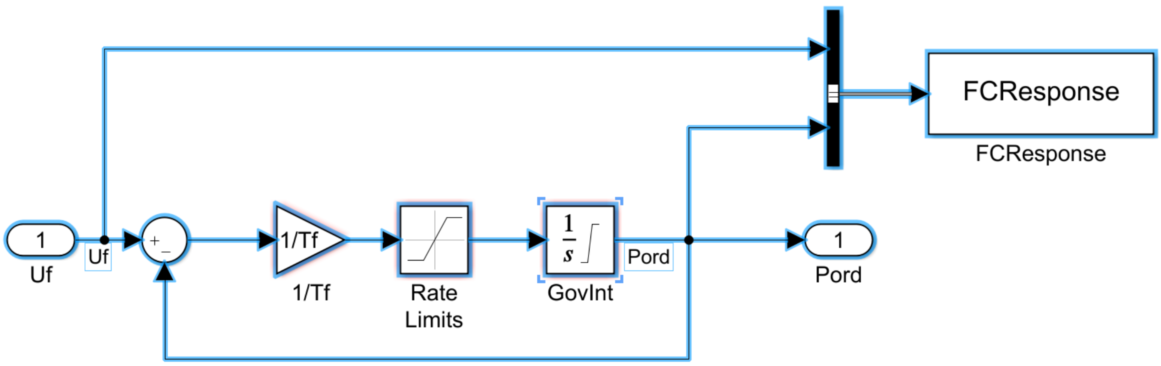

Figure 25: Frequency Controller Model

Block	Parameter	Item	Value
1/Tf	Gain	Tf	0.1
Rate Limits	Upper Limit	Rmx	0.1
Rate Limits	Lower Limit	Rmn	-0.1
GovInt	Initial condition	G0	Pmsp0 * SYS2SYN
GovInt	Upper Limit	Pmx	0.1
GovInt	Lower Limit	Pmn	0.0

Table 6: Parameter Setting for Frequency Controller Model Block

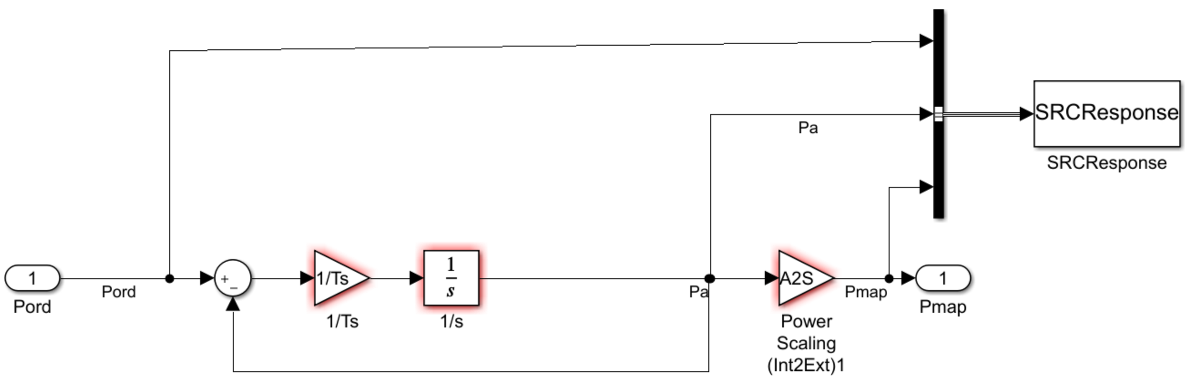

Figure 26: Asynchronous Source Model

Block	Parameter	Item	Value
1/Ts	Gain	Ts	0.08
1/s	Initial condition	G0	Pmsp0 * SYS2SYN
A2S	Gain	A2S	(1-a_sb)*a_apb

Table 7: Parameter Setting for Asynchronous Source Model Block

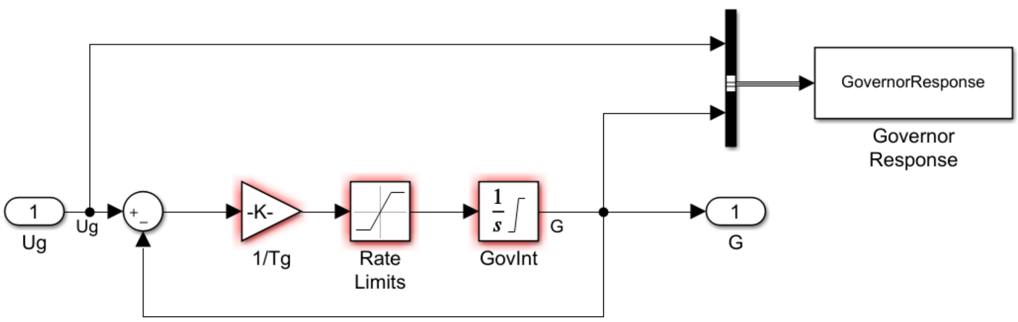

Figure 27: Governor Model

Block	Parameter	Item	Value
1/Tg	Gain	Tg	0.3
Rate Limits	Upper Limit	LR	0.1
Rate Limits	Lower Limit	LL	-1.0
GovInt	Initial condition	G0	Pmsp0 * SYS2SYN
GovInt	Upper Limit		1
GovInt	Lower Limit		0

Table 6: Parameter Setting for Governor Model Block

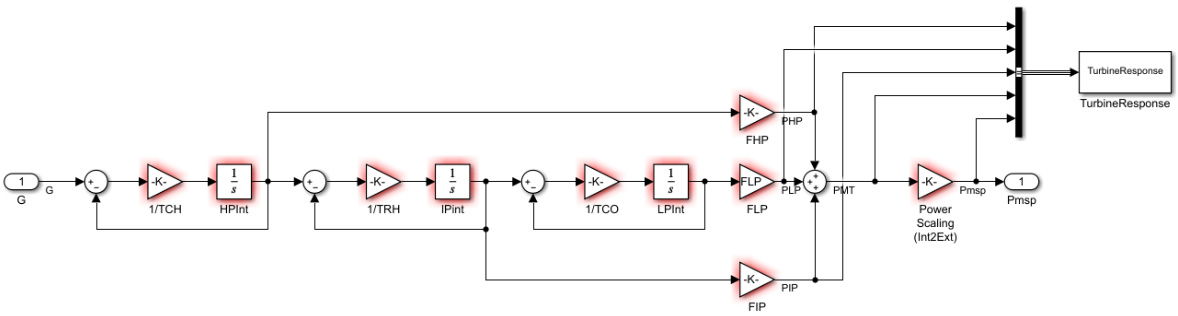

Figure 27: Turbine Model

To achieve simulating modelled asychronous frequency control, it is essential to mdeify the programming code in Matlab script to ensure the connected moodel can preform the frequency control for a simulated power system. The following piece of code is the edited part of Matlab code file FrequencyControlSystem_SimDriver.m. Completed version of Matlab code has been attached in the appendix.

```
% Asynchronous source / frequency controller model parameters

Ra       = problem.Ra;
Tf       = problem.Tf;
Rmx      = problem.Rmx;
Rmn      = problem.Rmn;
Pmx      = problem.Pmx;
Pmn      = problem.Pmn;
Ts       = problem.Ts;

A2S = (1-a_sb)*a_apb;

if (abs(A2S) > 0)
      S2A = 1 / A2S;
else
      S2A = 1.0;
End

response.Uf   = simout.FCResponse.Uf;
response.Pord = simout.FCResponse.Pord;
response.Pord  = simout.SRCResponse.Pord;
response.Pa   = simout.SRCResponse.Pa;
response.Pmap  = simout.SRCResponse.Pmap;
```

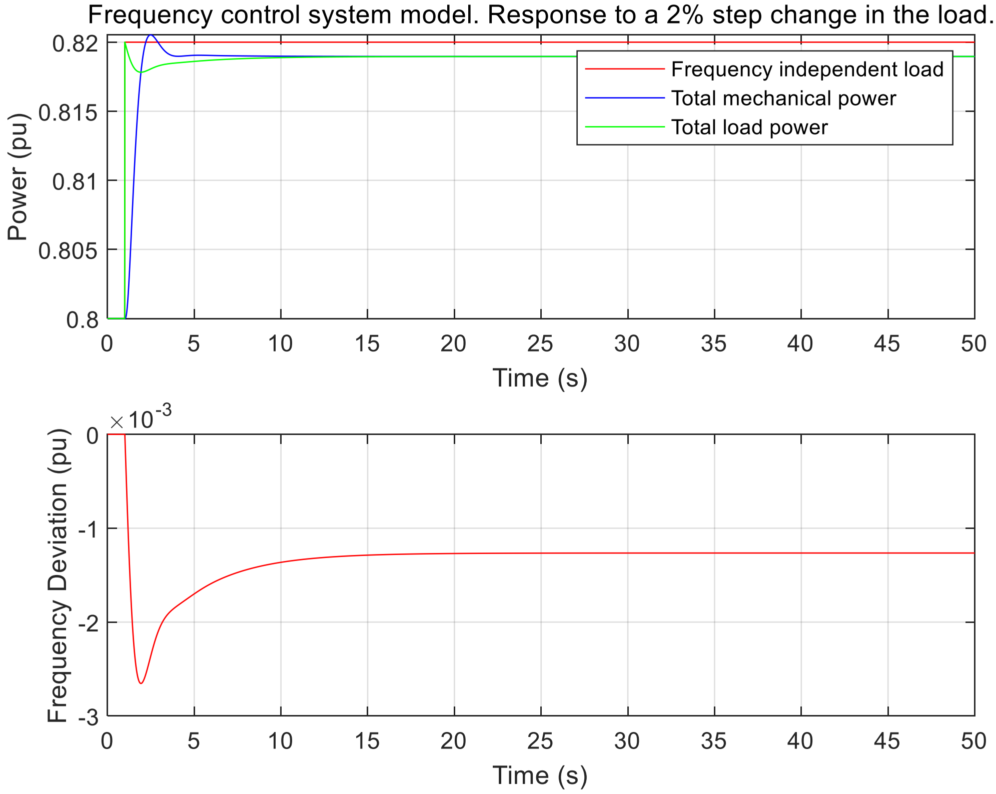

Figure 28: Frequency Control System Model for asynchronous Frequency control

Figure 28 is the frequency control system model for asynchronous frequency control and from the figure it can be discovered that the asynchronous source model has a faster response than the synchronous generators.

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

In this section, it is aimed to explore the frequency control of a power system that performed by the mixture of synchronous and asynchronous frequency controls. Factors that influence the system frequency control are investigated. Some measures to assess frequency control have taken into account include assessments as follows,

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_{max}, when it occurs after step is applied

Investigate the effect of varying the synchronous machine inertia constant, Hs, within the range from 1.0 to 6.0 pu.s on S_{sb}.

Hs = 1

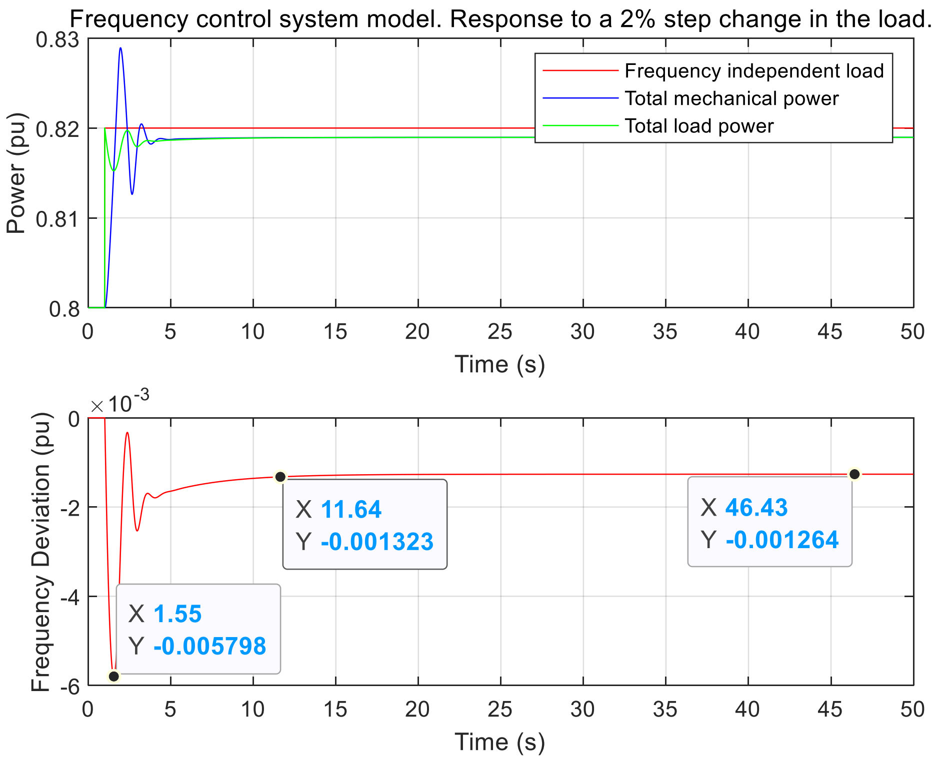

Figure 29: Mixture of asynchronous and synchronous generators frequency control (Hs = 1)

Hs =2

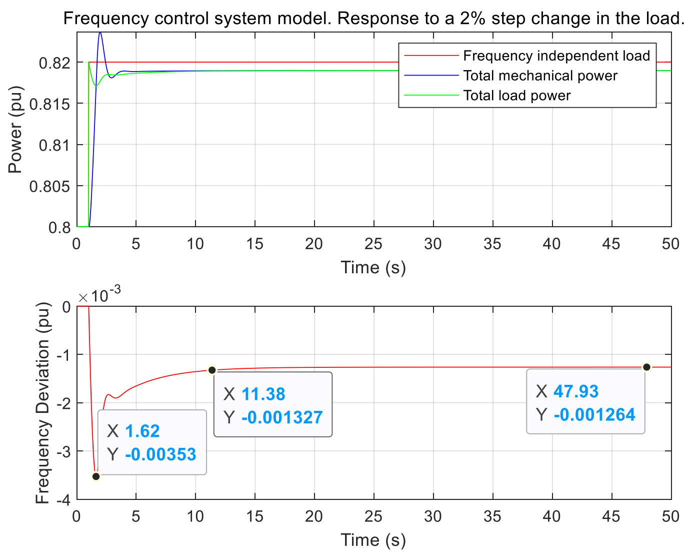

Figure 30: Mixture of asynchronous and synchronous generators frequency control (Hs = 2)

Hs = 3

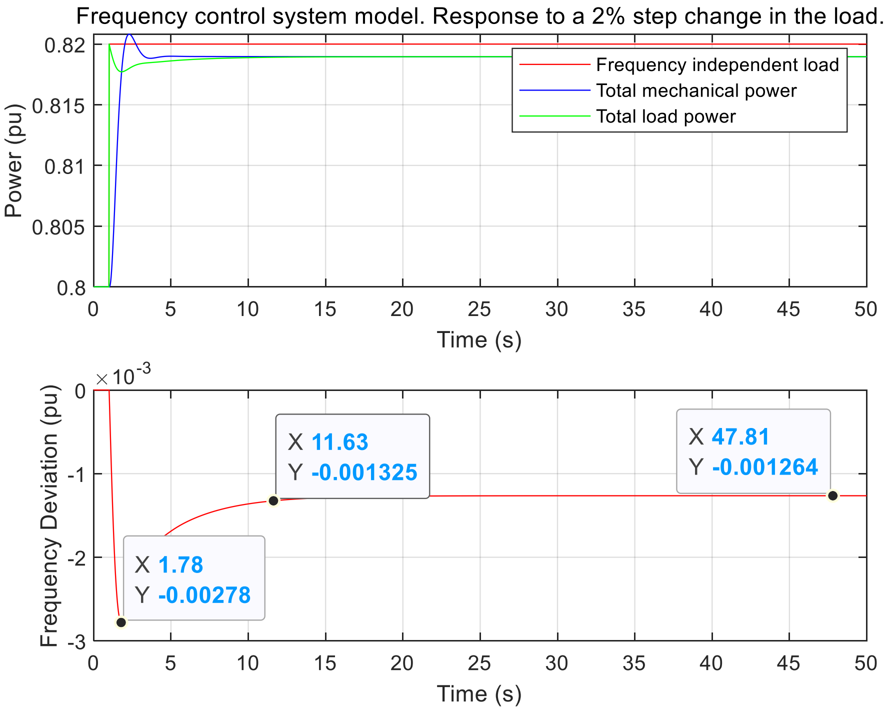

Figure 31: Mixture of asynchronous and synchronous generators frequency control (Hs = 3)

Hs = 4

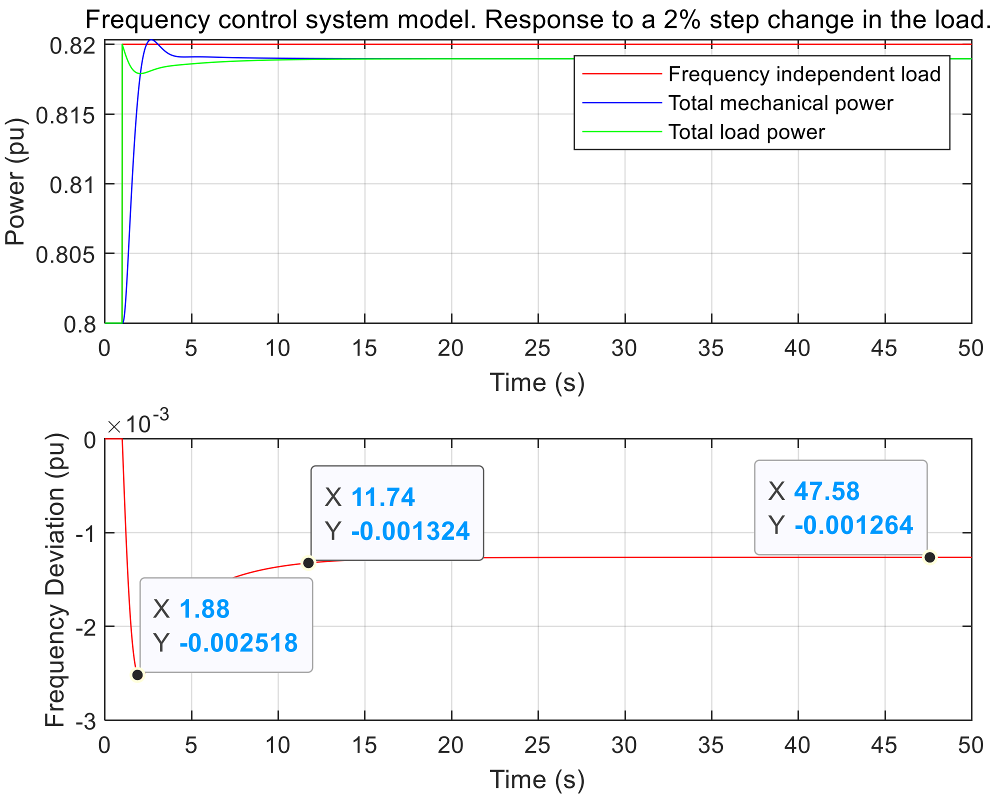

Figure 32: Mixture of asynchronous and synchronous generators frequency control (Hs = 3)

Hs = 6

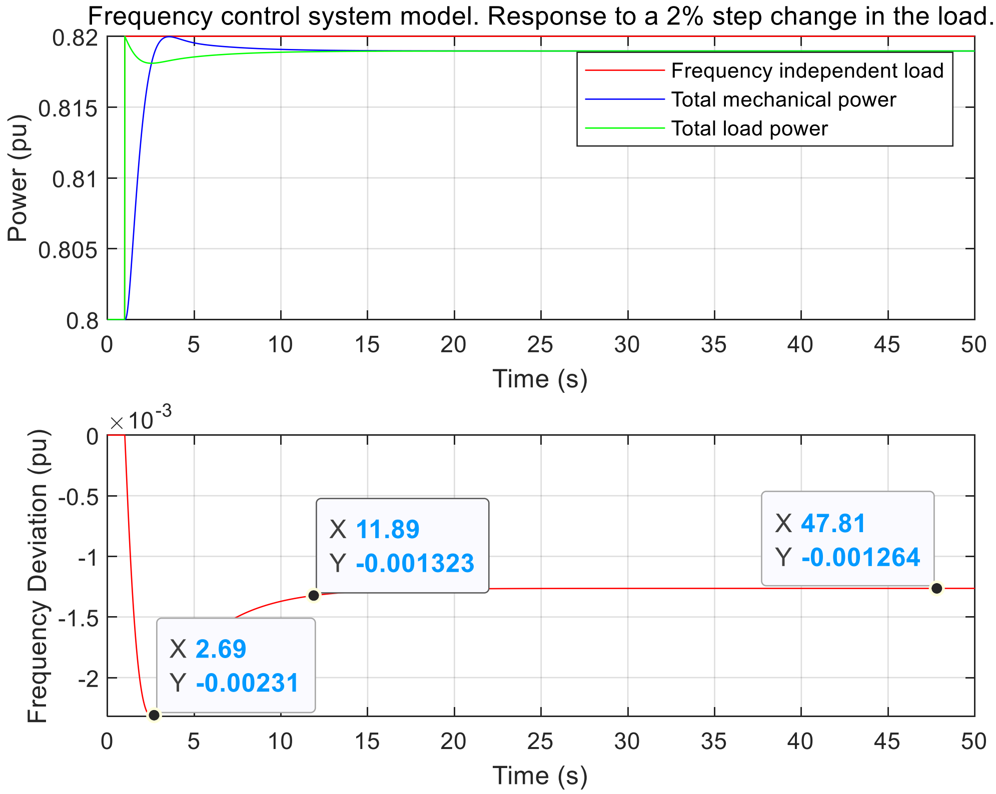

Figure 32: Mixture of asynchronous and synchronous generators frequency control (Hs = 6)

Hs [pu.s]	Δf_f [pu]	Initial RoCof [pu]	5% Settling time [s]	Δf_{max} [pu]	t_{max} [s]
1	-0.001264	-0.01848	11.64	-0.005798	1.55
2	-0.001264	-0.00979	11.38	-0.00353	1.62
3	-0.001264	-0.00652	11.63	-0.00278	1.78
4	-0.001264	-0.00489	11.74	-0.00252	1.88
6	-0.001264	-0.00324	11.89	-0.00231	2.69

Table 7: Mixture of asynchronous and synchronous generators frequency control with vary Hs from 1.0 to 6.0

Investigate the effect of varying the governor droop, R, within the range from 1.0 to 8.0 % on S_{spb}

R = 0.01

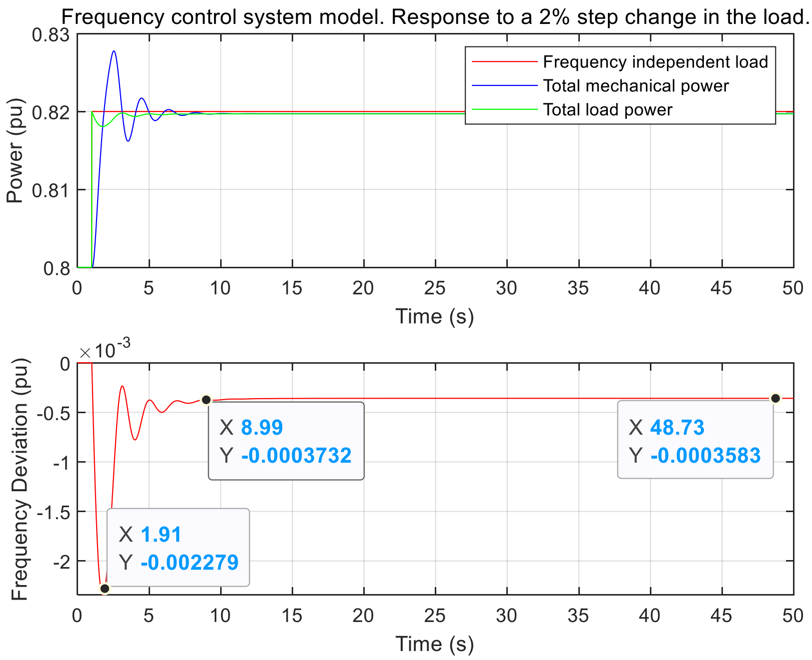

Figure 34: Mixture of asynchronous and synchronous generators frequency control (R=0.01)

R = 0.02

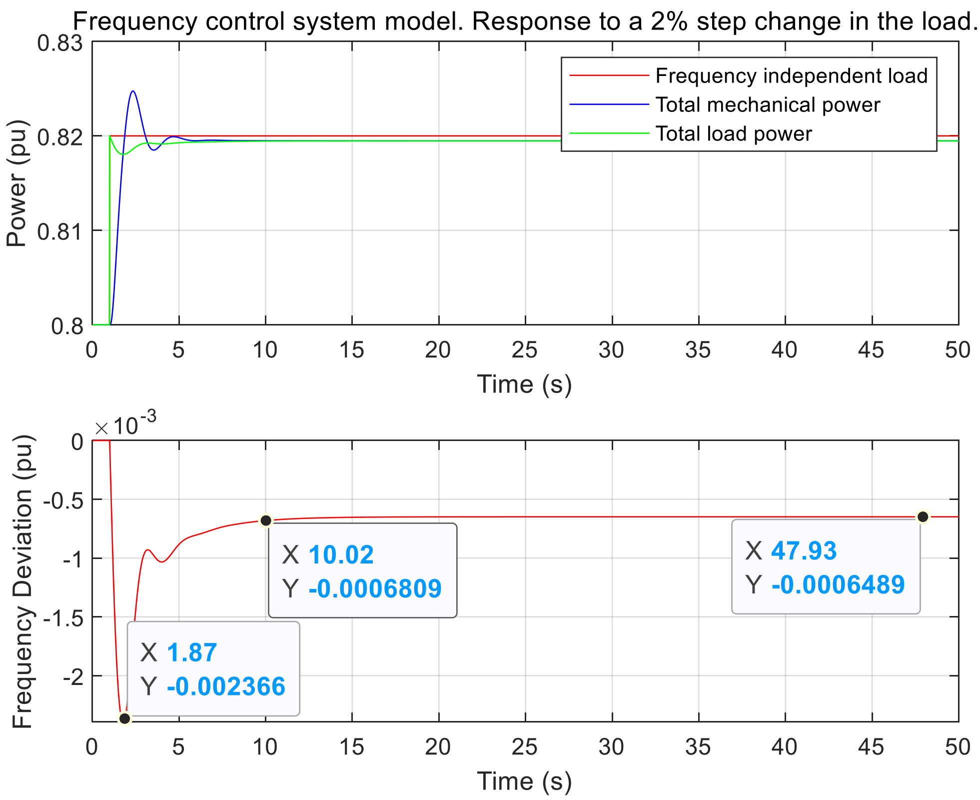

Figure 35: Mixture of asynchronous and synchronous generators frequency control (R=0.02)

R = 0.04

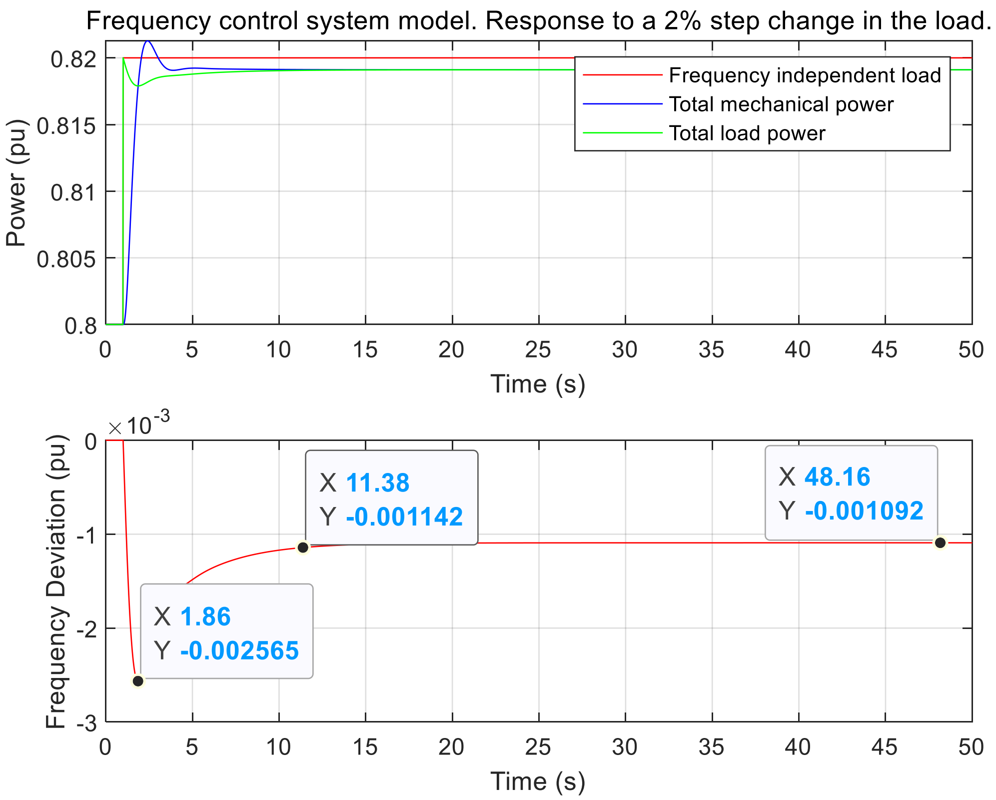

Figure 35: Mixture of asynchronous and synchronous generators frequency control (R=0.04)

R = 0.06

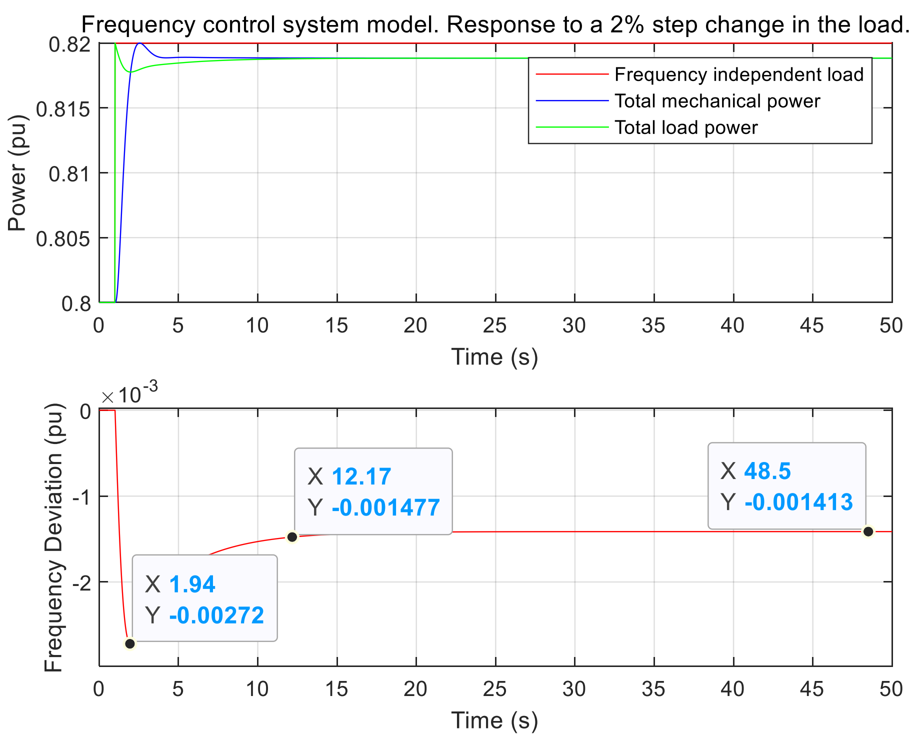

Figure 36: Mixture of asynchronous and synchronous generators frequency control (R=0.06)

R	Δf_f [pu]	Initial RoCof [pu]	5% Settling time [s]	Δf_{max} [pu]	t_{max} [s]
0.01	-0.000358	-0.00563	8.99	-0.00228	1.91
0.02	-0.000649	-0.00552	10.02	-0.002366	1.87
0.04	-0.001092	-0.00555	11.38	-0.002565	1.86
0.06	-0.001413	-0.00557	12.17	-0.00272	1.94

Table 8: Mixture of asynchronous and synchronous generators frequency control with vary R from 0.01 to 0.06

7 Conclusion

During this practical based assignment, students explored the frequency control analysis for a power system under various conditions. Factors that influence the power system frequency control were conducted by using the Matlab and Simulink to simulate a power system and observe the effects on the frequency by modifying the parameters. A simplified model for governors only model was used to conduct the frequency control analysis for the primary control only simulating model and a simplified model has been designed and constucted on Simulink by students to simulate the case of mixture of asynchronous and synchronous generators to further analysis the effect on a power system frequency control. From this assignment, students applied the knowledge from lectures and tutorials of ELEC ENG 3110 to a practical case for strengthen the theorical knowledge understanding level and gained the hands-on practical experience on the electric power system frequency control by using the Matlab and Simulink and also acquired the essential skills on Matlab programming and Simulink Simulation.

Appendix A: Matlab Code for FrequencyControlSystem_SimDriver.m

```
function response = FrequencyControlSystem_SimDriver(problem)

% Capacity fractions

a_sb     = problem.a_sb;
a_spb    = problem.a_spb;
a_apb    = problem.a_apb;

% Initial load fractions

b_sp     = problem.b_sp;
b_su     = problem.b_su;
b_ap     = problem.b_ap;
b_au     = problem.b_au;

% Equivalent generator parameters

Hs       = problem.Hs;
D        = problem.D;

% Turbine / governor model parameters

R        = problem.R;
Tg       = problem.Tg;
LR       = problem.LR;
LL       = problem.LL;
TCH      = problem.TCH;
TRH      = problem.TRH;
TCO      = problem.TCO;
FHP      = problem.FHP;
FIP      = problem.FIP;
FLP      = problem.FLP;

% Simulation parameters

DPLStep = problem.DPLStep;
TSTOP    = problem.TSTOP;
IsPlot   = problem.IsPlot;
ifig     = problem.ifig;

% Asynchronous source / frequency controller model parameters

Ra       = problem.Ra;
Tf       = problem.Tf;
Rmx      = problem.Rmx;
Rmn      = problem.Rmn;
Pmx      = problem.Pmx;
Pmn      = problem.Pmn;
Ts       = problem.Ts;

% Convert inertia constant to per-unit on the system MVA base (Sb)
H      = a_sb * Hs;

% Calculate initial steady-state output from each type of generation and
```

```matlab
% calculate the total system load (all in pu on Sb).
Pmsp0 = b_sp * a_spb * a_sb;
Pmsu0 = b_su * (1 - a_spb) * a_sb;
Pmap0 = b_ap * a_apb * (1 - a_sb);
Pmau0 = b_au * (1 - a_apb) * (1 - a_sb);
PL0   = Pmsp0 + Pmsu0 + Pmap0 + Pmau0;

% Base conversion from turbine to system base
SYN2SYS = a_spb * a_sb;

% Base conversion from the system to turbine. We need to gracefully handle
% situations when no synchronous generation is enabled for frequency
control.
if (abs(SYN2SYS) > 0)
   SYS2SYN = 1 / SYN2SYS;
else
   SYS2SYN = 1.0;
end

A2S  = (1-a_sb)*a_apb;

if (abs(A2S) > 0)
   S2A = 1 / A2S;
else
   S2A = 1.0;
end


% Initial valve opening (in per-unit on the turbine rating).
G0 = Pmsp0 * SYS2SYN;

response.H     = H;
response.Pmsp0 = Pmsp0;
response.Pmsu0 = Pmsu0;
response.Pmap0 = Pmap0;
response.Pmau0 = Pmau0;
response.PL0   = PL0;
response.G0    = G0;

% The simulation duration (StopTime) is TSTOP.
% We drive the Simulink simulation directly from Matlab. This facilitates
% the conduct of multiple simulations under program control rather than
% requiring the user to interactively drive the simulations.
simout = sim('FrequencyControlSystem', ...
             'SrcWorkspace', 'current', ...
             'StopTime',    num2str(TSTOP));

% The response data is stored in the simout sub-system components. It is
more
% convenient to promote selected responses to be directly accessible from
% the response structure

response.Uf   = simout.FCResponse.Uf;
response.Pord = simout.FCResponse.Pord;
response.DF   = simout.EquivalentMachineResponse.DF;
response.PM   = simout.EquivalentMachineResponse.PM;
response.PL   = simout.EquivalentMachineResponse.PL;
response.DPL = simout.EquivalentMachineResponse.DPL;
```

```
response.Pord  = simout.SRCResponse.Pord;
response.Pa  = simout.SRCResponse.Pa;
response.Pmap  = simout.SRCResponse.Pmap;
response.Ug  = simout.GovernorResponse.Ug;
response.G   = simout.GovernorResponse.G;

response.Pmsp = simout.TurbineResponse.Pmsp;
response.PHP  = simout.TurbineResponse.PHP;
response.PIP  = simout.TurbineResponse.PIP;
response.PLP  = simout.TurbineResponse.PLP;
response.PMT  = simout.TurbineResponse.PMT;

% Produce a simple Matlab plot of the monitored variables. This is
convenient
% for immediate feedback on the response of the model. However, for the
purpose
% of report writing it is usually necessary to overlay on a single figure
% responses from multiple simulation studies so the comparisons in
performance
% can be made easily.

deltaF = -0.0009606;
% deltaF_U = deltaF *1.05;
% deltaF_L = deltaF *0.95;

if (IsPlot)
   figure(ifig)
   clf

   subplot(2,1,1);
   plot(response.DPL.Time,response.DPL.Data + PL0, 'r', ...
        response.PM.Time, response.PM.Data,        'b', ...
        response.PL.Time, response.PL.Data,        'g');
   ylabel('Power (pu)')

   xlabel('Time (s)')
   legend({'Frequency independent load', 'Total mechanical power', 'Total
load power'})
   grid on
   title(['Frequency control system model. Response to a '
num2str(DPLStep*100) ...
          '% step change in the load.'], 'Fontsize', 10, 'FontWeight',
'normal')

   subplot(2,1,2);
   plot(response.DF.Time,response.DF.Data,'r');
   hold on

%    plot(response.PM.Time, deltaF*1.05*ones(length(response.PM.Time)) ,
'b', ...
%          response.PM.Time, deltaF*0.95*ones(length(response.PM.Time)) ,
'g');

   xlabel('Time (s)')
   ylabel('Frequency Deviation (pu)')
   %legend({'Frequency independent load', 'Total mechanical power', 'Total
load power'})
   grid on
```

```
%    figure
%    subplot(2,1,1);
%    plot(response.DF.Time,response.PMT.data,'g')
%    ylabel('Turbine Power Output (pu)')
%    xlabel('Time (s)')
%    ylim([0.8 0.825])
%    grid on
%    title("Turbine Power Output Pmt");
%
%    subplot(2,1,2);
%    plot(response.DF.Time,response.G.data ,'b')
%    xlabel('Time (s)')
%    ylabel('Governor position (pu)')
%    ylim([0.8 0.86])
%    grid on
%    title('Governor Valve Position G')

end
```

Appendix B: Matlab Code for FCS_01.m file

```
% Capacity fractions
base_problem.a_sb    =  0.5;
base_problem.a_spb   =  1.0;
base_problem.a_apb   =  0.5;

% Load fractions
base_problem.b_sp    =  0.8;
base_problem.b_su    =  0.8;
base_problem.b_ap    =  0.8;
base_problem.b_au    =  0.8;

% Equivalent generator parameters
base_problem.Hs      =  3.5;
base_problem.D       =  1.0;

% Turbine-governor parameters
base_problem.R       =  0.05;
base_problem.Tg      =  0.3;
base_problem.LR      =  0.1;
base_problem.LL      = -1.0;
base_problem.TCH     =  0.3;
base_problem.TRH     =  7.0;
base_problem.TCO     =  0.5;
base_problem.FHP     =  0.3;
base_problem.FIP     =  0.3;
base_problem.FLP     =  0.4;

%Asynchronous source/frequency controller model parameters
base_problem.Ra     =  0.05;
base_problem.Tf     =  0.1;
base_problem.Rmx    =  0.1;
base_problem.Rmn    =  -0.1;
base_problem.Pmx    =  1.0;
base_problem.Pmn    =  0.0;
base_problem.Ts     =  0.08;


% Simulation parameters
base_problem.DPLStep = 0.02;
base_problem.TSTOP   = 50.0;
base_problem.IsPlot  = 1;
base_problem.ifig    = 1;

% We copy the base_problem parameters to p01 and run the simulation
p01 = base_problem;
r01 = FrequencyControlSystem_SimDriver(p01);

% We copy the base_problem parameters to p02 and set the fraction of
synchronous
% generation to 0.25 (which means that the fraction of asynchronous
generation
% is 0.75)
% Re-run the simulation with the adjusted parameters.
% p02        = base_problem;
% p02.a_sb   =  1;
% p02.ifig   =  2;
```

```
%
% r02 = FrequencyControlSystem_SimDriver(p02);
%
% p03       = base_problem;
% p03.a_sb  =  0.1;
% p03.ifig  =  3;
%
% r03 = FrequencyControlSystem_SimDriver(p03);



% Dalta f = -0.024


% Illustration of overlaying responses from multiple studies
% figure(3)
% clf
%plot(r01.DF.Time, r01.DF.Data, 'r', ...
%      r02.DF.Time, r02.DF.Data, 'b')

% set(gca,'xlim',[0,30])
% xlabel('Time (s)')
% ylabel('Frequency deviation (pu)')
% title('Effect of reducing the fraction of synchronous generation from 1.0
to 0.25', ...
%    'FontSize', 12, ...
%    'FontWeight', 'normal')
% grid on
% legend({'\alpha_{sp} = 1.0', '\alpha_{sp} = 0.25'}, 'location',
'SouthEast');
```